CHAPTER 12

BRAZING

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CHAPTER 12

BRAZING

INTRODUCTION

DEFINITION AND GENERAL DESCRIPTION

BRAZING JOINS MATERIALS by heating them in the presence of a filler metal having a liquidus above 840°F (450°C) but below the solidus of the base metals. Heating may be provided by a variety of processes. The filler metal distributes itself between the closely fitted surfaces of the joint by capillary action. Brazing differs from soldering, in that soldering filler metals have a liquidus below 840°F (450°C).

Brazing with silver alloy filler metals is sometimes called *silver soldering*, a nonpreferred term. Silver brazing filler metals are not solders; they have liquidus temperatures above 840°F (450°C).

Brazing does not include the process known as braze welding. Braze welding is a method of welding with a brazing filler metal. In braze welding, the filler metal is melted and deposited in grooves and fillets exactly at the points where it is to be used. Capillary action is not a factor in distribution of the brazing filler metal. Indeed, limited base metal fusion may occur in braze welding. Braze welding is described in greater detail beginning on page 414.

Brazing must meet each of three criteria:

(1) The parts must be joined without melting the base metals.
(2) The filler metal must have a liquidus temperature above 840°F (450°C).
(3) The filler metal must wet the base metal surfaces and be drawn into or held in the joint by capillary action.

To achieve a good joint using any of the various brazing processes described in this chapter, the parts must be properly cleaned and must be protected by either flux or atmosphere during the heating process to prevent excessive oxidation. The parts must be designed to afford a capillary for the filler metal when properly aligned, and a heating process must be selected that will provide the proper brazing temperature and heat distribution.

APPLICATIONS

THE BRAZING PROCESS is used to join together various materials for numerous reasons. By using the proper joint design, the resulting braze can function better than the base metals being joined. In many instances it is desireable to join different materials to obtain the maximum benefit of both materials and have the most cost- or weight-effective joint. Applications of brazing cover the entire manufacturing arena from inexpensive toys to highest quality aircraft engines and aerospace vehicles. Brazing is used because it can produce results which are not always available with other joining processes. Advantages of brazing to join components include:

(1) Economical for complex assemblies
(2) Simple way to join large joint areas
(3) Excellent stress and heat distribution
(4) Ability to preserve coatings and claddings
(5) Ability to join dissimilar materials
(6) Ability to join nonmetals to metals
(7) Ability to join widely different thicknesses
(8) Capability of joining precision parts
(9) Joints require little or no finishing
(10) Can do many parts at one time (batch processing)

Throughout this chapter, examples of brazing illustrate when to select brazing and how to design the joint and select braze materials best suited for the individual application.

PROCESS ADVANTAGES AND DISADVANTAGES

LIKE ANY JOINING process, brazing has both advantages and disadvantages. The advantages vary with the heating method employed, but in general, brazing will be very economical when done in large batches. A major benefit of brazing is the ability to take brazed joints apart at a later time. It can also join dissimilar metals without melting the base metals as required by other joining methods. In many instances, several hundred parts with many feet of braze joints can be brazed at one time. When protective atmosphere brazing is used, parts are kept clean and the heat treatment cycle may be employed as part of the brazing cycle.

Since the brazing process uses a molten metal to flow between the materials to be joined, there is the possibility of liquid metal interactions which are unfavorable. Depending on the material combinations involved and the thickness of the base sheets, base metal erosion may occur. In many cases, the erosion may be of little consequence, but when brazing heavily loaded or thin materials, the erosion can weaken the joint and make it unsatisfactory for its intended application. Also, the formation of brittle intermetallics or other phases can make the resulting joint too brittle to be acceptable.

A disadvantage with some of the manual brazing processes is that highly skilled technicians are required to perform the operation. This is especially true for gas torch brazing using a high melting point brazing filler metal.

Nevertheless, with the proper joint design, brazing filler metal, and process selection, a satisfactory brazing technique can be developed for most joining applications where it is not feasible to join the materials with a fusion welding process because of strength or economic considerations.

PRINCIPLES OF OPERATION

CAPILLARY FLOW IS the dominant physical principle that assures good brazements whenever both faying surfaces to be joined are wet by the molten filler metal. The joint must be spaced to permit efficient capillary action and resulting coalescence. More specifically, capillarity is a result of surface tension between base metal(s) and filler metal, protected by a flux or atmosphere, and promoted by the contact angle between base metal and filler metal. In actual practice, brazing filler metal flow is influenced by dynamic considerations involving fluidity, viscosity, vapor pressure, gravity, and especially the effects of metallurgical reactions between filler metal and base metal.

The typical brazed joint has a relatively large area and very small gap. In the simplest brazing application, the surfaces to be joined are cleaned to remove contaminants and oxides. Next, they are coated with flux. A flux is a material which is capable of dissolving solid metal oxides and also preventing new oxidation. The joint area is then heated until the flux melts and cleans the base metals, which are protected against further oxidation by the layer of liquid flux.

Brazing filler metal is then melted at some point on the surface of the joint area. Capillary attraction between the base metal and the filler metal is much higher than that between the base metal and the flux. Accordingly, the flux is displaced by the filler metal. The joint, upon cooling to room temperature, will be filled with solid filler metal, and the solid flux will be found on the joint periphery.

Joints to be brazed are usually made with clearances of 0.001 to 0.010 in. (0.025 to 0.25 mm). The fluidity of the filler metal, therefore, is an important factor. High fluidity is a desirable characteristic of brazing filler metal since capillary action may be insufficient to draw a viscous filler metal into closely fitted joints.

Brazing is sometimes done under an active gas, such as hydrogen, or in an inert gas or vacuum. Atmosphere brazing eliminates the necessity for post cleaning and insures absence of corrosive mineral flux residue. Carbon steels, stainless steels, and superalloy components are widely processed in atmospheres of reacted gases, dry hydrogen, dissociated ammonia, argon, or vacuum. Large vacuum furnaces are used to braze zirconium, titanium, stainless steels, and the refractory metals. With good processing procedures, aluminum alloys can also be vacuum furnace brazed with excellent results.

Brazing is economically attractive for the production of high strength metallurgical bonds while preserving desired base metal properties.

BRAZING PROCESSES

BRAZING PROCESSES ARE customarily designated according to the sources or methods of heating. Industrial methods currently significant are the following:

(1) Torch brazing
(2) Furnace brazing
(3) Induction brazing
(4) Resistance brazing
(5) Dip brazing
(6) Infrared brazing

Whatever the process used, the filler metal has a melting point above 840°F (450°C), but below that of the base metal, and it spreads within the joint by capillary action.

TORCH BRAZING

TORCH BRAZING IS accomplished by heating with one or more gas torches.[1] Depending upon the temperature and

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[1] Chapter 11 contains information on gas torches used for welding and brazing.

the amount of heat required, the fuel gas (acetylene, propane, city gas, etc.) may be burned with air, compressed air, or oxygen. Manual torch brazing is shown in Figure 12.1.

Air-natural gas torches provide the lowest flame temperature as well as the least heat. Acetylene under pressure is used in the air-acetylene torch with air at atmospheric pressure. Both air-natural gas and air-acetylene torches can be used to advantage on small parts and thin sections.

Torches which employ oxygen with natural gas, or other cylinder gases (propane, butane) have higher flame temperatures. When properly applied as a neutral or slightly reducing flame, excellent results are obtainable with many brazing applications.

Oxyhydrogen torches are often used for brazing aluminum and nonferrous alloys. The lower temperature reduces the possibility of overheating the assembly during brazing. An excess of hydrogen provides the joint with additional cleaning and protection.

Specially designed torches having multiple tips or multiple flames can be used to an advantage to increase the rate of heat input. Care must be exercised to avoid local overheating by constantly moving the torch with respect to the work.

For manual torch brazing, the torch may be equipped with a single tip, either single- or multiple-flame. Manual torch brazing is particularly useful on assemblies involving sections of unequal mass. Machine operations can be set up, where the rate of production warrants, using one or more torches equipped with single or multiple-flame tips. The machine may be designed to move either the work or the torches, or both. For premixed city gas and air flames, a refractory type burner is used.

Figure 12.1–Manual Torch Brazing

Torch heating for brazing is limited in use to filler metals supplied with flux or self-fluxing. The list includes aluminum-silicon, silver, copper-phosphorus, copper-zinc, and nickel. With the exception of the copper-phosphorus filler metals, they all require fluxes. For certain applications even the self-fluxing copper-phosphorus filler metals require added flux, as shown in Table 12.1.

The filler metal can be preplaced on the joint and fluxed before heating, or it may be face- fed. Heat is applied to the joint, first melting the flux, then continuing until the brazing filler metal melts and flows into the joint. Overheating of the base metal and brazing filler metal should be avoided because rapid diffusion and "drop through" of the metal may result. Natural gas is well suited for torch brazing because its relatively low flame temperature reduces the danger of overheating.

Brazing filler metal may be preplaced at the joint in the forms of rings, washers, strips, slugs, or powder, or it may be fed from hand-held filler metal, usually in the form of wire or rod. In any case, proper cleaning and fluxing are essential.

Torch brazing techniques differ from those used for oxyfuel gas welding. Operators experienced only in welding techniques may require instruction in brazing techniques. It is good practice, for example, to prevent the inner cone of the flame from coming in contact with the joint except during preheating, since melting of the base metal and dilution with the filler metal may increase its liquidus temperature and make the flow more sluggish. In addition, the flux may be overheated and thus lose its ability to promote capillary flow, and low melting constituents of the filler metal may evaporate.

FURNACE BRAZING

FURNACE BRAZING, AS illustrated in Figure 12.2, is used extensively when (1) the parts to be brazed can be preassembled or jigged to hold them in the correct position, (2) the brazing filler metal can be placed in contact with the joint, (3) multiple brazed joints are to be formed simultaneously on a completed assembly, (4) many similar assemblies are to be joined, and (5) complex parts must be heated uniformly to prevent the distortion that would result from local heating of the joint area.

Electric, gas, or oil heated furnaces with automatic temperature control capable of holding the temperature within ±10°F (±6°C) should be used for furnace brazing. Fluxes or specially controlled atmospheres that perform fluxing functions must be provided.

Parts to be brazed should be assembled with the filler metal and flux, if used, located in or around the joints. The

Table 12.1
Classification of Brazing Fluxes with Brazing or Braze Welding Filler Metals

			Activity Temperature Range	
Classification*	Form	Filler Metal Type	°F	°C
FB1-A	Powder	BA1Si	1080-1140	580-615
FB1-B	Powder	BA1Si	1040-1140	560-615
FB1-C	Powder	BA1Si	1000-1140	540-615
FB2-A	Powder	BMg	900-1150	480-620
FB3-A	Paste	BAg and BCuP	1050-1600	565-870
FB3-C	Paste	BAg and BCuP	1050-1700	565-925
FB3-D	Paste	BAg, BCu, BNi, BAu and RBCuZn	1400-2200	760-1205
FB3-E	Liquid	BAg and BCup	1050-1600	565-870
FB3F	Powder	BAg and BCuP	1200-1600	650-870
FB3G	Slurry	BAg and BCuP	1050-1600	565-870
FB3-H	Slurry	BAg	1050-1700	565-925
FB3-I	Slurry	BAg, BCu, BNi, BAu and RBCuZn	1400-2200	760-1205
FB3-J	Powder	BAg, BCu, BNi, BAu and RBCuZn	1400-2200	760-1205
FB3-K	Liquid	BAg and RBCuZn	1400-2200	760-1205
FB4-A	Paste	BAg and BCuP	1100-1600	595-870

* Flux 3B shown in the Brazing Manual, 3rd Edition, 1976 has been discontinued. Type 3B has been divided into types FB3C and FB3D.

Note: The selection of a flux designation for a specific type of work may be based on the form, the filler metal type, and the description above, but the information here is generally not adequate for flux selection. Refer to the latest issue of the Brazing Manual for further assistance.

preplaced filler metal may be in the form of wire, foil, filings, slugs, powder, paste, or tape. The assembly is heated in the furnace until the parts reach brazing temperature and brazing takes place. The assembly is then removed. These steps are shown in Figure 12.2. A laboratory setup for induction brazing in vacuum is shown in Figure 12.3. Many commercial fluxes are available for both general and specific brazing operations. Satisfactory results are obtained if dry powdered flux is sprinkled along the joint. Flux paste is satisfactory in most cases, but in some cases it retards the flow of brazing alloy. Flux pastes containing water can be dried by heating the assembly at 350 to 400°F (175 to 200°C) for 5 to 15 minutes in drying ovens or circulating air furnaces.

Brazing time will depend somewhat on the thickness of the parts and the amount of fixturing necessary to position them. The brazing time should be restricted to that necessary for the filler metal to flow through the joint to avoid excessive interaction between the filler metal and base metal. Normally, one or two minutes at the brazing temperature is sufficient to make the braze. A longer time at the brazing temperature will be beneficial where the filler metal remelt temperature is to be increased and where diffusion will improve joint ductility and strength. Times of 30 to 60 minutes at the brazing temperature are often used to increase the braze remelt temperature.

Furnaces used for brazing are classified as (1) batch type with either air or controlled atmosphere, (2) continuous type with either air or controlled atmosphere, (3) retort type with controlled atmosphere, or (4) vacuum. A high temperature, high vacuum brazing furnace with control panel and charging carriage is shown in Figure 12.3. Most brazing furnaces have a temperature control of the potentiometer type connected to thermocouples and gas control valves or contactors. The majority of furnaces are heated by electrical resistance using silicon-carbide, nickel-chromium, or refractory metal (Mo, Ta, W) heating elements. When a gas or oil flame is used for heating, the flame must not impinge directly on the parts.

With controlled atmosphere furnaces, a continuous flow of the atmosphere gas is maintained in the work zone to avoid contamination from outgassing of the metal parts and dissociation of oxides. If the controlled atmosphere is flammable or toxic, adequate venting of the work area and protection against explosion are necessary.

Batch type furnaces heat each workload separately. They may be top loading (pit type), side loading, or bottom loading. When a furnace is lowered over the work, it is called a *bell furnace.* Gas or oil fired batch type furnaces without retorts require that flux be used on the parts for brazing. Electrically heated batch type furnaces are often equipped for controlled atmosphere brazing, since the heating elements can usually be operated in the controlled atmosphere.

Continuous furnaces receive a steady flow of incoming assemblies. The heat source may be gas or oil flames, or

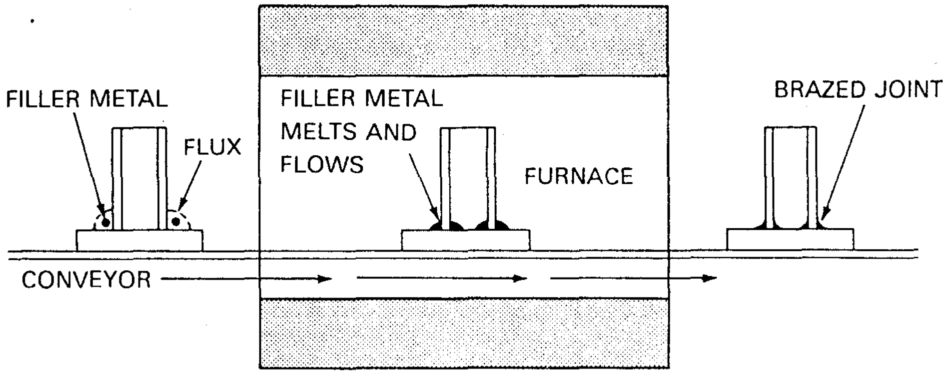

Figure 12.2–Illustration of Furnace Brazing Operation

electrical heating elements. The parts move through the furnace either singly or in trays or baskets. Conveyor types (mesh belts or roller hearth), shaker hearth, pusher, or slot type continuous furnaces are commonly used for high production brazing. Continuous furnaces usually contain a preheat or purging area which the parts enter first. In this area, the parts are slowly brought to a temperature below the brazing temperature. If brazing atmosphere gas is used in the brazing zone it also flows over and around the parts in the preheat zone, under positive pressure. The gas flow removes any entrapped air and starts the reduction of surface oxides. Atmosphere gas trails the parts into the cooling zone.

Retort type furnaces are batch furnaces in which the assemblies are placed in a sealed retort for brazing. The air in the retort is purged by controlled atmosphere gas and the retort is placed in the furnace. After the parts have been brazed, the retort is removed from the furnace, cooled, and its controlled atmosphere is purged. The retort is opened, and the brazed assemblies are removed. A protective atmosphere is sometimes used within a high temperature furnace to reduce external scaling of the retort.

Vacuum furnace brazing is widely used in the aerospace and nuclear fields, where reactive metals are joined or where entrapped fluxes would be intolerable. If the vacuum atmosphere is maintained by continuous pumping, it will remove volatile constituents liberated during brazing.

Vacuum brazing equipment is currently used to a large extent to braze stainless steels, superalloys, aluminum alloys, titanium alloys, and metals containing refractory or reactive elements. Vacuum is a relatively economical "atmosphere" which prevents oxidation by removing air from around the assembly. Surface cleanliness is nevertheless required for good wetting and flow. Base metals containing chromium and silicon can be vacuum brazed. Base metals that can generally be brazed only in vacuum are those containing more than a few percent of aluminum, titanium, zirconium, or other elements with particularly stable oxides. However, a nickel plated barrier is still preferred to obtain optimum quality.

Vacuum brazing furnaces are of three types:

(1) *Hot retort, or single pumped retort furnace.* This is a sealed retort, usually of fairly thick metal. The retort with work loaded inside is sealed, evacuated, and heated from the outside by a furnace. Most brazing work requires vacuum pumping continuously throughout the heat cycle to remove gases being given off by the workload. The furnaces are gas fired or electrical. The retort size and its maximum operating temperature are limited by the ability of the retort to withstand the collapsing force of atmospheric pressure at brazing temperature. Top temperature for vacuum brazing furnaces of this type is about 2100°F (1150°C).

Argon, nitrogen, or other gas is often introduced into the retort to accelerate cooling after brazing.

(2) *Double pumped or double wall hot retort vacuum furnace.* The typical furnace of this type has an inner retort containing the work, within an outer wall or vacuum chamber. Also within the outer wall are the thermal insulation and electrical heating elements. A moderately reduced pressure, typically 1.0 to 0.1 torr (133 to 13.3 Pa), is maintained within the outer wall, and a much lower pressure, below 10^{-2} torr (1.3 Pa), within the inner retort. Again most brazing requires continuous vacuum pumping of the inner retort throughout the heat cycle to remove gases given off by the workload.

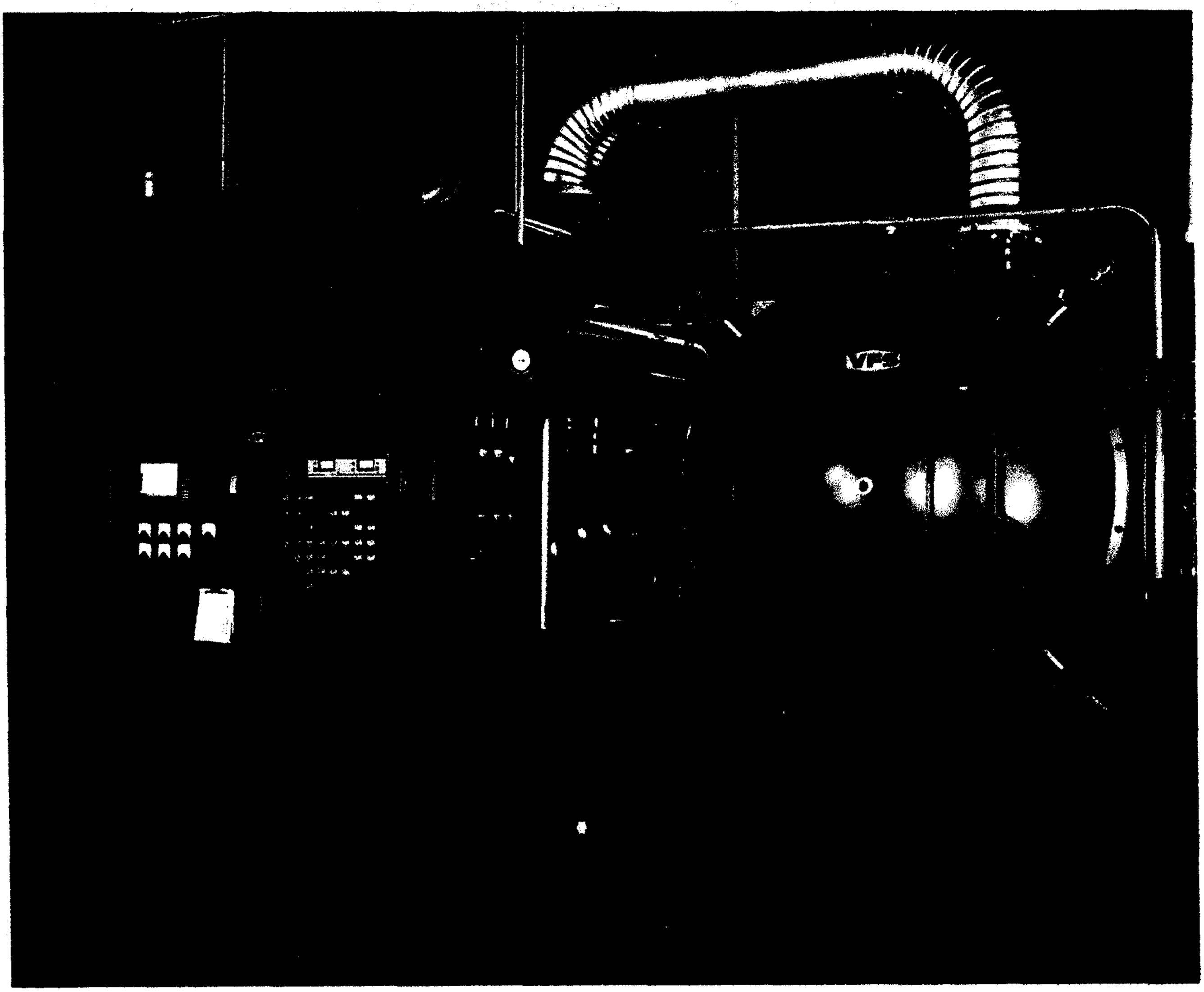

Figure 12.3—A High Temperature, High Vacuum Brazing Furnace with Control Panel and Charging Dolly

In this type of furnace, the heating elements and the thermal insulation are not subjected to the high vacuum. Heating elements are typically of nickel-chromium alloy, graphite, stainless steel, or silicon carbide materials. Thermal insulation is usually silica or alumina brick, or castable or fiber materials.

(3) *Cold wall vacuum furnace.* A typical cold wall vacuum furnace has a single vacuum chamber, with thermal insulation and electrical heating elements located inside the chamber. The vacuum chamber is usually water cooled. The maximum operating temperature is determined by the materials used for the thermal insulation (the heat shield) and the heating elements, which are subjected to the high vacuum as well as the operating temperature of the furnace.

Heating elements for cold wall furnaces are usually made of high temperature, low vapor pressure materials, such as molybdenum, tungsten, graphite, or tantalum. Heat shields are typically made of multiple layers of molybdenum, tantalum, nickel, or stainless steel. Thermal insulation may be high purity alumina brick, graphite, or alumina fibers sheathed in stainless steel. The maximum operating temperature and vacuum obtainable with cold wall vacuum furnaces depends on the heating element material and the thermal insulation or heat shields. Temperatures up to 4000°F (2200°C) and pressures as low as 10^{-6} torr (1.33×10^{-4} Pa) are obtainable.

Configurations for all three types of furnaces include side loading (horizontal), bottom loading, and top loading (pit type). Work zones are usually rectangular for side loading furnaces, and circular for bottom and top loading types.

Vacuum pumps for brazing furnaces may be oil sealed mechanical types for pressures from 0.1 to 10 torr (13 to 1300 Pa). Brazing of base metals containing chromium, silicon, or other rather strong oxide formers usually requires pressures of 10^{-2} to 10^{-3} torr (1.3 to 0.13 Pa), which are best obtained with a high-speed, dry Roots, or turbo-mechanical type pump. Vacuum pumps of this type are not capable of exhausting directly to atmosphere and require a roughing vacuum pump.

Brazing of base materials containing more than a few percent of aluminum, titanium, zirconium, which form very stable oxides, requires vacuum of 10^{-3} torr (0.13 Pa) or lower. Vacuum furnaces for such brazing usually require a diffusion pump that will obtain pressures of 10^{-2} to 10^{-6} torr (1.3 to 0.0001 Pa). The diffusion pump is backed by a mechanical vacuum pump or by both a Roots-type pump and a mechanical pump.

INDUCTION BRAZING

THE HEAT FOR brazing with this process is obtained from an electric current induced in the parts to be brazed, hence the name *induction brazing*. For induction brazing, the parts are placed in or near a water-cooled coil carrying alternating current. They do not form a part of the electrical circuit. Parts to be heated act as the short circuited secondary of a transformer where the work coil, which is connected to the power source, is the primary. On both magnetic and nonmagnetic parts, heating is obtained from the resistance of the parts to currents induced in them by the transformer action. See Figure 12.4.

The brazing filler metal is preplaced. Careful design of the joint and the coil setup are necessary to assure that the surfaces of all members of the joint reach the brazing temperature at the same time. Flux is employed except when an atmosphere is specifically introduced to perform the same function.

Frequencies for induction brazing generally vary from 10 KHz to 450 khz. The lower frequencies are obtained with solid-state generators and the higher frequencies with vacuum tube oscillators. Induction generators are manufactured in sizes from one kilowatt to several hundred kilowatts output. Various induction brazing coil designs are illustrated in Figure 12.5. One generator may be used to energize several individual workstations in sequence, using a transfer switch, or assemblies in holding fixtures may be indexed or continuously processed through a conveyor-type coil for heating to brazing temperature.

Induction brazing is used when very rapid heating is required. Time for processing is usually in the range of seconds when large numbers of parts are handled automatically. Induction brazing has been used extensively to produce consumer and industrial products; structural assemblies; electrical and electronic products; mining, machine, and hand tools; military and ordnance equipment; and aerospace assemblies. An aerospace application of vacuum induction brazing is shown in Figure 12.6.

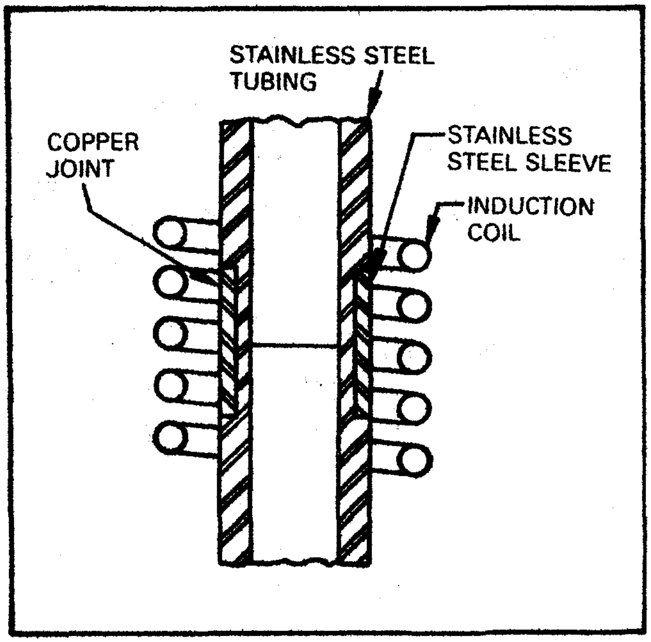

Figure 12.4—Joint in Stainless Steel Tubing Induction Brazed in a Controlled Atmosphere. Note Placement of Joint in Induction Coil.

Assemblies may be induction brazed in a controlled atmosphere by placing the components and coil in a nonmetallic chamber, or by placing the chamber and work inside the coil. The chamber can be quartz Vycor or tempered glass. A dual station bell jar fixture of this type is shown in Figure 12.7.

RESISTANCE BRAZING

THE HEAT NECESSARY for resistance brazing is obtained from the flow of an electric current through the electrodes and the joint to be brazed. The parts comprising the joint become part of the electric circuit. The brazing filler metal, in some convenient form, is preplaced or face-fed. Fluxing is done with due attention to the conductivity of the fluxes. (Most fluxes are insulators when dry.) Flux is employed except when an atmosphere is specifically introduced to perform the same function. The parts to be brazed are held between two electrodes, and proper pressure and current are applied. The pressure

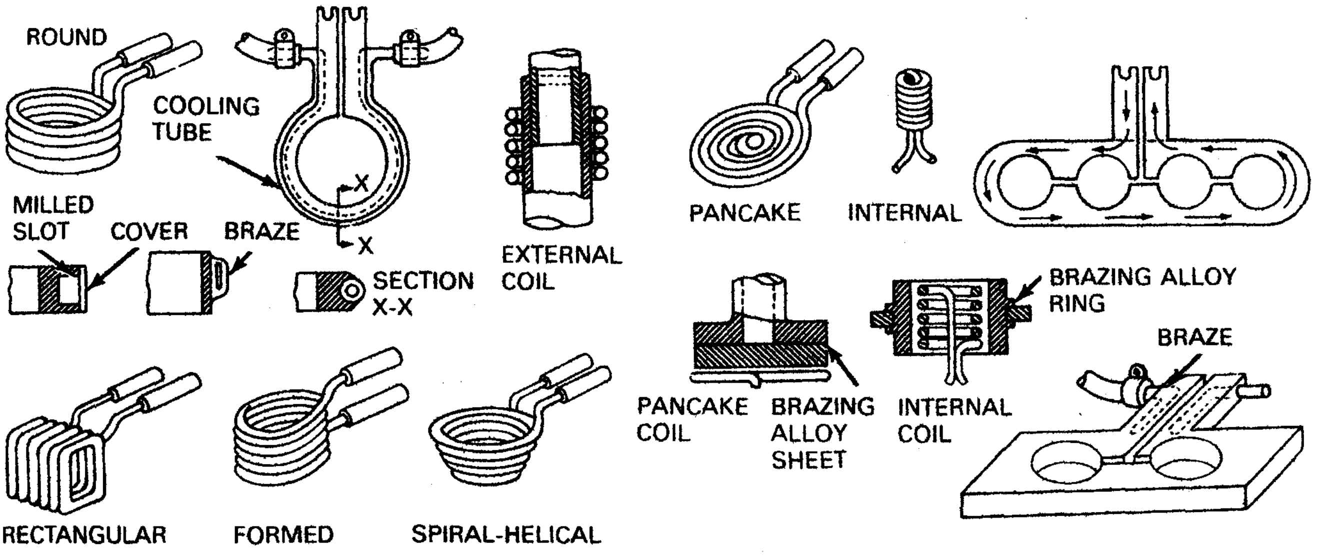

Figure 12.5–Typical Induction Brazing Coils and Plates

should be maintained until the joint has solidified. In some cases, both electrodes may be located on the same side of the joint with a suitable backing to maintain the required pressure.

Brazing filler metal is used in the form of preplaced wire, shims, washers, rings, powder, or paste. In a few instances, face feeding is possible. For copper and copper alloys, the copper-phosphorus filler metals are most satisfactory since they are self-fluxing. Silver base filler metals may be used, but a flux or atmosphere is necessary. A wet flux is usually applied as a very thin mixture just before the assembly is placed in the brazing fixture. Dry fluxes are not used because they are insulators and will not permit sufficient current to flow.

The parts to be brazed must be clean. The parts, brazing filler metal, and flux are assembled and placed in the fixture and pressure applied. As current flows, the electrodes become heated, frequently to incandescence, and the flux and filler metal melt and flow. The current should be adjusted to obtain uniform rapid heating in the parts. Overheating risks oxidizing or melting the work, and the electrodes will deteriorate. Too little current lengthens the time of brazing. Experimenting with electrode compositions, geometry, and voltage will give the best combination of rapid heating with reasonable electrode life.

Quenching the parts from an elevated temperature will help flux removal. The assembly first must cool sufficiently to permit the braze to hold the parts together. When brazing insulated conductors it may be advisable to quench the parts rapidly while they are still in the electrodes to prevent overheating of the adjacent insulation. Water-cooled clamps prevent damage to the insulation.

Resistance brazing is most applicable to joints which have a relatively simple configuration. It is difficult to obtain uniform current distribution, and therefore uniform heating, if the area to be brazed is large or discontinuous or is much longer in one dimension. Parts to be resistance brazed should be so designed that pressure may be applied to them without causing distortion at brazing temperature. Wherever possible, the parts should be designed to be self-nesting, which eliminates the need for dimensional features in the fixtures. Parts should also be free to move as the filler metal melts and flows in the joint.

The equipment consists of tongs or clamps with the electrodes attached at the end of each arm. The tongs should preferably be water cooled to avoid overheating. The arms are current-carrying conductors attached by leads to a transformer.

One common source of current for resistance brazing is a stepdown transformer whose secondary circuit can furnish sufficient current at low voltage (2-25 V). The current will range from about 50 A for small, delicate jobs to many thousands of amperes for larger jobs. Commercial equipment is available for resistance brazing.

Electrodes for resistance brazing are made of high resistance electrical conductors, such as carbon or graphite blocks, tungsten or molybdenum rods, or even steel in some instances. The heat for brazing is mainly generated in the electrodes and flows into the work by conduction. It is generally unsatisfactory to attempt to use the resistance of the workpieces alone as a source of heat.

The pressure applied by a spot welding machine, clamps, pliers, or other means must be sufficient to maintain good electrical contact and to hold the pieces firmly together as

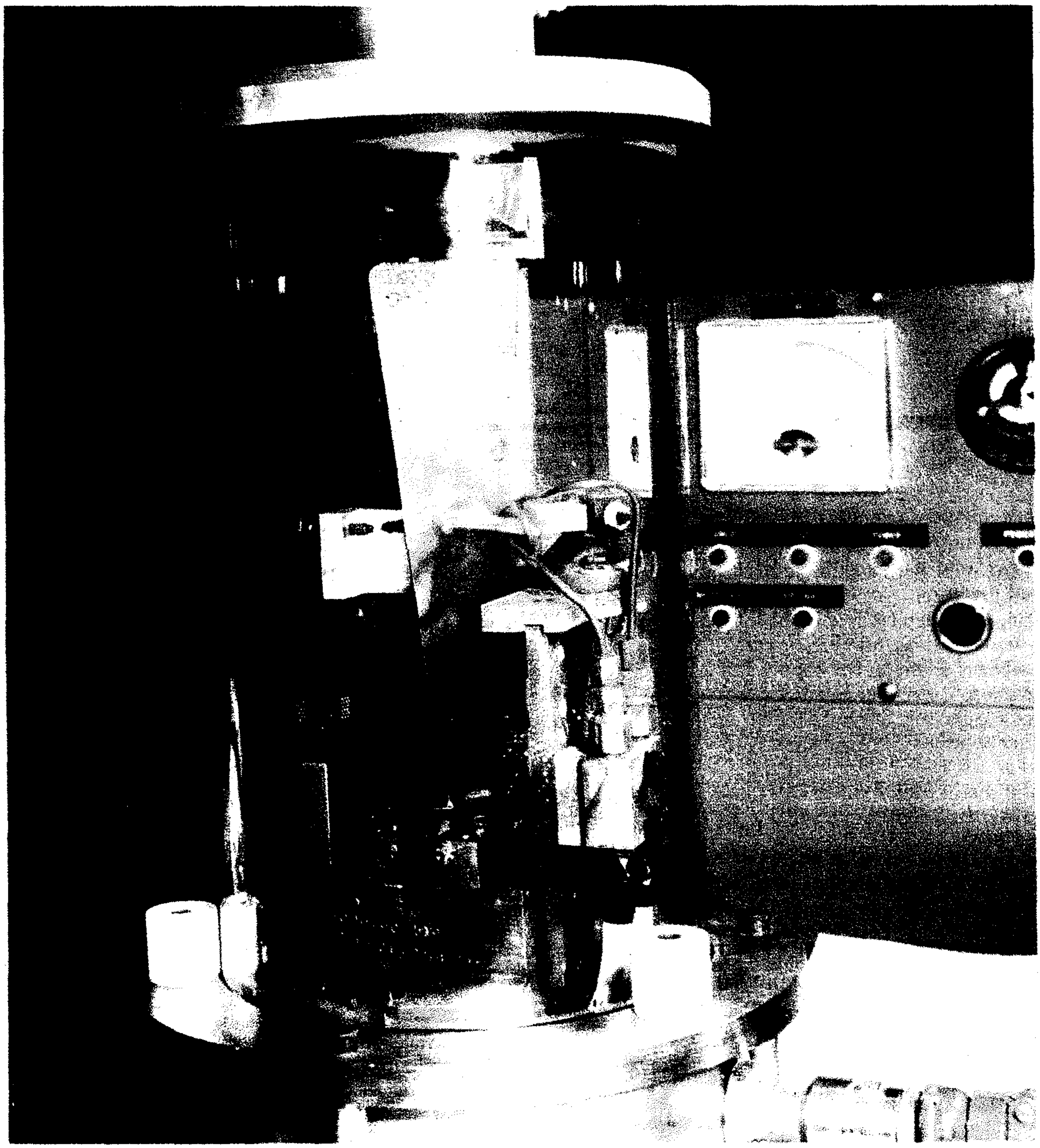

Figure 12.6–Example of Vacuum Induction Brazing. A Tungsten Carbide Wear Pad is Being Brazing to A Titanium Compressor Blade

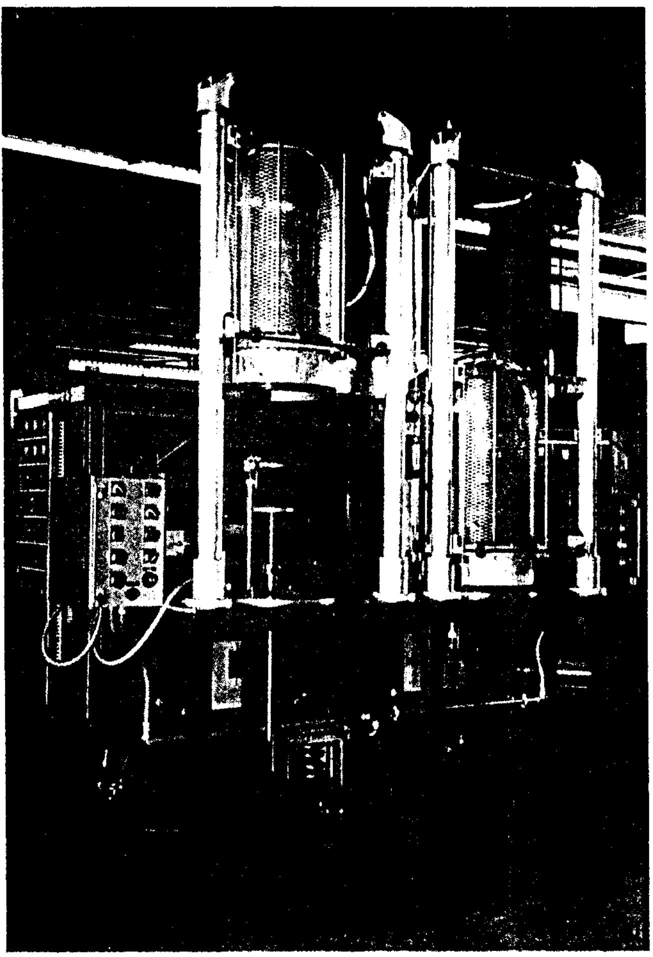

Figure 12.7–Production Arrangement for Induction Brazing in Controlled Atmosphere or Vacuum Showing Dual Station Bell Jar Fixture, Induction Generator, Movable Stand, Generator and Gas Controls, and Supports to Facilitate Up and Down Movement of Bell Jar

the filler metal melts. The pressure must be maintained during the time of current flow and after the current is shut off until the joint solidifies. The time of current flow will vary from about one second for small, delicate work to several minutes for larger work. This time is usually controlled manually by the operator, who determines when brazing has occurred by the temperature and the extent of filler metal flow.

DIP BRAZING

TWO METHODS OF dip brazing are molten metal bath dip brazing and molten chemical (flux) bath dip brazing.

Molten Metal Bath Method

THIS METHOD IS usually limited to the brazing of small assemblies, such as wire connections or metal strips. A crucible, usually made of graphite, is heated externally to the required temperature to maintain the brazing filler metal in fluid form. A cover of flux is maintained over the molten filler metal. The size of the molten bath (crucible) and the heating method must be such that the immersion of parts in the bath will not lower the bath temperature below brazing temperature. Parts should be clean and protected with flux prior to their introduction into the bath. The ends of the wires or parts must be held firmly together when they are removed from the bath until the brazing filler metal has fully solidfied.

Molten Chemical (Flux) Bath Method

THIS BRAZING METHOD requires either a metal or ceramic container for the flux and a method of heating the flux to the brazing temperature. Heat may be applied externally with a torch or internally with an electrical resistance heating unit. A third method involves electrical resistance heating of the flux itself; in that case, the flux must be initially melted by external heating. Suitable controls are provided to maintain the flux within the brazing temperature range. The size of the bath must be such that immersion of parts for brazing will not cool the flux below the brazing temperature. See Figure 12.8.

Parts should be cleaned, assembled, and preferably held in jigs prior to immersion into the bath. Brazing filler metal is preplaced as rings, washers, slugs, paste, or as a cladding on the base metal. Preheat may be necessary to assure dryness of parts and to prevent the freezing of flux on parts which may cause selective melting of flux and brazing filler metal. Preheat temperatures are usually close to the melt-

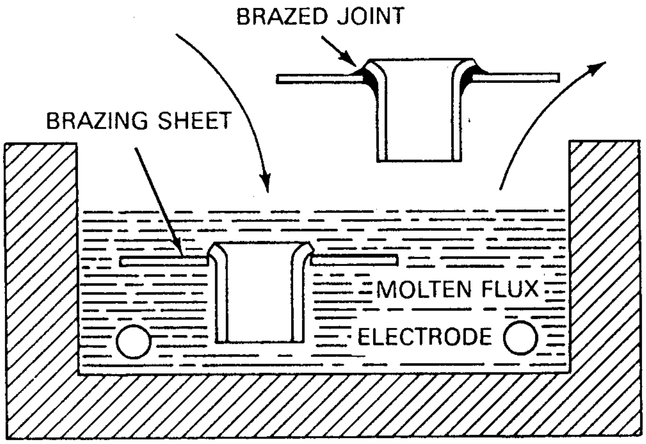

Figure 12.8–Illustration of Chemical Bath Dip Brazing

ing temperature of the flux. A certain amount of flux adheres to the assembly after brazing. Molten flux must be drained off while the parts are hot. Flux remaining on cold parts must be removed by water or by chemical means.

INFRARED BRAZING

INFRARED BRAZING MAY be considered a form of furnace brazing with heat supplied by long-wave light radiation. Heating is by invisible radiation from high intensity quartz lamps capable of delivering up to 5000 watts of radiant energy. Heat input varies inversely as the square of the distance from the source, but the lamps are not usually shaped to follow the contour of the part to be heated. Concentrating reflectors focus the radiation on the parts.

For vacuum brazing or inert-gas protection, the assembly and the lamps are placed in a bell jar or retort that can be evacuated or filled with inert gas. The assembly is then heated to a controlled temperature, as indicated by thermocouples. Figure 12.9 shows an infrared brazing arrangement. The part is moved to the cooling platens after brazing.

SPECIAL PROCESSES

Blanket Brazing

BLANKET BRAZING USES a blanket that is resistance heated; the heat is transferred to the parts by conduction and radiation, but mostly by radiation.

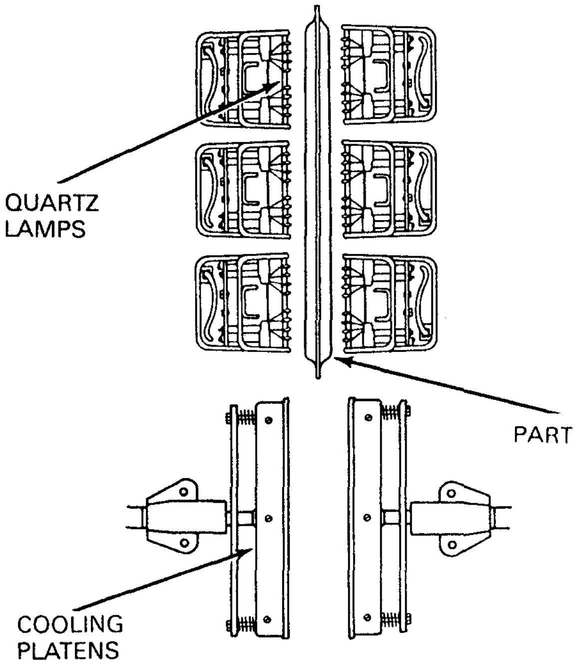

Figure 12.9–Infrared Brazing Apparatus

EXOTHERMIC BRAZING

EXOTHERMIC BRAZING IS a special process which heats a commercial filler metal by a solid-state exothermic chemical reaction. An exothermic chemical reaction generates heat released as the free energy of the reactants. Nature has provided countless numbers of such reactions; those solid-state or nearly solid-state metal-metal oxide reactions are suitable for use in exothermic brazing units.

Exothermic brazing uses simplified tooling and equipment. The reaction heat brings adjoining metal interfaces to a temperature at which preplaced brazing filler metal melts and wets the base metal interface surfaces. Several commercially available brazing filler metals have a suitable flow temperature. The process is limited only by the thickness of the base metal and the effect of brazing heat, or any previous heat treatment, on the metal properties.

BRAZING AUTOMATION

THE IMPORTANT VARIABLES involved in brazing are the temperature, time at temperature, filler metal, and brazing atmosphere. Other variables are joint fit-up, amount of filler metal, and rate and mode of heating. All of these features may be automated.

Heating by welding torches may be automated. So may furnace brazing (e.g., vacuum and atmosphere), resistance brazing, induction brazing, dip brazing, and infrared brazing. Generally, the amount of heat supplied to the joint is automated by controlling temperature and time at temperature.

Brazing filler metal may be preplaced at the joints during assembly of components, or automatically fed into the joints while at brazing temperature. So also may fluxing be provided.

Further automation may include in-line inspection and cleaning (flux removal), simultaneous brazing of multiple joints in an assembly, and continuous brazing operations.

Generally, the more automated a process becomes, the more rigorous must be its economic justification. Usually the increased cost of automation is justified by increased productivity. In the case of brazing, further justification may well be found in the energy saved with efficient joint heating.

Basically, the major advantages of automatic brazing are these:

(1) High production rates
(2) High productivity per worker
(3) Filler metal savings
(4) Consistency of results
(5) Energy savings
(6) Adaptability and flexibility

Manual torch brazing, totally unautomated, represents the simplest brazing technique, but it has economic justification. First, the braze joint is visible to the operator, who adjusts the process based on observation. Second, heat is directed only to the joint area. Whenever energy costs represent a large fraction of the cost of a braze joint, this is an important consideration.

Nevertheless, torch brazing is labor intensive and low in productivity. A continuous belt furnace increases production but loses in-line inspection and lowers energy efficiency because the entire assembly is heated.

Automatic brazing machines improve torch brazing. Typically, heat is directed just to the joint area by one or more torches. Similar effects can be obtained by induction heating. A typical machine has provisions for assembly and fixturing, automatic fluxing, preheating (if needed), brazing, air or water quenching, part removal, and inspection.

BRAZING FILLER METALS

CHARACTERISTICS

BRAZING FILLER METALS must have the following properties:

(1) Ability to form brazed joints with mechanical and physical properties suitable for the intended service application

(2) Melting point or melting range compatible with the base metals being joined, and sufficient fluidity at brazing temperature to flow and distribute themselves into properly prepared joints by capillary action

(3) Composition of sufficient homogeneity and stability to minimize separation of constituents (liquation) during brazing

(4) Ability to wet surfaces of base metals and form a strong, sound bond

(5) Depending on requirements, ability to produce or avoid filler-metal interactions with base metals

MELTING AND FLUIDITY

PURE METALS MELT at a constant temperature and are generally very fluid. Binary compositions (two metals) have differing characteristics, depending upon the relative contents of the two metals. Figure 12.10 is the equilibrium diagram for the silver-copper binary system. The solidus line, ADCEB, traces the start-of-melting temperature of the alloys, while the liquidus line, ACB, shows the temperatures at which the alloys become completely liquid. At point C the two lines meet (72 percent silver-28 percent copper), indicating that that particular alloy melts at that fixed temperature (the eutectic temperature). This alloy is the eutectic composition; it is as fluid as a pure metal, while the other alloy combinations are mushy between their solidus and liquidus temperatures. The wider that temperature spread, the more sluggish are the alloys with respect to flow in a capillary joint.

The α region is a solid solution of copper in silver, the β region is a solid solution of silver in copper. The central solid zone consists of an intimate mixture of α and β solid solutions. Above the liquidus line, the silver and copper atoms are thoroughly interspersed as a liquid solution.

LIQUATION

BECAUSE THE SOLID and liquid alloy phases of a brazing filler metal generally differ, the composition of the melt will gradually change as the temperature increases from the solidus to the liquidus. If the portion that melts first is allowed to flow out, the remaining solid may not melt and so may remain behind as a residue or "skull." Filler metals with narrow melting ranges do not tend to separate, so they flow quite freely into joints with extremely narrow clearance. Filler metals with wide melting ranges need rapid heating or delayed application to the joint until the base metal reaches brazing temperature, to minimize separation, which is called *liquation*. Filler metals subject to liquation have a sluggish flow, require wide joint clearances, and form large fillets at joint extremities.

WETTING AND BONDING

TO BE EFFECTIVE, a brazing filler metal must alloy with the surface of the base metal without (1) undesirable diffusion into the base metal, (2) dilution with the base metal, (3) base metal erosion, and (4) formation of brittle com-

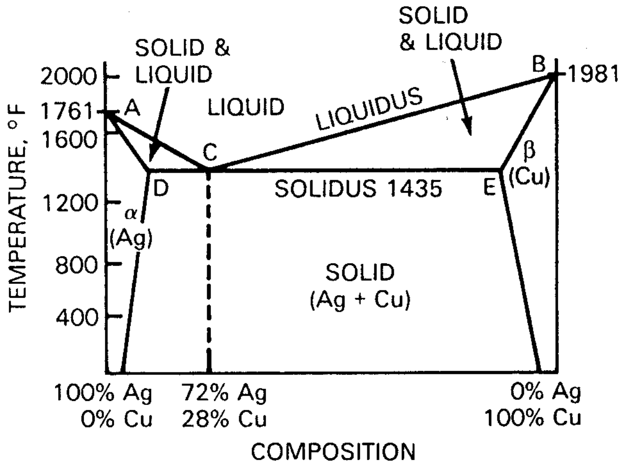

Figure 12.10–Silver-Copper Constitutional Diagram

pounds. Effects (1), (2), and (3) depend upon the mutual solubility between the brazing filler metal and the base metal, the amount of brazing filler metal present, and the temperature and time duration of the brazing cycle.

Some filler metals diffuse excessively, changing the base metal properties. To control diffusion, select a suitable filler metal, apply the minimum quantity of filler metal, and follow the appropriate brazing cycle. If the filler metal wets the base metal, capillary flow is enhanced. In long capillaries between the metal parts, mutual solubility can change the filler metal composition by alloying. This will usually raise its liquidus temperature and cause it to solidify before completely filling the joint.

Base metal erosion (3) occurs if the base metal and the brazing filler metal are mutually soluble. Sometimes such alloying produces brittle intermetallic compounds (4) that reduce the joint ductility.

Compositions of brazing filler metals are adjusted to control the above factors and to provide desirable characteristics, such as corrosion resistance in specific media, favorable brazing temperatures, or material economies. Thus, to overcome the limited alloying ability (wettability) of silver-copper alloys used to braze iron and steel, those filler metals contain zinc or cadmium, or both, to lower the liquidus and solidus temperatures. Tin is added in place of zinc or cadmium when constituents with high vapor pressure would be objectionable.

Similarly, silicon is used to lower the liquidus and solidus temperatures of aluminum and nickel-base brazing filler metals. Other brazing filler metals contain elements such as lithium, phosphorus, or boron, which reduce surface oxides on base metal and form compounds with melting temperatures below the brazing temperature. Those molten oxides then flow out of the joint, leaving a clean metal surface for brazing. These filler metals are essentially self-fluxing.

FILLER METAL SELECTION

FOUR FACTORS SHOULD be considered when selecting a brazing filler metal:

(1) Compatibility with base metal and joint design

(2) Service requirements for the brazed assembly

Compositions should be selected to suit operating requirements, such as service temperature (high versus cryogenic), thermal cycling, life expectancy, stress loading, corrosive conditions, radiation stability, and vacuum operation.

(3) Brazing temperature required

Low brazing temperatures are usually preferred to economize on heat energy, minimize heat effects on base metal (annealing, grain growth, warpage), minimize base metal-filler metal interaction, and increase the life of fixtures and other tools.

High brazing temperatures are used in order to take advantage of a higher melting, but more economical, brazing filler metal; to combine annealing, stress relief, or heat treatment of the base metal with brazing; to permit subsequent processing at elevated temperatures; to promote base metal-filler metal interactions to increase the joint remelt temperature; or to promote removal of certain refractory oxides by vacuum or an atmosphere.

(4) Method of heating

Filler metals with narrow melting ranges—less than 50°F (28°C) between solidus and liquidus—can be used with any heating method, and the brazing filler metal may be preplaced in the joint area in the form of rings, washers, formed wires, shims, powder, or paste.

Alternatively, such alloys may be manually or automatically face-fed into the joint after the base metal is heated. Filler metals that tend to liquate should be used with heating methods that bring the joint to brazing temperature quickly, or the brazing filler metal should be introduced after the base metal reaches the brazing temperature.

To simplify filler metal selection, ANSI/AWS A5.8, *Specification for Brazing Filler Metal*, divides filler metals into seven categories and various classifications within each category. The specification lists products which are common, commercially available filler metals. Suggested base metal-filler metal combinations are given in Table 12.2. Other brazing filler metals not currently covered by the specification are available for special applications.

ALUMINUM-SILICON FILLER METALS

THIS GROUP IS used for joining aluminum grades 1060, 1100, 1350, 3003, 3004, 3005, 5005, 5050, 6053, 6061, 6951, and cast alloys A712.0 and C711.0. All types are suited for furnace and dip brazing, while some types are also suited for torch brazing, using lap joints rather than butt joints.

Brazing sheet or tubing is a convenient source of aluminum filler metal. It consists of a core of aluminum alloy and a coating of lower melting filler metal. The coatings are aluminum-silicon alloys, applied to one or both sides of the sheet. Brazing sheet is frequently used as one member of an assembly, with the mating piece made of an unclad brazeable alloy. The coating on the brazing sheet or tubing melts at brazing temperature and flows by capillary attraction and gravity to fill the joints.

MAGNESIUM FILLER METALS

MAGNESIUM FILLER METAL (BMg-1) is used to join AZ10A, K1A, and M1A magnesium alloys by torch, dip, or furnace brazing processes. Heating must be closely controlled to prevent melting of the base metal. Joint clearances of 0.004 to 0.010 in (0.10 to 0.25 mm) are best for most applications. Corrosion resistance is good if the flux is completely removed after brazing. Brazed assemblies are generally suited for continuous service up to 250°F (120°C) or intermittent service to 300°F (150°C), subject to the usual limitations of the actual operating environment.

Table 12.2
Base Metal-Filler Metal Combinations

	Al & Al Alloys	Mg & Mg Alloys	Cu & Cu Alloys	Carbon & Low Alloy Steels	Cast Iron	Stainless Steel	Ni & Ni Alloys	Ti & Ti Alloys	Be, Zr, & Alloys (Reactive Metals)	W, Mo, Ta, Cb & Alloys (Refractory Metals)	Tool Steels
Al & Al alloys	BAlSi										
Mg & Mg alloys	X	BMg									
Cu & Cu alloys	X	X	BAg, BAu, BCuP, RBCuZn	BNi							
Carbon & low alloy steels	BAlSi	X	BAg, BAu, RBCuZN, BNi	BAg, BAu, BCu, RBCuZn, BNi							
Cast iron	X	X	BAg, BAu, RBCuZN, BNi	BAg, RBCuZn, BNi	BAg, RBCuZn, BNi						
Stainless steel	BAlSi	X	BAg, BAu	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi					
Ni & Ni alloys	X	X	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, RBCuZn, BNi	BAg, BCu, RBCuZn	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi				
Ti & Ti alloys	BAlSi	X	BAg	BAg	BAg	BAg	BAg	Y			
Be, Zi & alloys (reactive metals)	X BAlSi(Be)	X	BAg	BAg, BNi*	BAg, BNi*	BAg, BNi*	BAg, BNi*	Y	Y		
W, Mo, Ta, Cb & alloys (refractory metals)	X	X	BAg, BNi	BAg, BCu, BNi*	BAg, BCu, BNi*	BAg, BCu, BNi*	BAg, BCu, BNi*	Y	Y	Y	
Tool steels	X	X	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, RBCuZn, BNi	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, RBCuZn, BNi	X	X	X	BAg, BAu, BCu, RBCuZn, BNi

Note: Refer to AWS Specification A5.8 for information on the specific compositions within each classification.
X—Not recommended; however, special techniques may be practicable for certain dissimilar metal combinations.
Y—Generalizations on these combinations cannot be made. Refer to the Brazing Handbook for usable filler metals.
*—Special brazing filler metals are available and are used successfully for specific metal combinations.

Filler Metals:
BAlsi—Aluminum
BAg—Silver base
BAu—Gold base
BCu—Copper
BCuP—Copper phosphorus
RBCuZn—Copper zinc
BMg—Magnesium base
BNi—Nickel base

COPPER AND COPPER-ZINC FILLER METALS

THESE BRAZING FILLER metals are used to join ferrous metals and nonferrous metals. The corrosion resistance of the copper-zinc alloy filler metals is generally inadequate for joining copper, silicon bronze, copper-nickel alloys, or stainless steel.

The essentially pure copper brazing filler metals are used to join ferrous metals, nickel-base alloys, and copper-nickel alloys. They are free flowing and often used in furnace brazing with a combusted gas, hydrogen, or dissociated ammonia atmosphere without flux. Copper filler metals are available in wrought and powder forms.

One copper filler metal is a copper oxide to be suspended in an organic vehicle.

Copper-zinc filler metals are used on steel, copper, copper alloys, nickel and nickel-base alloys, and stainless steel where corrosion resistance is not a requirement. They are used with the torch, furnace, and induction brazing processes. Fluxing is required, and a borax-boric acid flux is commonly used.

COPPER-PHOSPHORUS FILLER METALS

THESE FILLER METALS are primarily used to join copper and copper alloys. They have some limited use for joining silver, tungsten, and molybdenum. They should not be used on ferrous or nickel-base alloys, nor on copper-nickel alloys with more than 10 percent nickel. These filler metals are suited for all brazing processes and have self-fluxing properties when used on copper. They tend to liquate if heated slowly.

SILVER FILLER METALS

THESE FILLER METALS are used to join most ferrous and nonferrous metals, except aluminum and magnesium, with all methods of heating. They may be preplaced in the joint or fed into the joint area after heating.

Silver-copper alloys high in silver do not wet steel well when brazing is done in air with a flux. Copper forms alloys with cobalt and nickel much more readily than silver does. Thus, copper wets many of these metals and their alloys satisfactorily, where silver does not. When brazing in certain protective atmospheres without flux, silver-copper alloys will wet and flow freely on most steels at the proper temperature.

Zinc is commonly used to lower the melting and flow temperatures of silver-copper alloys. It is by far the most helpful wetting agent when joining alloys based on iron, cobalt, or nickel. Alone, or in combination with cadmium or tin, zinc produces alloys that wet the iron group metals but do not alloy with them to any appreciable depth.

Cadmium is incorporated in some silver-copper-zinc filler metals alloys to further lower the melting and flow temperatures, and to increase the fluidity and wetting action on a variety of base metals. Since cadmium oxide fumes are a health hazard, cadmium-bearing filler metals should be used with caution.

Tin has a low vapor pressure at normal brazing temperatures. It is present in silver brazing filler metals in place of zinc or cadmium when volatile constituents are objectionable, such as when brazing is done without flux in atmosphere or vacuum furnaces, or when the brazed assemblies will be used in high vacuum at elevated temperatures. Silver-copper filler metals with tin additions have wide melting ranges. Fillers containing zinc wet ferrous metals more effectively than those containing tin, and where zinc is tolerable, they are preferred to fillers with tin.

Stellites, cemented carbides, and other molybdenum- and tungsten-rich refractory alloys are brazed with filler metals with added manganese, nickel, and, infrequently, cobalt to increase wettability.

When stainless steels and alloys that form refractory oxides are brazed in reducing or inert atmospheres without flux, silver brazing filler metals containing lithium as the wetting agent are quite effective. The heat of formation of Li_2O is high, so lithium metal reduces adherent oxides on the base metal. The resultant lithium oxide is readily displaced by the brazing filler metal.

GOLD FILLER METALS

GOLD FILLER METALS are used to join parts in electron tube assemblies where volatile components are undesirable. They are used to braze iron, nickel, and cobalt-base metals where resistance to oxidation or corrosion is required. They are commonly used on thin sections because of their low rate of interaction with the base metal.

NICKEL FILLER METALS

NICKEL BRAZING FILLER metals are generally used on 300 and 400 series stainless steels, nickel and cobalt-base alloys, even carbon steel, low alloy steels, and copper when specific properties are desired. They exhibit good corrosion and heat resistance properties. They are normally applied as powders, pastes, rod, foil, or in the form of sheet or rope with plastic binders.

Nickel filler metals have the very low vapor pressure needed in vacuum systems and vacuum tube applications at elevated temperatures.

The phosphorus-containing filler metals suffer from low ductility because they form nickel phosphides. The boron-containing filler metals must be carefully controlled when used to braze thin sections, to prevent erosion.

COBALT FILLER METAL

THIS FILLER METAL is used for its high temperature properties and its compatibility with cobalt-base metals. Brazing in a high quality atmosphere or diffusion brazing gives optimum results. Special high temperature fluxes are available for torch brazing.

FILLER METALS FOR REFRACTORY METALS

BRAZING IS EXCELLENT for fabricating assemblies of refractory metals, in particular those involving thin sections. However, only a few filler metals have been specifically designed for both high temperature and high corrosion applications.

Those filler metals and pure metals used to braze refractory metals are given in Table 12.3. Low melting filler metals, such as silver-copper-zinc, copper-phosphorus, and copper, are used to join tungsten for electrical contact applications, but these filler metals cannot operate at high temperatures. The use of higher melting rare metals, such as tantalum and columbium, is warranted in those cases.

Nickel-base and precious-metal-base filler metals may also be used to join tungsten.

Various brazing filler metals will join molybdenum. The effect of brazing temperature on base metal recrystallization must be considered. When brazing above the recrystallization temperature, brazing time must be kept short. If high temperature service is not required, copper and silver-base filler metals may be used.

Columbium and tantalum are brazed with a number of refractory or reactive-metal-base filler metals. The metal systems Ti-Zr-Be and Zr-Cb-Be are typical, also platinum, palladium, platinum-iridium, platinum-rhodium, titanium, and nickel-base filler metals (such as nickel-chromium-silicon alloys). Copper-gold alloys containing gold in amounts between 46 and 90 percent form age hardening compounds which are brittle. Silver-base filler metals are not recommended because they may embrittle the base metals.

Table 12.3
Brazing Filler Metals for Refractory Metals[a]

	Liquidus Temperature			Liquidus Temperature	
Brazing Filler Metal	**°F**	**°C**	**Brazing Filler Metal**	**°F**	**°C**
Cb	4380	2416	Mn-Ni-Co	1870	1021
Ta	5425	2997			
Ag	1760	960	Co-Cr-Si-Ni	3450	1899
Cu	1980	1082	Co-Cr-W-Ni	2600	1427
Ni	2650	1454	Mo-Ru	3450	1899
Ti	3300	1816	Mo-B	3450	1899
Pd-Mo	2860	1571	Cu-Mn	1600	871
Pt-Mo	3225	1774	Cb-Ni	2175	1190
Pt-30W	4170	2299			
Pt-50Rh	3720	2049	Pd-Ag-Mo	2400	1306
			Pd-Al	2150	1177
Ag-Cu-Zn-Cd-Mo	1145-1295	619-701	Pd-Ni	2200	1205
Ag-Cu-Zn-Mo	1324-1450	718-788	Pd-Cu	2200	1205
Ag-Cu-Mo	1435	780	Pd-Ag	2400	1306
Ag-Mn	1780	971	Pd-Fe	2400	1306
			Au-Cu	1625	885
Ni-Cr-B	1950	1066	Au-Ni	1740	949
Ni-Cr-Fe-Si-C	1950	1066	Au-Ni-Cr	1900	1038
Ni-Cr-Mo-Mn-Si	2100	1149	Ta-Ti-Zr	3800	2094
Ni-Ti	2350	1288			
Ni-Cr-Mo-Fe-W	2380	1305	Ti-V-Cr-Al	3000	1649
Ni-Cu	2460	1349	Ti-Cr	2700	1481
Ni-Cr-Fe	2600	1427	Ti-Si	2600	1427
Ni-Cr-Si	2050	1121	Ti-Zr-Be[b]	1830	999
			Zr-Cb-Be[b]	1920	1049
			Ti-V-Be[b]	2280	1249
			Ta-V-Cb[b]	3300-3500	1816-1927
			Ta-V-Ti[b]	3200-3350	1760-1843

a. Not all the filler metals listed are commercially available.

b. Depends on the specific composition.

FLUXES AND ATMOSPHERES

METALS AND ALLOYS may react with the atmosphere to which they are exposed, more so as the temperature is raised. The common reaction is oxidation, but nitrides and carbides are sometimes formed.

Fluxes, gas atmospheres, and vacuum are used to prevent undesirable reactions during brazing. Some fluxes and atmospheres may also reduce oxides already present.

Titanium, zirconium, columbium (niobium), and tantalum become permanently embrittled when brazed in any atmosphere containing hydrogen, oxygen, or nitrogen. Hydrogen will embrittle copper that has not been thoroughly deoxidized.

The use of flux or atmosphere does not eliminate the need to clean parts prior to brazing. Recommended cleaning procedures are contained in Chapter 7 of the *AWS Brazing Manual*, 3rd edition, 1976. The functions of individual fluxing ingredients are discussed in Chapter 4 of that Manual.

Since the purpose of a braze filler is to flow over the base material and into capillaries, it also may flow over portions of the piece being joined. This may be undesirable from a cosmetic viewpoint or there may be holes or features on the part that must not be filled or plugged for the device to function properly. When extraneous flow must be prevented, the brazer applies a "stopoff" material to retard the flow of the filler material. Great care must be exercised to prevent the stopoff material from getting into the actual braze joint because this would produce an unbonded condition. Stopoff materials are generally oxides applied by brush, tape, spray, or a hypodermic needle system. The common stopoffs are oxides of titanium, calcium, aluminum, or magnesium.

Stopoffs retard braze flow by intentionally putting oxides on the surface of the materials being joined. This works quite well when furnace brazing without flux. However, when flux is used, the cleaning action of the flux may counteract the stopoff effect. After brazing, the stopoff material can be removed by washing with hot water or by chemical or mechanical stripping.

APPLICATIONS

SELECTION OF BASE METALS

THE EFFECT OF brazing on the mechanical properties of the metal in a brazement and the final joint strength must be considered. Base metals strengthened by cold working will be annealed by brazing process temperatures and times in the annealing range of the base metal being processed. "When brazed, "hot-cold worked", heat-resistant base metals will also exhibit only the annealed physical properties. The brazing cycle by its very nature will usually anneal cold worked base metal unless the brazing temperature is very low and the time at temperature is very short.

It is not practical to cold work the base metal after the brazing operation.

When a brazement must have strength after brazing that will be above the annealed properties of the base metal, a heat treatable base metal should be selected. The base metal can be an oil-quench type, an air-quench type that can be brazed and hardened in the same or a separate operation, or a precipitation-hardening type that can be brazed and solution treated in a combined cycle. Parts already hardened may be brazed with a low temperature filler metal using short times at temperature to maintain the mechanical properties.

ALUMINUM AND ALUMINUM ALLOYS

THE NONHEAT TREATABLE wrought aluminum alloys that are brazed most successfully are the ASTM 1XXX and 3XXX series, and low magnesium alloys of the ASTM 5XXX series. Available filler metals melt below the solidus temperatures of all commercial wrought, nonheat treatable alloys.

The heat treatable wrought alloys most commonly brazed are the ASTM 6XXX series. The ASTM 2XXX and 7XXX series of aluminum alloys are low melting and, therefore, not normally brazeable, with the exception of 7072 and 7005 alloys.

Aluminum sand and permanent mold casting alloys most commonly brazed are ASTM 443.0, 356.0, and 712.0 alloys. Aluminum die castings are generally not brazed because of blistering from their high gas content.

Table 12.4 lists the common aluminum base metals that can be brazed.

Most aluminum brazing is done by torch, dip, or furnace processes. Furnace brazing may be done in air or controlled atmosphere, including vacuum.

Additional information on brazing aluminum and aluminum alloys is contained in Chapter 12, *Brazing Manual*, 3rd Edition.

MAGNESIUM AND MAGNESIUM ALLOYS

BRAZING TECHNIQUES SIMILAR to those used for aluminum are used for magnesium alloys. Furnace, torch, and dip brazing can be employed, although the latter process is the most widely used.

Magnesium alloys that are considered brazeable are given in Table 12.5. Furnace and torch brazing experience

Table 12.4
Nominal Composition and Melting Range of Common Brazeable Aluminum Alloys

Commercial Designation	ASTM Alloy	Brazeability Rating[b]	Nominal Composition[a] Cu	Si	Mn	Mg	Zn	Cr	Approximate Melting Range °F	°C
EC	EC	A	Al 99.45% min						1195-1215	646-657
1100	1100	A	Al 99% min						1190-1215	643-657
3003	3003	A	--	--	1.2	--	--	--	1190-1210	643-654
3004	3004	B	--	--	1.2	1.0	--	--	1165-1205	629-651
3005	3005	A	0.3	0.6	1.2	0.4	0.25	0.1	1180-1215	638-657
5005	5005	B	--	--	--	0.8	--	--	1170-1210	632-654
5050	5050	B	--	--	--	1.2	--	--	1090-1200	588-649
5052	5052	C	--	--	--	2.5	--	--	1100-1200	593-649
6151	6151	C	--	1.0	--	0.6	--	0.25	1190-1200	643-649
6951	6951	A	0.25	0.35	--	0.65	--	--	1140-1210	615-654
6053	6053	A	--	0.7	--	1.3	--	--	1105-1205	596-651
6061	6061	A	0.25	0.6	--	1.0	--	0.25	1100-1205	593-651
6063	6063	A	--	0.4	--	0.7	--	--	1140-1205	615-651
7005	7005	B	0.1	0.35	0.45	1.4	4.5	0.13	1125-1195	607-646
7072	7072	A	--	--	--	--	1.0	--	1125-1195	607-646
Cast 43	Cast 443.0	A	--	5.0	--	--	--	--	1065-1170	629-632
Cast 356	Cast 356.0	C	--	7.0	--	0.3	--	--	1035-1135	557-613
Cast 406	Cast 406	A	Al 99% min						1190-1215	643-657
Cast A612	Cast A712.0	B	--	--	--	0.7	6.5	--	1105-1195	596-646
Cast C612	Cast C712.0	A	--	--	--	0.35	6.5	--	1120-1190	604-643

a. Percent of alloying elements: aluminum and normal impurities constitute remainder.

b. Brazeability ratings: A = Alloys readily brazed by all commercial methods and procedures.
B = Alloys that can be brazed by all techniques with a little care.
C = Alloys that require special care to braze.

is limited to M1A alloy. Dip brazing can be used for AZ10A, AZ31B, AZ61A, K1A, M1A, ZE10A, ZK21A, and ZK60A alloys.

The filler metals used for brazing magnesium are also summarized in Table 12.5. BMg-1 brazing filler metal is suitable for the torch, dip, or furnace brazing process. The BMg-2a alloy is usually preferred in most brazing applications because of its lower melting range. A zinc base filler metal known as GA432 is an even lower melting composition suitable only for dip brazing use.

BERYLLIUM

BRAZING IS THE preferred method for metallurgically joining beryllium.[2] Suitable brazing filler metal systems and their temperature ranges include:

(1) Zinc: 800-850°F (427-454°C)
(2) Aluminum-silicon: 1050-1250°F (566-677°C)
(3) Silver-copper: 1200-1660°F (649-904°C)
(4) Silver: 1620-1750°F (882-954°C)

Zinc melts below 840°F, the temperature defined by AWS for brazing filler metal. Nevertheless, it is generally accepted as the lowest melting filler metal for brazing beryllium.

Aluminum-silicon filler metals can be used in high-strength, wrought beryllium assemblies because the brazing temperature is well below the base metal recrystallization temperature. BAlSi-4 type filler metal brazes well with fluxes. Fluxless brazing requires stringent control. Aluminum-base filler metals have less metallurgical interaction with the base metal than silver-base fillers. This is a significant advantage when thin beryllium sections or foils are to be joined.

Silver and silver-base brazing filler metals find use in structures exposed to elevated temperatures. Atmosphere brazing with these alloy systems is straight forward and may be performed in purified atmospheres or vacuum.

COPPER AND COPPER ALLOYS

THE COPPER ALLOY base metals include copper-zinc alloys (brass), copper-silicon alloys (silicon bronze), copper-aluminum alloys (aluminum bronze), copper-tin alloys (phosphor bronze), copper-nickel alloys, and several others. The brazing of copper and copper alloys and [illegible]

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[2] Beryllium and its compounds are toxic. Proper handling and identification of beryllium metal is required by federal regulations.

Table 12.5
Brazeable Magnesium Alloys and Filler Metals

AWS A5.8 Classification	ASTM Alloy Designation	Avail. Forms	Solidus		Liquidus		Brazing Range		Suitable Filler	
			°F	°C	°F	°C	°F	°C	BMg-1	BMG-2a
					Base Metal					
—	AZ10A	E	1170	632	1190	643	1080-1140	582-616	X	X
—	AZ31B	E. S	1050	566	1160	627	1080-1100	582-593		X
—	K1A	C	1200	649	1202	650	1080-1140	582-616	X	X
—	M1A	E. S	1198	648	1202	650	1080-1140	582-616	X	X
—	ZE10A	S	1100	593	1195	646	1080-1100	582-593		X
—	ZK21A	E	1159	626	1187	642	1080-1140	582-616	X	X
					Filler Metal					
BMg-1	AZ92A	W. R. ST. P	830	443	1110	599	1120-1140	604-616	—	—

E = Extruded shapes and structural sections
S = Sheet and plate
C = Castings
W = Wire
R = Rod
ST = Strip
P = Powder

metals are discussed in detail in Chapter 14, *Brazing Manual*, 3rd Edition.

LOW CARBON AND LOW ALLOY STEELS

LOW CARBON AND low alloy steels are brazed without difficulty. They are frequently brazed at temperatures above 1980°F (1080°C) with copper filler metal in a controlled atmosphere, or at lower temperatures with silver base filler metals.

For alloy steels, the filler metal should have a solidus well above any heat-treating temperature to avoid damage to joints that will be heat-treated after brazing. In some cases, air hardening steels can be brazed and then hardened by quenching from the brazing temperature.

A filler metal with brazing temperature lower than the critical temperature of the steel can be used when no change in the metallurgical properties of the base metal is wanted.

HIGH-CARBON AND HIGH-SPEED TOOL STEELS

HIGH-CARBON STEELS contain more than 0.45 percent carbon. High-carbon tool steels usually contain 0.60 to 1.40 percent carbon.

Brazing of high-carbon steels is best accomplished prior to or during the hardening operation. Hardening temperatures for carbon steels range from 1400 to 1500°F (760 to 820°C). Filler metals having brazing temperatures above 1500°F (820°C) should be used. When brazing and hardening are done in one operation, the filler metal should have a solidus at or below the austenitizing temperature.

Tempering and brazing can be combined for high-speed tool steels and high-carbon, high-chromium alloy tool steels which have tempering temperatures in the range of 1000 to 1200°F (540°C to 650°C). Filler metals with brazing temperatures in that range are used. The part is removed from the tempering furnace, brazed by localized heating methods, and then returned to the furnace for completion of the tempering cycle.

CAST IRONS

CAST IRONS GENERALLY require special brazing considerations. The types of cast iron include white, gray, malleable, and ductile. White cast iron is seldom brazed.

Prior to brazing, faying surfaces generally are cleaned electrochemically or chemically, seared with an oxidizing flame, or grit blasted. When low-melting silver brazing filler metals are used, wetting by the brazing filler metal is easiest. Ductile and malleable cast irons should be brazed below 1400°F (760°C).

When high carbon cast iron is brazed with copper, the brazing temperature should be low to avoid melting of localized areas of the cast iron, particularly in light sections.

STAINLESS STEELS

ALL OF THE stainless steel alloys are difficult to braze because of their high chromium content. Brazing of these alloys is best accomplished in purified (dry) hydrogen or in a vacuum. Dew points below -60°F (-51°C) must be maintained because wetting becomes difficult following the formation of chromium oxide. Torch brazing requires fluxing to reduce any chromium oxides present.

Most of the silver alloy, copper, and copper-zinc filler metals are used for brazing stainless steels. Silver alloys containing nickel are generally best for corrosion resistance. Filler metals containing phosphorus should not be used on highly stressed parts because brittle nickel and iron phosphides may be formed at the joint interface.

Boron-containing nickel filler metals are generally best for stainless steels containing titanium or aluminum, or both, because boron has a mild fluxing action which aids in wetting these base metals. Diffusion brazing produces joints with improved physical properties.

Brazing of the austenitic chromium-nickel stainless steels is discussed further in Chapter 18, *Brazing Manual*, 3rd Edition.

Chromium Irons and Steels

THE MARTENSITIC STAINLESS steels (403, 410, 414, 416, 420, and 431) air harden upon cooling from brazing, which occurs above their austenitizing temperature range. Therefore, they must be annealed after brazing or during the brazing operation. These steels are also subject to stress cracking with certain brazing filler metals.

The ferritic stainless steels (405, 406, and 430) cannot be hardened and their grain structure cannot be refined by heat treatment. These alloys degrade in properties when brazed at temperatures above 1800°F (980°C), because of excessive grain growth. They lose ductility after long heating times between 650 and 1100°F (340 and 600°C). However, some of the ductility can be recovered by heating the brazement to approximately 1450°F (790°C) for a suitable time.

Precipitation-Hardening Stainless Steels

THESE STEELS ARE basically stainless steels with additions of one or more of the elements copper, molybdenum, aluminum, and titanium. Such alloying additions make it possible to strengthen the alloys by precipitation hardening heat treatments. When alloys of this type are brazed, the brazing cycle and temperature must match the heat treatment cycle of the alloy. Manufacturers of these alloys have developed recommended brazing procedures for their particular steels.

NICKEL AND HIGH-NICKEL ALLOYS

NICKEL AND THE high nickel alloys are embrittled by sulfur and low-melting metals present in brazing alloys, such as zinc, lead, bismuth, and antimony. Base metal surfaces must be thoroughly cleaned prior to brazing to remove any substances that may contain these elements. Sulfur and sulfur compounds must also be excluded from the brazing atmosphere.

Nickel and its alloys are subject to stress cracking in the presence of molten brazing filler metals. Parts should be annealed prior to brazing to remove residual stresses, or carefully stress relieved during the braze cycle.

Silver brazing filler metals are commonly used. In corrosive environments, high silver brazing alloys are preferred. Cadmium-free brazing filler metals are chosen to avoid stress corrosion cracking.

Nickel-base brazing filler metals offer the greatest corrosion and oxidation resistance and elevated temperature strength.

Brazing is a preferred method for joining dispersion-strengthened nickel alloys that must function at elevated temperatures. High strength brazements have been made with special nickel-base brazing filler metals and then tested up to 2400°F (1300°C).

HEAT-RESISTANT ALLOYS

HEAT-RESISTANT ALLOYS are generally brazed in a hydrogen atmosphere or high temperature vacuum furnaces using nickel-base or special filler metals.

The cobalt-base alloys are the easiest of the super alloys to braze because most of them do not contain titanium or aluminum. Alloys that are high in titanium or aluminum are difficult to braze in dry hydrogen because titanium and aluminum oxides are not reduced at brazing temperatures.

TITANIUM AND ZIRCONIUM

TITANIUM AND ZIRCONIUM combine readily with oxygen, and react to form brittle intermetallic compounds with many metals and with hydrogen and nitrogen. Parts must be cleaned before brazing and brazed immediately after cleaning.

Silver and silver-based filler metals were used in early brazing of titanium, but brittle intermetallics were formed and crevice corrosion resulted. Type 3003 aluminum foil will join thin, lightweight structures, such as complex honeycomb sandwich panels. Electroplating various elements on the base metal faying surfaces will let them react in situ with the titanium during brazing to form a titanium alloy eutectic. That transient liquid phase flows well and forms fillets, then solidifies due to interdiffusion.

Other brazing filler metals with high service capability and corrosion resistance include Ti-Zr-Ni-Be, Ti-Zr-Ni-Cu, and Ti-Ni-Cu alloys. The best braze processing is obtained in high vacuum furnaces using closely controlled temperatures in the range of 1650 to 1750° (900 to 955°C).

CARBIDES AND CERMETS

CARBIDES OF THE refractory metals tungsten, titanium, and tantalum that are bonded with cobalt are used for cutting tools and dies. Closely related materials called *cermets* are ceramic particles bonded with various metals.

Brazing carbides and cermets is more difficult than brazing metals. Torch, induction, or furnace brazing is used, often with a sandwich brazing technique: a layer of weak, ductile metal (pure nickel or pure copper) is interposed between the carbide or cermet and a hard metal support. The cooling stresses cause the soft metal to deform instead of cracking the ceramic.

Silver-base brazing alloys, copper-zinc alloys, and copper are often used on carbide tools. Silver alloys containing nickel are preferred for their better wettability. The nickel base alloys containing boron and a 60% Pd - 40% Ni alloy may be satisfactory for brazing nickel- and cobalt-bonded cermets of tungsten carbide, titanium carbide, and columbium carbide.

CERAMICS

ALUMINA, ZIRCONIA, MAGNESIA, forsterite (Mg_2SiO_4), beryllia, and thoria are ceramic materials which can be joined by brazing. They are inherently difficult to wet with conventional filler metals. Differences in thermal expansion, heat conduction, and ductility result in cracking and crack propagation at relatively low stresses.

If the ceramic is premetallized to facilitate wetting, copper, silver-copper, and gold-nickel filler metals are used. Titanium or zirconium hydride can be decomposed at the ceramic-metal interface to form an intimate bond.

Nonmetallized ceramics are brazed with silver-copper-clad or nickel-clad titanium wires. Useful titanium and zirconium alloys are Ti-Zr-Be, Ti-V-Zr, Zr-V-Cb, Ti-V-Be, and Ti-V-Cr.

PRECIOUS METALS

THE PRECIOUS METALS silver, gold, platinum, and palladium present few brazing difficulties. Their thin oxide films are readily removed by fluxes and reducing atmospheres.

Resistance or furnace brazing is common for electrical contacts. Silver (BAg) and precious metal (BAu) filler metals braze contacts to holders.

REFRACTORY METALS

TUNGSTEN, MOLYBDENUM, TANTALUM, and columbium brazing is still in the developmental stages.

Tungsten

TUNGSTEN CAN BE brazed to itself and to other metals and nonmetals with nickel-base filler metals, but interaction between tungsten and nickel will recrystallize the base metal. The tungsten should be stress relieved by heat treatment prior to brazing, and the brazing cycle should be short to limit interaction with the filler metal.

Molybdenum

MOLYBDENUM AND ITS alloys are brazed with palladium-base filler metals and molybdenum-base metals (Mo-0.5Ti) with high recrystallization temperatures. Chromium plating, as a barrier layer, prevents formation of intermetallic compounds. Most high-temperature brazing filler metals are suitable for oxidation resistant service for coating applications.

Tantalum and Columbium

TANTALUM AND COLUMBIUM require special techniques to be satisfactorily brazed. All reactive gases must be removed from the brazing atmosphere. These include oxygen, nitrogen, carbon monoxide, ammonia, and hydrogen. Tantalum forms oxides, nitrides, carbides, and hydrides very readily, leading to a loss of ductility. For oxidation protection at high temperatures, tantalum and columbium are often electroplated with copper or nickel. The brazing filler metal must be compatible with any plating used.

DISSIMILAR METAL COMBINATIONS

MANY DISSIMILAR METAL combinations may be brazed, even those with metallurgical incompatibility that precludes welding.

Important criteria to be considered start with differences in thermal expansion. If a metal with high thermal expansion surrounds a low expansion metal, clearances at room temperature which are satisfactory for capillary flow will be too great at brazing temperature. Conversely, if a low expansion metal surrounds a high expansion metal, no clearance may exist at brazing temperature. For example, when brazing a molybdenum plug in a copper block, the parts must be a press fit at room temperature; if a copper plug is to be brazed in a molybdenum block, a properly centered loose fit at room temperature is required.

In brazing tube-and-socket type joints between dissimilar base metals, the tube should be the low expansion metal and the socket the high expansion metal. At brazing temperature, the clearance will be maximum and the capillary will fill with brazing alloy. When the joint cools to room temperature, the brazed joint and the tube will be in compression.

A tongue-in-groove joint should place the groove in the low expansion material. The fit at room temperature should be designed to give capillary joint clearances on both sides of the tongue at brazing temperature. Longitudinal shear stresses in the braze metal are limited by making overlap distances small.

"Sandwich brazing" is commonly used to manufacture carbide-tipped metal cutting tools. A relatively ductile metal is coated on both sides with brazing filler metal, and the composite is used in the joint. This places a third material in that joint which will deform during cooling and reduce the stresses caused by differential contraction of the parts brazed together.

The filler metal used to braze dissimilar metals must be compatible with both base metals. It should have corrosion or oxidation resistance at least equal to the poorer of the two metals being brazed. It should not form galvanic couples which could promote crevice corrosion in the braze area. Brazing filler metals form low melting phases with many base metals, requiring adaption of the brazing cycle, quantity and placement of filler metal, and joint design.

Metallurgical reactions between the brazing filler metal and dissimilar base metals may be objectionable. One example is the brazing of aluminum to copper. Copper reacts with aluminum to form a low melting brittle compound. Such problems can be overcome by coating one of the base metals with a metal which is compatible with the brazing filler metal. To braze aluminum to copper, the copper is plated with silver, or a high silver alloy. The joint is then brazed at 1500°F (816°C) with a standard aluminum brazing filler metal. Nickel plating would also form a suitable diffusion barrier.

JOINT DESIGN

BASICALLY TWO TYPES of joints are used in brazing: the lap joint and, the butt joint. These joints are shown in Figure 12.11.

The lap joint may be made as strong as the weaker member, even when using a low strength filler metal or in the presence of small defects in the joint, by using an overlap at least three times the thickness of the thinner member. Lap joints feature high joint efficiency and ease of fabrication; they have the disadvantage that the increased metal thickness at the joint creates a stress concentration at those abrupt changes in cross section.

Butt joints are used where the lap joint thickness would be objectionable, and where the strength of a brazed butt joint will satisfactorily meet service requirements. The joint strength depends only partly on the filler metal strength.

The scarf joint is a variation of the butt joint. As shown in Figure 12.12, the cross-sectional area of this joint is increased without an increase in metal thickness. Two disadvantages which limit its use: the sections are difficult to align, and the joint is difficult to prepare, particularly in thin members. Since the joint is at an angle to the axis of tensile loading, the load-carrying capacity is that of a lap joint.

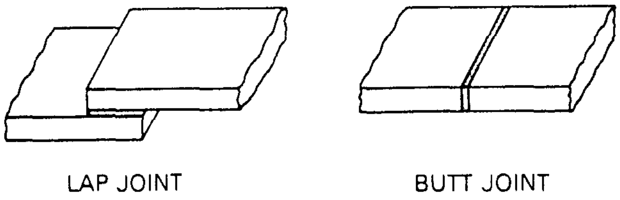

Figure 12.11–Basic Lap and Butt Joints for Brazing

JOINT CLEARANCE

JOINT CLEARANCE HAS a major effect on the mechanical performance of a brazed joint. This applies to all types of loading, such as static, fatigue, and impact, and to all joint designs. Several effects of joint clearance on mechanical performance are (1) the purely mechanical effect of restraint to plastic flow of the filler metal by a higher strength base metal, (2) the possibility of slag entrapment, (3) the possibility of voids, (4) the relationship between joint clearance and capillary force which accounts for filler metal distribution, and (5) the amount of filler metal that must be diffused with the base metal when diffusion brazing.

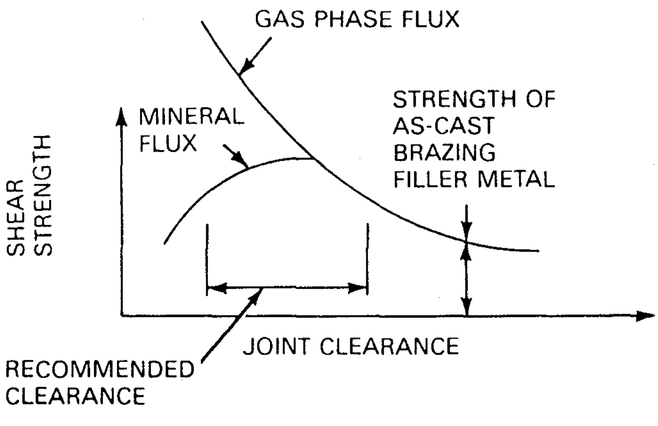

Figure 12.12–Relationship Between Joint Clearance and Shear Strength for two Fluxing Methods

If the brazed joint is free of defects (no flux inclusions, voids, unbrazed areas, pores, or porosity), its strength in shear depends upon the joint thickness, as illustrated in Figure 12.13. This figure indicates the change in joint shear strength with joint clearance. Table 12.6 may be used as a guide for clearances at brazing temperature when designing brazed joints for maximum strength.

Some specific clearance versus strength data for silver brazed butt joints in steel are shown in Figures 12.14 and 12.15.[3] Figure 12.14 shows the optimum shear values obtained with joints in 0.5 in. (12.7 mm) round drill rod using pure silver. The rods were butt brazed by induction heating in a dry 10 percent hydrogen-90 percent nitrogen atmosphere. Figure 12.15 relates tensile strength to joint thickness for butt brazed joints of the same size. Note how the strength decreased at extremely small clearances.

Preplaced filler is brazing filler metal placed in the joint, such as foil placed between two plates. In this application, the clearances noted in Table 12.6 generally do not apply. In applications using preplaced filler metal, the members being joined should be preloaded so that the joint clearance will decrease during the brazing operation. That forces the filler metal into voids created by the normal roughness of the faying surfaces. In some applications, additional filler metal is made available by extending the filler metal shim out beyond the joint edges.

The type of fluxing will have an important bearing on the joint clearance to used to accomplish a given brazement.

Figure 12.13–Typical Scarf Joint Designs

A mineral flux must melt at a temperature below the melting range of the brazing filler metal, and it must flow into the joint ahead of the filler metal. When the joint clearance is too small, the mineral flux may be held in the joint and not be displaced by the molten filler metal. This will produce joint defects. When the clearance is too large, the molten filler metal will flow around pockets of flux, causing excessive flux inclusions.

The joint clearance at the brazing temperature of a joint between dissimilar base metals must be calculated from thermal expansion data. Figure 12.16 shows thermal expansion data for some materials. Figure 12.17 can be used to find the diametral clearance at brazing temperature between dissimilar metals.

Table 12.6
Recommended Joint Clearance at Brazing Temperature

Filler Metal AWS Classification[a]	in.	mm	Joint Clearance[b]
BA1Si Group	0.006-0.010	0.15-0.25	For length at lap less than 1/4 in. (6.35 mm)
	0.010-0.025	0.25-0.61	For length at lap greater than 1/4 in. (6.35 mm)
BCuP Group	0.001-0.005	0.03-0.12	
BAg Group	0.002-0.005	0.05-0.12	Flux brazing (mineral fluxes)
	0.001-0.002[c]	0.03-0.05	Atmosphere brazing (gas phase fluxes)
BAu Group	0.002-0.005	0.05-0.12	Flux brazing (mineral fluxes)
	0.000-0.002[c]	0.00-0.05	Atmosphere brazing (gas phase fluxes)
BCu Group	0.000-0.002[c]	0.00-0.05	Atmosphere brazing (gas phase fluxes)
BCuZn Group	0.002-0.005	0.05-0.12	Flux brazing (mineral fluxes)
BMg Group	0.004-0.010	0.10-0.25	Flux brazing (mineral fluxes)
BNi Group	0.002-0.005	0.05-0.12	General applications (flux or atmosphere)
	0.000-0.002	0.00-0.05	Free flowing types, atmosphere brazing

a. See Table 12.2 for an explanation of filler metals.

b. Clearance on the radius when rings, plugs, or tubular members are involved. On some applications it may be necessary to use the recommended clearance on the diameter to assure not having excessive clearance when all the clearance is on one side. An excessive clearance will produce voids. This is particularly true when brazing is accomplished in a high quality atmosphere (gas phase fluxing).

c. For maximum strength, a press fit of 0.001 mm/mm or in./in. of diameter should be used.

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[3] The data in Figures 12.14 and 12.15 were obtained with nonstandard test specimens.

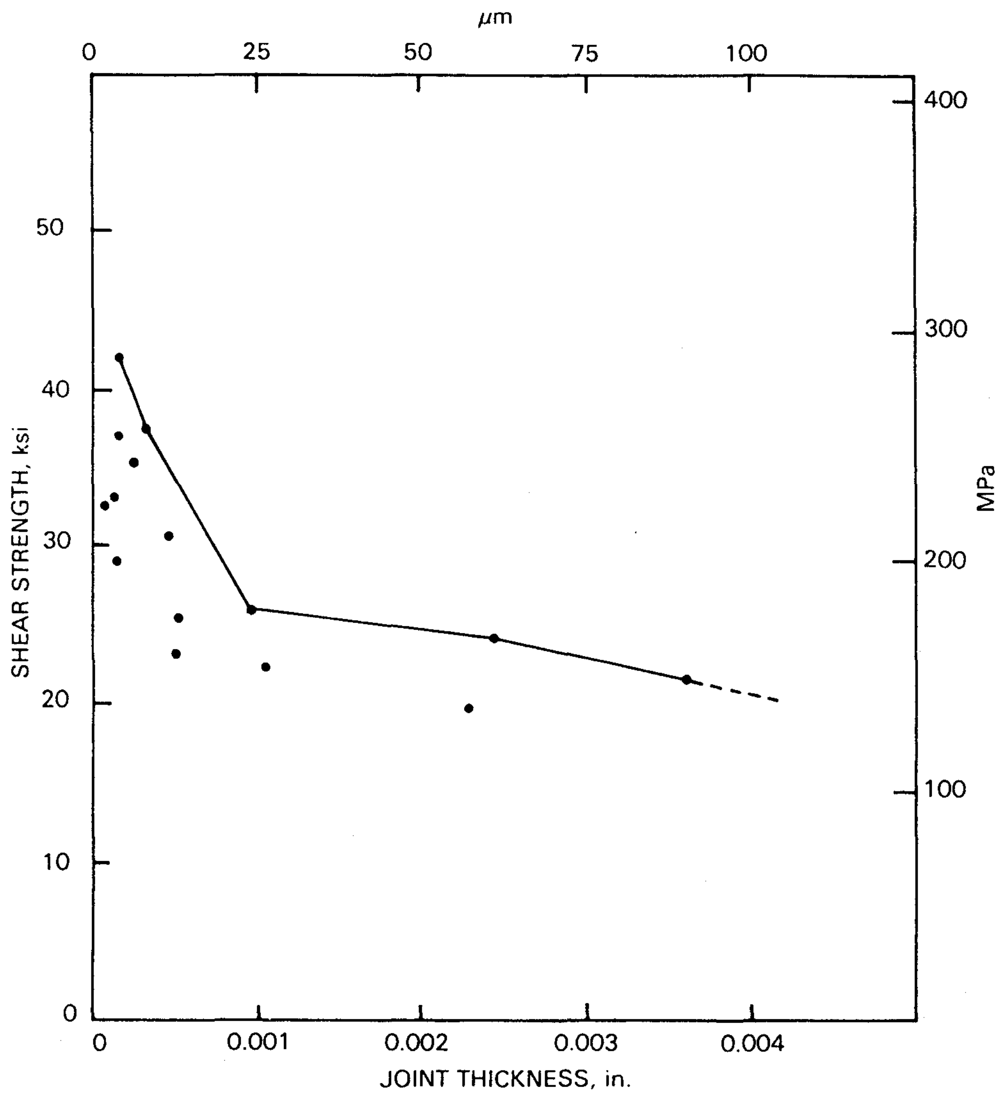


Figure 12.14–Relationship of Shear Strength to Brazed Joint Thickness for Pure Silver Joints in 0.5 in. (12.7 mm) Diameter Steel Drill Rod

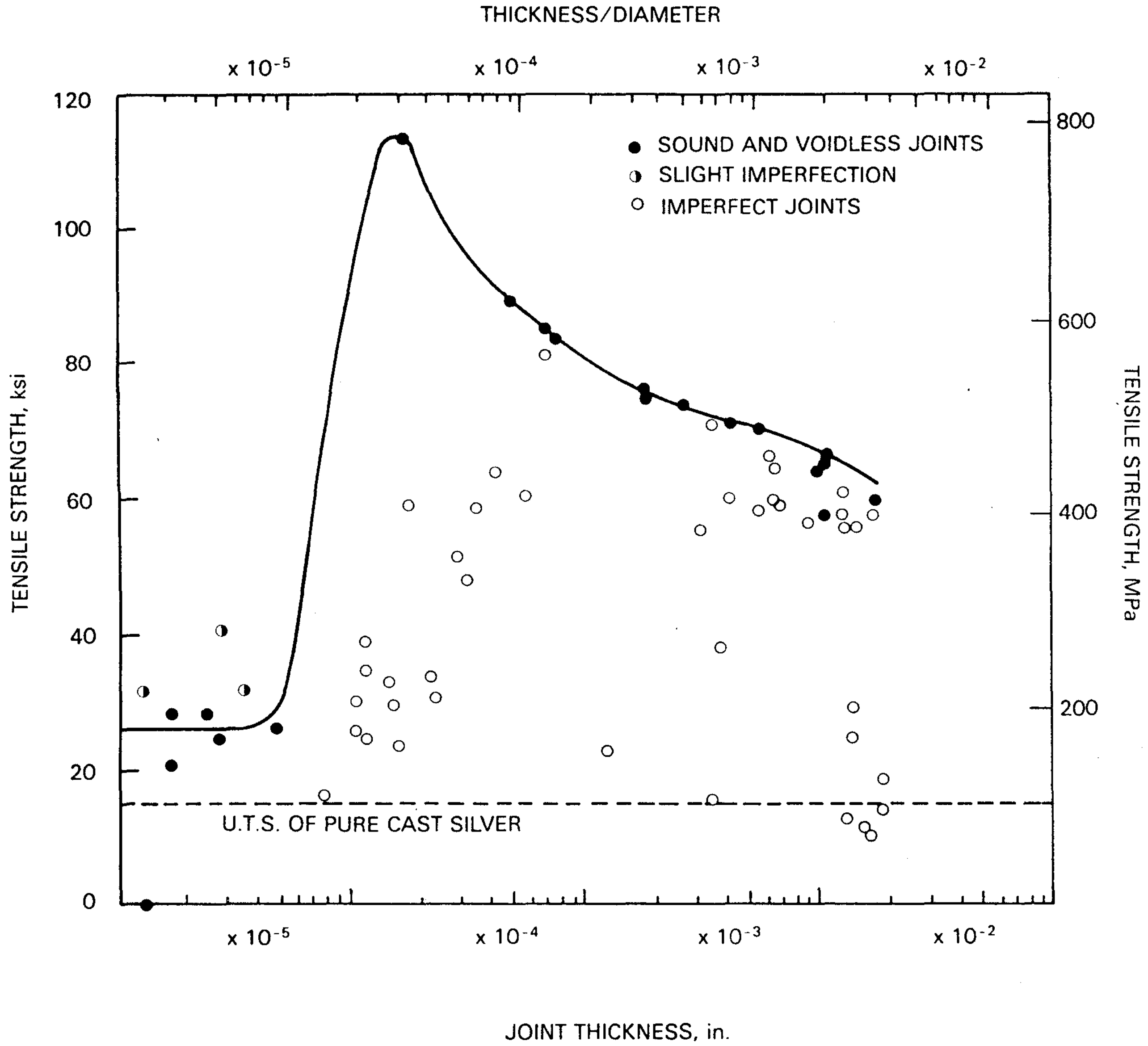


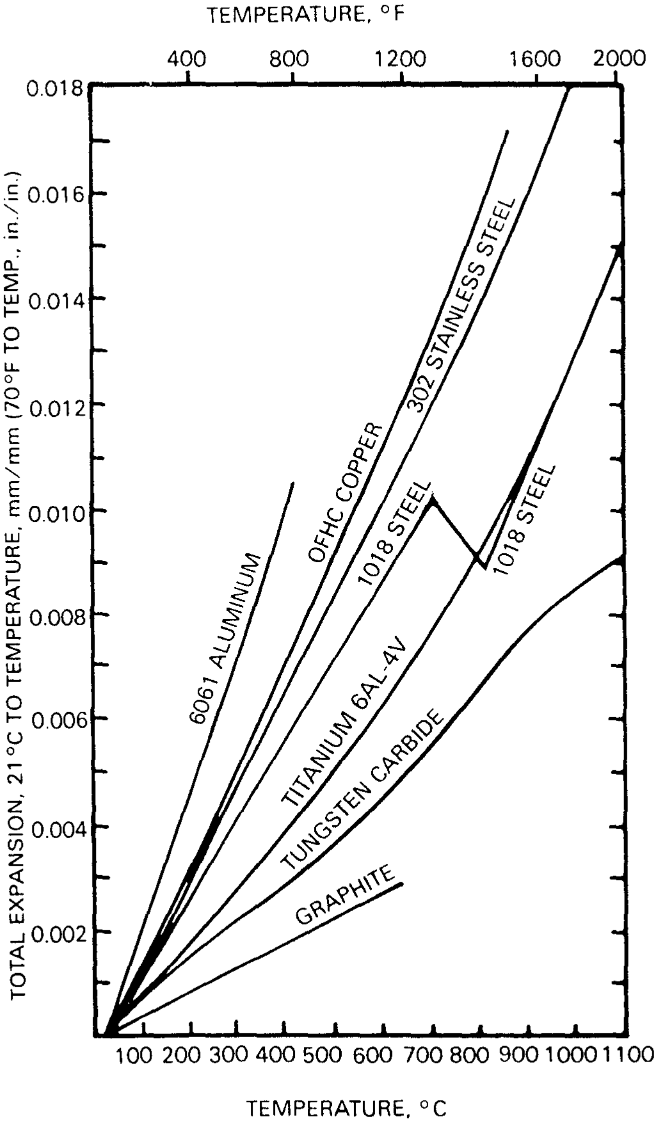
Figure 12.15–Relationship of Tensile Strength to Brazed Joint Thickness of 0.5 in. (12.7 mm) Diameter Silver Brazed Butt Joints in 4340 Steel

To withstand high differential thermal expansion of two metals being brazed, the brazing filler metal must be strong enough to resist fracture and the base metal must yield during cooling. Some residual stress will remain in the final brazement. Thermal cycling of such a brazement during its service life will repeatedly stress the joint area, which may shorten the service life. Dissimilar metal brazements should be designed so that residual stresses do not add to the stress imposed during service.

STRESS DISTRIBUTION

HIGH-STRENGTH BRAZEMENTS ARE designed to fail in the base metal. In brazements where joints will be lightly loaded, it is economical to use simplified joint designs which may break in the brazed joint if overstressed in testing or in service.

A good brazement design will incorporate joints that avoid high-stress concentration at the edges of the braze

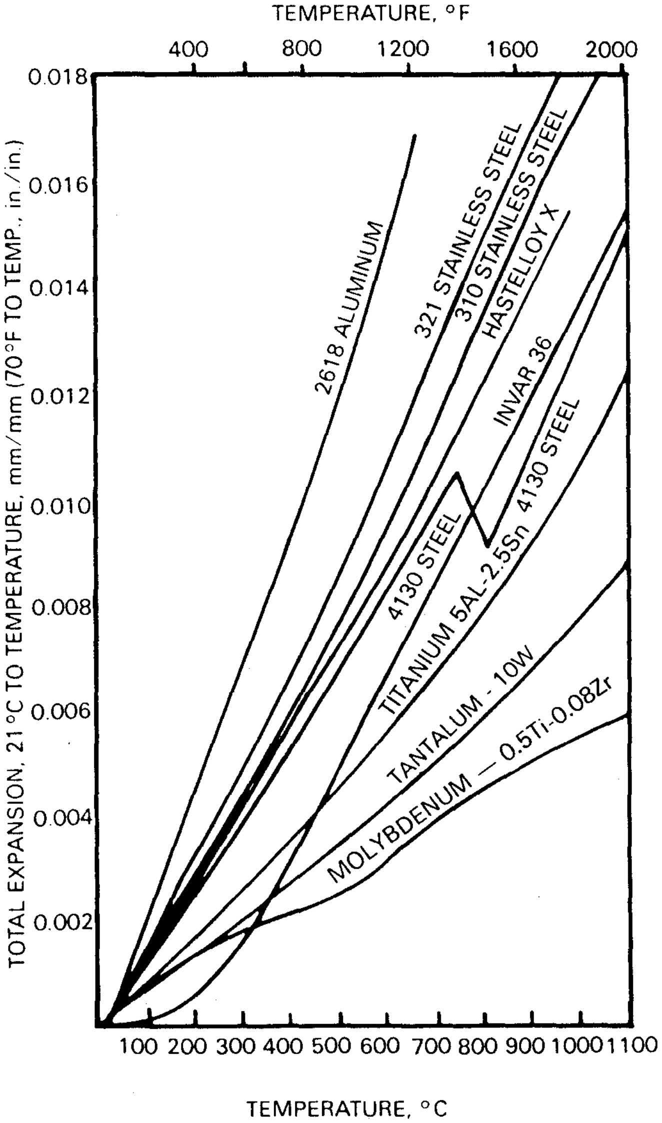


(A)

Figure 12.16–Thermal Expansion Curves for Some Common Materials

and will distribute the stresses uniformly into the base metal. Typical designs are shown in Figures 12.18 through 12.21.

A fillet of brazing filler metal is not good brazing design. It is seldom possible to make the brazing filler metal consistently form a desired fillet size and contour. When the fillets become too large, shrinkage or piping porosity will act as a stress concentration.



(B)

Figure 12.16 (Continued)–Thermal Expansion Curves for Some Common Materials

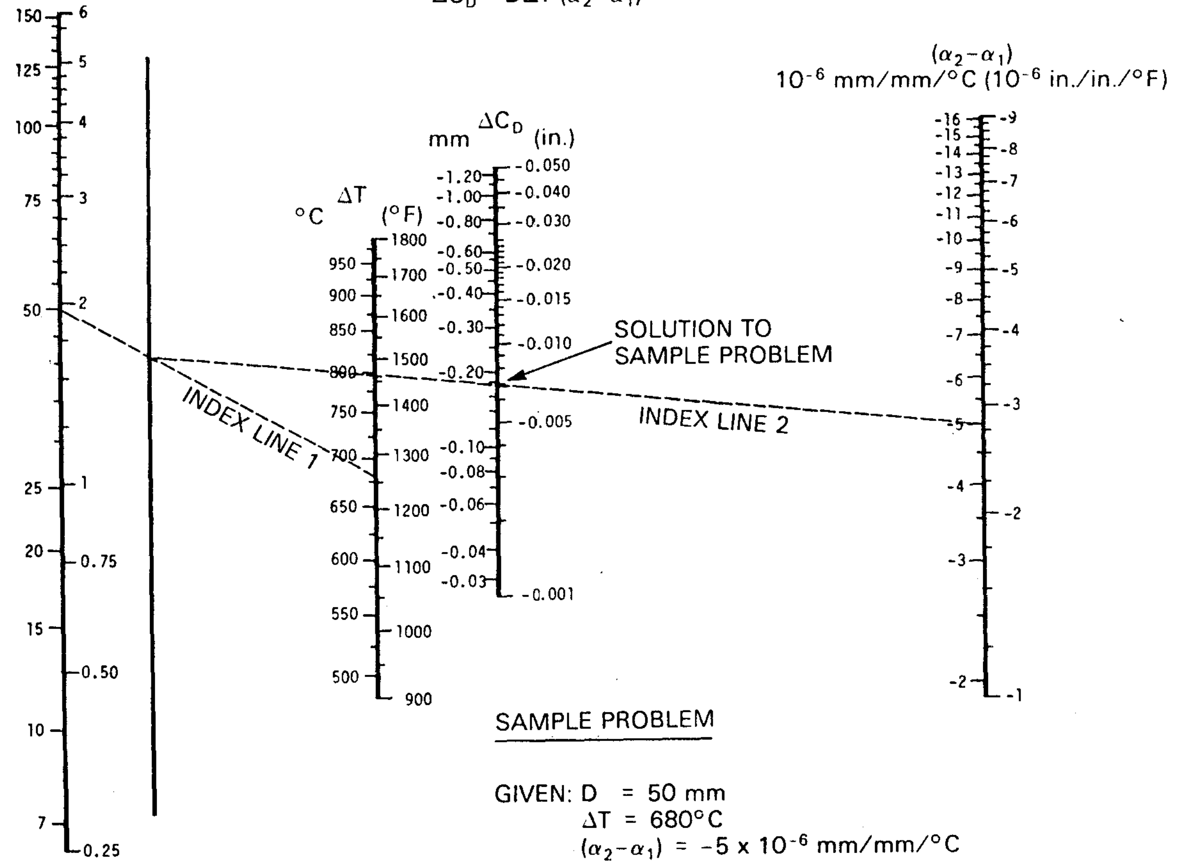
ELECTRICAL CONDUCTIVITY

BRAZING FILLER METALS in general have low electrical conductivity compared to copper. However, a braze joint will not add appreciable resistance to the circuit when properly designed.

With butt joints, the brazed joint thickness (resistance) is very small compared to the length-wise resistance of the conductor, even though the unit resistivity of the filler metal is much higher than that of the base metal. Never-

NOMOGRAPH FOR EQUATION

$\Delta C_D = D\Delta T(\alpha_2 - \alpha_1)$



SAMPLE PROBLEM

GIVEN: $D = 50$ mm
$\Delta T = 680$°C
$(\alpha_2 - \alpha_1) = -5 \times 10^{-6}$ mm/mm/°C

SOLUTION: $\Delta C_D = -0.17$ mm

NOTES:

1. This nomograph gives change in diameter caused by heating. Clearance to promote brazing filler metal flow must be provided at brazing termperature.
2. D = nominal diameter of joint, mm (in.)
   ΔC_D = change in clearance, mm (in.)
   ΔT = brazing temperature minus room temperature, °C (°F)
   $\alpha 1$ = mean coefficient of thermal expansion, male member, mm/mm/°C (in./in./°F)
   $\alpha 2$ = mean coefficient of thermal expansion, female member, mm/mm/°C (in./in./°F)
3. This nomograph assumes a case where α_1 exceeds α_2 so that scale value for $(\alpha_1 - \alpha_2)$ is negative. Resultant values for ΔC_D are therefore also negative, signifying that the joint gap reduces upon heating. Where $(\alpha_2 - \alpha_1)$ is positive, values of ΔC_D are read as positive, signifying enlargement of the joint gap upon heating.

Figure 12.17—Nomograph for Finding the Change in Diametral Clearance in Dissimilar Metal Joints

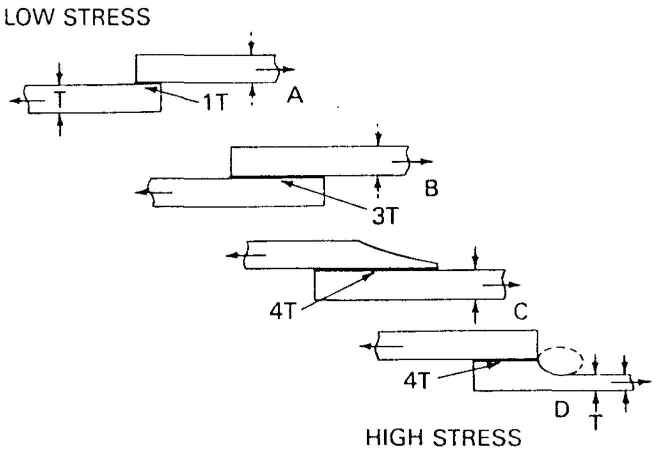


Figure 12.18–Brazed Lap Joint Designs for use at Low and High Stresses—Flexure of Right Member in C and D will Distribute the Load Through the Base Metal

theless, a filler metal with low resistivity should be used, provided it will meet all other requirements of the project.

Since voids in the brazed joint will reduce the effective area of the electrical path, lap joints are recommended. A lap length at least 1-1/2 times the thickness of the thinner member will have a joint resistance approximately equal to the same length in solid copper.

TESTING OF BRAZED JOINTS

STANDARDIZING TESTING TO evaluate the strength of brazed joints must be adopted. Different designs of test specimens yield different results. Note in Figure 12.22 that the "apparent joint strength" measured for a low overlap distance is high in comparison to the long overlap strength. Two laboratories that each test only one overlap distance may be testing at opposite ends of the curve, with widely different conclusions. The entire usable overlap range of the curve must be sampled to obtain adequate data.

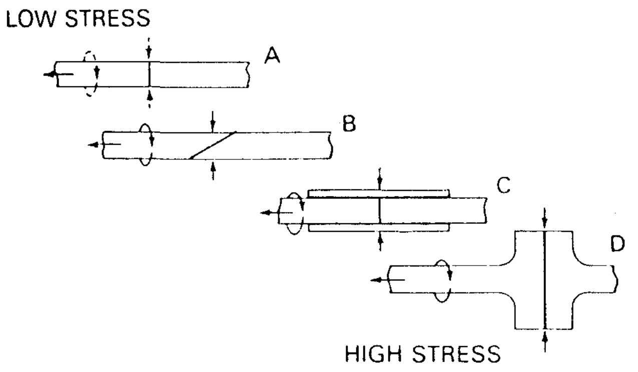


Figure 12.19–Brazed Butt Joint Designs to Increase Capacity of Joint for High Stress and Dynamic Loading

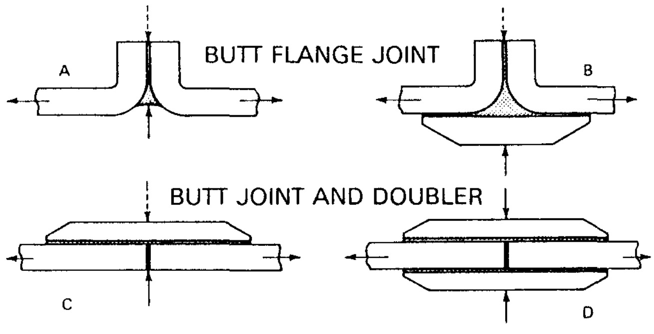


Figure 12.20–Butt Joing Designs for Sheet Metal Brazements—The Loading in Joint A cannot be Symmetrical

The load-carrying capacity of the joint is best revealed in the right-hand portion of the base metal curve. The brazement should be designed to fail in the base metal without an excessive overlap.

For further information, refer to the latest edition of AWS C3.2, *Standard Method for Evaluating the Strength of Brazed Joints in Shear.*

BRAZING METALLURGY

BRAZING TEMPERATURES ARE below the solidus of the metal(s) being joined. Metallurgical changes that accom-

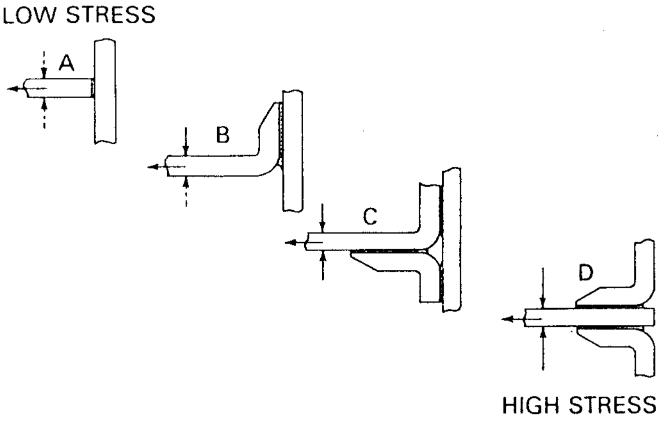


Figure 12.21–T-joint Designs for Sheet Metal Brazements

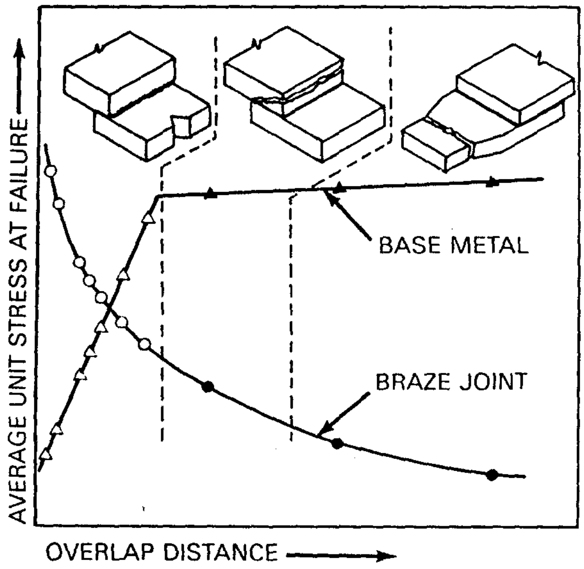


Figure 12.22–Average Unit Shear Stress in the Brazed Lap Joint and Average Unit Tensile Strength in the Base Metal as Functions of Overlap Distance—(Open Symbols Represent Failures in the Filler Metal; Filled Symbols Represent Failures in the Base Metal)

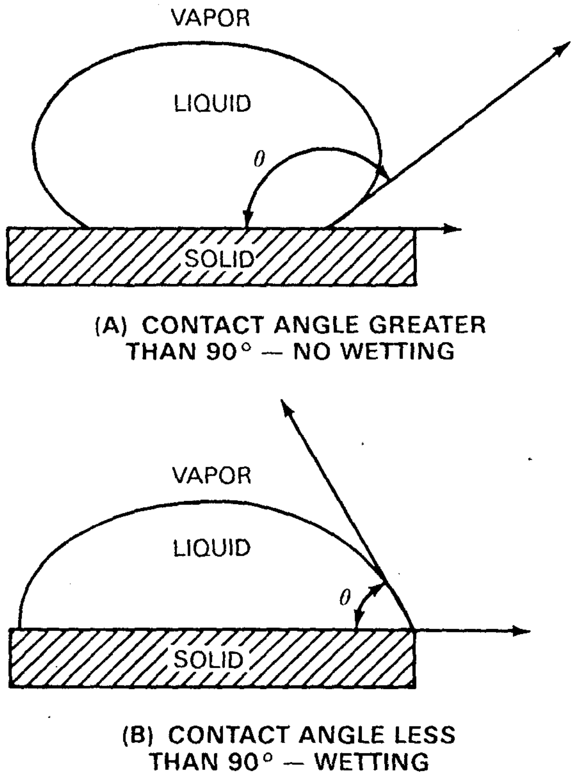
pany brazing are restricted to solid-state reactions in the base metal, solidification and interface reactions between the brazing filler metal and base metal, reactions within the solid filler metal.

The capillary flow of brazing metal depends upon its surface tension, wetting characteristics, and physical and metallurgical reactions with the base material, flux or atmosphere, and oxides on the base metal surface. The flow is further controlled by hydrostatic pressure within the joint. Figure 12.23 is an idealized presentation of the wetting concept.

A contact angle less than 90 degrees measured between the solid and liquid usually identifies a positive wetting characteristic. Contact angles greater than 90 degrees indicate no wetting (dewetting).

In some brazing processes, wetting and spreading are assisted by the addition of flux. In vacuum brazing, flow and wetting depend entirely upon surface interactions between the liquid metal and base metal. Most oxides are readily displaced or removed by flux. Oxides of chromium, aluminum, titanium, and manganese require special treatments.

At peak temperature in the brazing cycle, when liquid filler metal is present in the joint, erosion can occur in the base metal. The rate of dissolution of the base metal by the filler metal depends on the mutual solubility limits, the quantity of brazing filler metal available to the joint, the brazing temperature, and the potential formation of lower temperature eutectics.



(A) CONTACT ANGLE GREATER THAN 90° — NO WETTING

(B) CONTACT ANGLE LESS THAN 90° — WETTING

Figure 12.23–Wetting Angles of Brazing Filler Metals

Sometimes an interlayer of intermetallic compound may form between the filler metal and the base metal during the joining operation. Phase diagrams are used to predict intermetallic compound formation.

Once the filler metal has solidified to form the joint, subsequent effects may be controlled by diffusion phenomena. When joining super alloys with a nickel-base filler metal containing boron, subsequent thermal cycles diffuse the boron into the base metal. This method of metallurgical joining is called *liquid-activated diffusion welding*, but actually, it is an extension of the joining mechanism in brazing.

Liquid filler metal penetration between base metal grain boundaries may occur. Base metals in a stressed state are particularly susceptible to liquid metal penetration. Copper-based filler metals used on high iron-nickel alloys under stress fail rapidly. Alloying elements diffuse more rapidly into grain boundaries than into a crystal lattice.

If a eutectic is formed, being low-melting it may fill any grain-boundary crack as it separates; then little damage may be done. This is known as an *intrusion*.

The dynamic characteristics of the brazing process are receiving increasing recognition, and careful consideration is being given to the subsequent diffusion and metallurgical changes that can occur in service. At elevated temperatures, changes may occur in the solid-state as a direct result of diffusion, oxidation, or corrosion. This means that the metallurgical and mechanical properties of these joints may change in service and must be evaluated as part of the joint qualification procedure.

BRAZING PROCEDURES

PRECLEANING AND SURFACE PREPARATION

CLEAN, OXIDE-FREE SURFACES are essential to ensure sound brazed joints of uniform quality. Grease, oil, dirt, and oxides prevent the uniform flow and bonding of the brazing filler metal, and they impair fluxing action resulting in voids and inclusions. With the refractory oxides or critical atmosphere brazing applications, precleaning must be more thorough and the cleaned components must be preserved and protected from contamination.

The length of time that cleaning remains effective depends upon the metals involved, the atmospheric conditions, the amount of handling the parts may receive, the manner of storage, and similar factors. It is recommended that brazing be done as soon as possible after the parts have been cleaned.

Degreasing is generally done first. The following degreasing methods are commonly used, and their action may be enhanced by mechanical agitation or by applying ultrasonic vibrations to the bath:

(1) Solvent cleaning: petroleum solvents or chlorinated hydrocarbons
(2) Vapor degreasing: stabilized trichloroethylene or stabilized perchloroethylene
(3) Alkaline cleaning: commercial mixtures of silicates, phosphates, carbonates, detergents, soaps, wetting agents and, in some cases, hydroxides
(4) Emulsion cleaning: mixtures of hydrocarbons, fatty acids, wetting agents, and surface activators
(5) Electrolytic cleaning: both anodic and cathodic

Scale and oxide removal can be accomplished mechanically or chemically. Prior degreasing allows intimate contact of the pickling solution with the parts, and vibration aids in descaling with any of the following solutions:

(1) Acid cleaning: phosphate type acid cleaners
(2) Acid pickling: sulfuric, nitric, and hydrochloric acid
(3) Salt bath pickling: electrolytic and nonelectrolytic

The selection of chemical cleaning agent will depend on the nature of the contaminant, the base metal, the surface condition, and the joint design. For example, base metals containing copper and silver should not be pickled with nitric acid. In all cases, the chemical residue must be removed by thorough rinsing to prevent formation of other equally undesirable films on the joint surfaces, or subsequent chemical attack of the base metal.

Mechanical cleaning removes oxide and scale and also roughens the mating surfaces to enhance capillary flow and wetting by the brazing filler metal. Grinding, filing, machining, and wire brushing can be used. Grit blasting can be done with clean blasting material such as silica sand, alumina, and other nonmetallics. They must not leave any deposit on the surfaces that would impair brazing.

FLUXING AND STOPOFF

WHEN A FLUX is selected for use, it must be applied as an even coating, completely covering the joint surfaces of the parts. Fluxes are most commonly applied in the form of pastes or liquids. Dry powdered flux may be sprinkled on the joint or applied by dipping the heated end of the filler metal rod into the flux container. The particles should be small and thoroughly mixed to improve metal coverage and fluxing action. The areas surrounding the joints may be kept free from discoloration and oxidation by applying flux to a wide area on each side of the joint.

The paste and liquid flux should adhere to clean metal surfaces. If the metal surfaces are not clean, the flux will ball up and leave bare spots. Thick paste fluxes can be applied by brushing. Less viscous consistencies can be applied by dipping, hand squirting, or automatic dispensing. The proper consistency depends upon the types of oxides present, as well as the heating cycle. For example, ferrous oxides formed during fast heating of the base metal are soft and easy to remove, and only limited fluxing action is required. However, when joining copper or stainless steel or when the heating cycle is long, a concentrated flux is required. Flux reacts with oxygen, and once it becomes saturated, it loses all its effectiveness. The viscosity of the flux may be reduced without dilution by heating it to 120 to 140°F (50 to 60°C), preferably in a ceramic-lined flux or glue pot with a thermostat control. Warm flux has low surface tension and adheres to the metal more readily.

When filler metal flow must be restricted to definite areas, "stopoffs" are employed to outline the areas that are not to be brazed. Some commercial stopoff preparations are a slurry in water or an organic binder of oxides of aluminum, chromium, titanium, or magnesium. Others are called *parting compounds* and *surface reaction stopoffs*.

BRAZING FILLER METAL PLACEMENT

WHEN DESIGNING A brazed joint, the brazing process to be used and the manner in which the filler metal will be placed in the joint should be established. In most manually brazed joints, the filler metal is simply fed from the face side of the joint. For furnace brazing and high production brazing, the filler metal is preplaced at the joint. Automatic dispensing equipment may perform this operation.

Brazing filler metal is available in the form of wire, shims, strip, powder, and paste. Figures 12.24 and 12.25 illustrate methods of preplacing brazing filler metal in wire and sheet forms. When the base metal is grooved to accept preplaced filler metal, the groove should be cut in the heavier section. When computing the strength of the intended joint, the groove area should be subtracted from the joint area, since the brazing filler metal will flow out of the groove and into the joint interfaces, as shown in Figure 12.26.

Powdered filler metal can be applied in any of the locations indicated in Figure 12.24. It can be applied dry to the joint area and then wet down with binder, or it can be premixed with the binder and applied to the joint. The density of powder is usually only 50 to 70 percent of a solid metal, so the groove volume must be larger for powder.

Where preplaced shims are used, the sections being brazed should be free to move together when the shims melt. Some type of loading may be necessary to move them together and force excess filler metal and flux out of the joint.

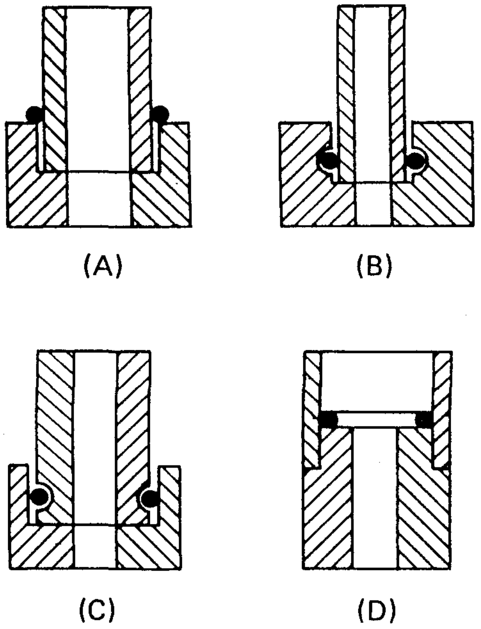


Figure 12.24–Methods of Preplacing Brazing Filler Wire

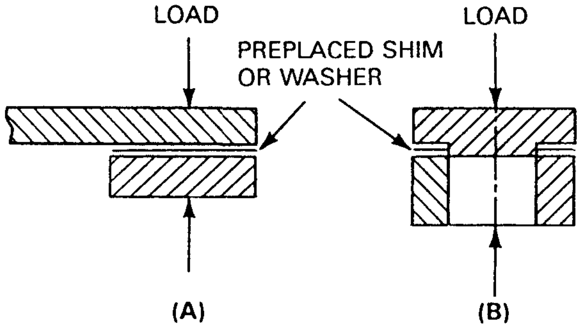


Figure 12.25–Preplacement of Brazing Filler Shims

ASSEMBLY

THE PARTS TO be brazed should be assembled immediately after fluxing, before the flux has time to dry and flake off. Assemblies designed to be self-locating and self-supporting are the most economical.

When fixtures are needed to maintain alignment or dimensions, the mass of a fixture should be minimized. It should have pinpoint or knife-edge contact with the parts, away from the joint area. Sharp contacts minimize heat loss through conduction to the fixture. The fixture material must have adequate strength at brazing temperature to support the brazement. It must not readily alloy at elevated temperatures with the work at the points of contact. In torch brazing, extra clearance will be needed to access the joint with the torch flame as well as the brazing filler metal. In induction brazing, fixtures are generally made of ceramic materials to avoid putting extraneous metal in the field of the induction coil. Ceramic fixtures may be designed to serve as a heat shield or a heat absorber.

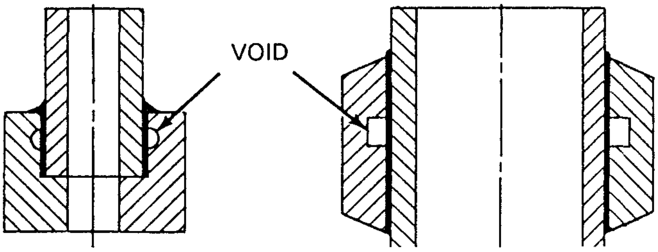


Figure 12.26–Brazed Joints with Grooves for Preplacement of Filler Metal; After the Brazing Cycle the Grooves are Void of Filler Metal

Flux Removal

FOR ALL PROCESSES, all traces of flux should be removed from the brazement. Flux residues usually may be removed by rinsing with hot water. Oxide-saturated flux is glass-like and more difficult to remove. If the metal and joint design can withstand quenching, saturated flux can be removed by quenching the brazement from an elevated temperature. This treatment cracks off the flux coating. In stubborn cases, it may be necessary to use a warm acid solution, such as 10 percent sulfuric acid, or one of the proprietary cleaning compounds which are available commercially. Nitric acid should not be used on alloys containing copper or silver.

Fluxes used for brazing aluminum are not readily soluble in cold water. They are usually rinsed in very hot water, above 180°F (82°C), with a subsequent immersion in nitric acid, hydrofluoric acid, or a combination of those acids. A thorough water after-rinse is then necessary.

Oxidized areas adjacent to the joint may be restored by chemical cleaning or by mechanical methods, such as wire brushing or blast cleaning.

Stopoff Removal

STOPOFF MATERIALS OF the "parting-compound" type can be easily removed mechanically by wire brushing, air blasting, or water flushing. The "surface-reaction" type used on corrosion and heat resistant base metals can best be removed by pickling in hot nitric acid-hydrofluoric acid, except in assemblies containing copper and silver. Sodium hydroxide (caustic soda) or ammonium bifluoride solutions can be used in all applications, including copper and silver, because they will not attack base metals or filler metals. A few stop off materials can readily be removed by dipping in 5 to 10 percent nitric or hydrochloric acid.

INSPECTION

INSPECTION OF BRAZEMENTS should always be required to protect the ultimate user, but it's often specified by regulatory codes and by the fabricator. Inspection of brazed joints may be conducted on test specimens or by tests of the finished brazed assembly. The tests may be nondestructive or destructive.

Generally, brazing discontinuities are of three general classes:

(1) Those associated with drawing or dimensional requirements

(2) Those associated with structural discontinuities in the brazed joint

(3) Those associated with the braze metal or the brazed joint

NONDESTRUCTIVE TESTING METHODS

THE OBJECTIVES OF nondestructive inspection of brazed joints should be (1) to seek out discontinuities defined in quality standards or codes, and (2) to obtain clues to the causes of irregularities in the fabricating process.

Visual Inspection

EVERY BRAZED JOINT should be examined visually. It is a convenient preliminary test when other test methods are to be used.

The joint should be free from foreign materials: grease, paint, oil, oxide film, flux, and stopoff. Visual examination should reveal flaws due to damage, misalignment and poor fit-up of parts, dimensional inaccuracies, inadequate flow of brazing filler metals, exposed voids in the joint, surface flaws such as cracks or porosity, and heat damage to base metal.

Visual inspection will not detect internal flaws, such as flux entrapment in the joint or incomplete filler metal flow between the faying surfaces.

Proof Testing

PROOF TESTING IS a method of inspection that subjects the completed joint to loads slightly in excess of those that will be experienced during its subsequent service life. These loads can be applied by hydrostatic methods, by tensile loading, by spin testing, or by numerous other methods. Occasionally, it is not possible to assure a serviceable part by any of the other nondestructive methods of inspection, and proof testing then becomes the most satisfactory method.

Leak Testing

PRESSURE TESTING DETERMINES the gas or liquid tightness of a closed vessel. It may be used as a screening method to find gross leaks before adopting sensitive test methods. A low pressure air or gas test may be done by one of three methods (sometimes used in conjunction with a pneumatic proof test): (1) submerging the pressurized vessel in water and noting any signs of leakage by rising air bubbles; (2) pressurizing the assembly, closing the air or gas inlet source, and then noting any change in internal pressure over a period of time (corrections for temperature may be necessary); or (3) pressurizing the assembly and checking for leaks by brushing the joint area with a soap solution or a commercially available liquid and noting any bubbles and their source.

A method sometimes used in conjunction with a hydrostatic proof test is to examine the brazed joints visually for indications of the hydrostatic fluid escaping through the joint.

The leak testing of brazed assemblies with freon is extremely sensitive. The part under test is pressurized using either pure freon gas, or a gas such as nitrogen containing a tracer, usually Freon 12. Areas are sniffed or probed with a sampling device which is sensitive to the halide ion. The detection of a leak is indicated by a meter or an audible alarm. A leak may be measured quantitatively by this method. Precaution must be taken to avoid contaminating the surrounding air with freon which will decrease the sensitivity of the method.

A less sensitive method is to probe for leaks of the tracer gas with a butane gas torch flame. The presence of Freon 12 is indicated by a change in the flame color. Flame testing must not be used near combustible material.

The mass spectrometer leak test is the most sensitive and accurate way of detecting extremely small leaks. A tracer gas, such as helium or hydrogen, is used in conjunction with a mass spectrometer in one of two ways: (1) Evacuate the brazed assembly and surround the area to be tested with the tracer gas—the mass spectrometer is coupled to the interior; or (2) Pressurize the brazed assembly with the tracer gas and sniff the exterior with the mass spectrometer probe. A sensitive-sensing device detects the tracer gas and converts it to an electrical signal.

Liquid Penetrant Inspection

THIS NDT METHOD finds cracks, porosity, incomplete flow, and similar surface flaws in a brazed joint. Commercially colored or fluorescent penetrants penetrate surface openings by capillary action. After the surface penetrant has been removed, any penetrant in a flaw will be drawn out by a white developer that is applied to the surface. Colored penetrant is visible under ordinary light. Fluorescent penetrant flaw indications will glow under an ultraviolet (black) light source. Since penetration of minute openings is involved, interpretation is sometimes difficult because of the irregularities in braze fillets and residues of flux deposits. Inpection by another method must be used to differentiate surface irregularities from joint discontinuities.

Radiographic Inspection

RADIOGRAPHIC INSPECTION OF brazements detects lack of bond or incomplete flow of filler metal. The joints should be uniform in thickness and the exposure made straight through the joint. The sensitivity of the method is generally limited to two percent of the joint thickness. X-ray absorption by certain filler metals, such as gold and silver, is greater than absorption by most base metals. Therefore, areas in the joint that are void of braze metal show much darker than the brazed area on the film or viewing screen.

Ultrasonic Inspection

THE ULTRASONIC TESTING method using low energy, high frequency mechanical vibration (sound waves) readily detects, locates, or identifies discontinuities in brazed joints. The applicability to brazements of this method depends largely on the design of the joint, surface condition, material grain size, and the configuration of adjacent areas.

Thermal Heat Transfer Inspection

INSPECTION BY HEAT transfer will detect lack of bond in such brazed assemblies as honeycomb and covered skin panel surfaces. With one technique, the surfaces are coated with a developer which is a low melting point powder. The developer melts and migrates to cool areas upon the application of heat from an infrared lamp. The bonded areas act as heat sinks, resulting in a thermal gradient to which the developer will react. Sophisticated techniques use phosphors, liquid crystals, and temperature-sensitive materials.

Infrared-sensitive electronic devices with some form of readout are available to monitor temperature differences less than 2°F (1°C) which indicate variations in braze quality.

DESTRUCTIVE TESTING METHODS

DESTRUCTIVE METHODS OF inspection clearly show whether a brazement design will meet the requirements of intended service conditions. Destructive methods must be restricted to partial sampling. It is used to verify the nondestructive methods of inspection, by sampling production material at suitable intervals.

Metallographic Inspection

THIS METHOD REQUIRES the removal of sections from the brazed joints and preparing them for macroscopic or microscopic examination. This method detects flaws (especially porosity), poor flow of brazing filler metal, excessive base metal erosion, the diffusion of brazing filler metal, improper fit-up of the joint, and it will reveal the microstructure of the brazed joint.

Peel Tests

PEEL TESTS ARE frequently employed to evaluate lap type joints. One member of the brazed specimen is clamped rigidly in a vise, and the free member is peeled away from the joint. The broken parts reveal the general quality of the bond and the presence of voids and flux inclusions in the joint. The permissible number, size, and distribution of these discontinuities should be defined in the job contract, specification, or code.

Tension and Shear Tests

THESE TESTS DETERMINE quantitatively the strength of the brazed joint, or verify the relative strengths of the joint and base metal. This method is widely used when developing a brazing procedure. Random sampling of brazed joints is used for quality control and verification of brazing performance.

Torsion Tests

THE TORSION TEST evaluates brazed joints with a stud, screw, or tubular member brazed to a base member. The base member is clamped rigidly and the stud, screw, or tube is rotated to failure which will occur in either the base metal or the brazing alloy.

COMMON IMPERFECTIONS IN BRAZED JOINTS

NONDESTRUCTIVE AND DESTRUCTIVE inspections identify the following types of brazing imperfections. The limits of acceptability should be specifically defined.

Lack of Fill (Voids, Porosity)

LACK OF FILL can be the result of improper cleaning, excessive clearances, insufficient filler metal, entrapped gas, and movement of the mating parts caused by improper fixturing. The filler metal is vulnerable when in the liquid or partially liquid state. Lack of fill reduces the strength of the joint by reducing the load-carrying area, and it may provide a path for leakage.

Flux Entrapment

ENTRAPPED FLUX MAY be found in any brazing operation where a flux is added to prevent and remove oxidation during the heating cycle. Flux trapped in the joint prevents flow of the filler into that area, thus reducing the joint strength. It may also falsify leak- and proof-test indications. Entrapped corrosive flux may reduce service life.

Noncontinuous Fillets

MISSING FILLETS ARE usually noted during visual inspection. Whether their omissions can be waived depends upon the job contract.

Base Metal Erosion

EROSION RESULTS WHEN the brazing filler metal alloys with the base metal. It may result in undercuts or the disappearance of the mating surface. Erosion reduces the strength of the joint by changing the composition of the materials and by reducing the base metal cross-sectional area.

Unsatisfactory Surface Appearance

UNSATISFACTORY BRAZING FILLER metal appearance, including excessive spreading and roughness, is objectionable for more than aesthetic reasons. Appearance defects may act as stress concentrations, corrosion sites, or may interfere with inspection of the brazement.

Cracks

CRACKS REDUCE BOTH strength and service life. They act as stress raisers, lowering the mechanical strength of the brazement and causing premature fatigue failure.

TROUBLESHOOTING

POOR BRAZING IS usually the result of the following failures:

(1) No wetting - no capillary flow, which leaves voids
(2) Excessive wetting - too much filler metal where it is not desired, e.g., in holes, or on machined surfaces
(3) Erosion - attack on the base metal by the brazing filler metal, which reduces the thickness of parent metal areas

If the basic cause of each of these failures can be identified, the solution of the brazing problem will be at hand. Table 12.7 lists items to consider for each of these failure problems.

Table 12.7
Solutions to Typical Brazing Problems

PROBLEM —No Flow, No Wetting

CAUSES:
—Braze filler—different lot or wrong one
—Low temp—poor technique, thermocouple/controller error
—Time—too short
—Dirty parts—not cleaned properly
—Poor atmosphere—too little flux, wrong flux, bad gas or vacuum
—No Ni-plate—allowing oxidation of base metal
—Gap too large—poor fitup control

PROBLEM —Excess Flow or Wetting—Causes Hole Plugging, Brazing Wrong Joints

CAUSES:
—Temperature too high—poor technique, furnace error
—Time—too long
—Too much filler metal—poor technique, different gap size
—Braze filler—different lot or wrong one
—No stopoff used

PROBLEM Erosion—Braze Filler Metal Eats Away Parent Metal

CAUSES:
—Temperature too high—poor technique, furnace error
—Time at temperature too long—poor technique, controller error
—Excessive braze filler metal—poor technique, change in gap, parts in different attitude
—Cold worked parts—highly susceptible—change in part manufacturer—not stress relieved
—Braze filler metals are too high above liquidus or high concentration of melting point depressants.

BRAZE WELDING

INTRODUCTION

BRAZE WELDING IS accomplished using a brazing filler metal having a liquidus above 840°F (450°C) but below the solidus of the base metals to be welded. As noted on the first page of this chapter, braze welding differs from brazing in that the filler metal is not distributed in the joint by capillary attraction. The filler metal is added to the joint as welding rod or is deposited from an arc welding electrode.[4] The base metals are not melted, only the filler metal melts. Bonding takes place between the deposited filler metal and the hot unmelted base metals in the same manner as conventional brazing, but without intentional capillary flow. Joint designs for braze welding are similar to those used for oxyacetylene welding.

Braze welding was originally developed to repair cracked or broken cast iron parts. Fusion welding of cast iron requires extensive preheating and slow cooling, to minimize the development of cracks and the formation of hard cementite. With braze welding, cracks and cementite are easier to avoid, and fewer expansion and contraction problems are encountered.

Most braze welding is done with an oxyfuel gas welding torch, a copper alloy brazing rod, and a suitable flux. Braze welding also is done with carbon arc, gas tungsten arc, and plasma arc torches, without flux. The carbon arc torch is used to weld galvanized sheet steel. The GTAW and PAW torches, which use inert gas shielding, braze weld with filler metals that have relatively high melting temperatures.

Braze welding has the following advantages over conventional fusion welding processes:

(1) Less heat is required to accomplish bonding, which permits faster joining and lower fuel consumption. The process produces little distortion from thermal expansion and contraction.

(2) The deposited filler metal is relatively soft and ductile, readily machinable, and under low residual stress.

(3) Welds have strength adequate for many applications.

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[4] Braze welding of cast iron is sometimes done by the shielded metal arc welding process. See Chapter 2.

(4) The equipment is simple and easy to use.

(5) Metals that are brittle, such as gray cast iron, can be braze welded without extensive preheat.

(6) The process provides a convenient way to join dissimilar metals, for example copper to steel and cast iron, and nickel-copper alloys to cast iron and steel.

Braze welding does have these disadvantages:

(1) Weld strength is limited to that of the filler metal.

(2) Permissible performance temperatures of the product are lower than those of fusion welds because of the lower melting temperature of the filler metal. With copper alloy filler metal, service is limited to 500°F (260°C) or lower.

(3) The braze welded joint may be subject to galvanic corrosion and differential chemical attack.

(4) The brazing filler metal color may not match the base metal color.

EQUIPMENT

CONVENTIONAL BRAZE WELDING is done using an oxyfuel gas welding torch and the associated equipment described in Chapter 11. In some applications, an oxyfuel preheating torch may be needed. Special applications use carbon arc, gas tungsten arc, or plasma arc welding equipment described in other chapters of the Handbook.

Clamping and fixturing equipment may also be needed to hold the parts in place and align the joint.

MATERIALS

Base Metals

BRAZE WELDING IS generally used to join cast iron and steel. It can also be used to join copper, nickel, and nickel alloys. Other metals can be braze welded with suitable filler metals that wet and form a strong metallurgical bond with them.

Dissimilar metal weldments between many of the above metals are possible with braze welding if suitable filler metals are used.

Filler Metals

COMMERCIAL BRAZE WELDING filler metals are the brasses containing approximately 60 percent copper and 40 percent zinc. Brazing alloys with small additions of tin, iron, manganese, and silicon have improved flow characteristics, decreased volatilization of the zinc, and they scavenge oxygen and increase the weld strength and hardness. Filler metal with added nickel (10 percent) has a whiter color and higher weld metal strength.

Chemical compositions and properties of three standard copper-zinc welding rods used for braze welding are given in Table 12.8. The minimum joint tensile strength will be approximately 40 to 60 ksi (275 to 413 MPa). The joint strength decreases rapidly when the weldment is above 500°F (260°C).

Because a braze weld is a bimetal joint, corrosion must be considered in its application. The completed joint will be subject to galvanic corrosion in certain environments, and the filler metal may be less resistant to certain chemical solutions than the base metal.

Fluxes

FLUXES FOR BRAZE welding are proprietary compounds developed for braze welding of stated base metals with brass filler metal rods. They are designed for use at temperatures higher than met in brazing operations, and so they remain active for longer times at temperature than similar fluxes used for capillary brazing. The following types of flux are in general use for braze welding of iron and steels:

(1) A basic flux that cleans the base metal and weld beads and assists in the precoating (tinning) of the base metal. It is used for steel and malleable iron.

(2) A flux that performs the same functions as the basic flux and also suppresses the formation of zinc oxide fumes.

(3) A flux that is formulated specifically for braze welding of gray or malleable cast iron. It contains iron oxide or manganese dioxide to combine with free carbon on the cast iron surface and so remove it.

Flux may be applied by one of the following four methods:

Table 12.8
Copper-Zinc Welding Rods for Braze Welding

AWS	Approximate Chemical Composition, %					Min Tensile Strength		Liquidus Temperature	
Classification*	Copper	Zinc	Tin	Iron	Nickel	ksi	MPa	°F	°C
RBCuZn-A	60	39	1			40	275	1650	900
RBCuZn-C	60	38	1	1		50	344	1630	890
RBCuZn-D	50	40			10	60	413	1714	935

* See AWS Specifications A5.7 and A5.8 for additional information.

(1) The heated filler rod may be dipped into the flux and transferred to the joint during braze welding.

(2) The flux may be brushed on the joint prior to brazing.

(3) The filler rod may be precoated with flux.

(4) The flux may be introduced through the oxyfuel gas flame.

METALLURGICAL CONSIDERATIONS

THE BOND BETWEEN filler metal and base metal in braze welding is the same bonding that occurs with conventional brazing. The clean base metal is heated to a temperature at which its surface is wet by the molten filler metal, producing a metallurgical bond between them. Cleanliness is prerequisite. The presence of dirt, oil, grease, oxide film, or carbon will inhibit wetting.

Following wetting, atomic diffusion takes place between the brazing filler metal and the base metal in a narrow zone at the interface. Indeed, with some base metals the brazing filler metal may slightly penetrate the grain boundaries of the base metal, further contributing to bond strength.

Braze welding filler materials are alloys that have sufficient ductility as-cast to let them flow plastically during solidification and subsequent cooling. The alloys thereby accommodate shrinkage stresses. Two-phase alloys that have a low-melting grain boundary constituent are not useable—those boundaries crack open during solidification and cooling.

GENERAL PROCESS APPLICATIONS

THE GREATEST USE of braze welding is the repair of broken or defective steel and cast iron parts. Since large components can be repaired in place, significant cost savings result. Braze welding also rapidly joins thin-gage mild steel sheet and tubing where fusion welding would be difficult.

Galvanized steel duct work is braze welded using a carbon arc heat source. The brazing temperature is held to below the vaporization temperature of the zinc. This minimizes the loss of the protective zinc coating from the steel surfaces, but it exposes the welder to a significant amount of zinc fumes, requiring exhaust ventilation.

The thicknesses of metals that can be braze welded range from thin gage sheet to very thick cast iron sections. Fillet and groove welds are used to make butt, corner, lap, and T-joints.

BRAZE WELDING PROCEDURE

Fixturing

ADEQUATE FIXTURING IS usually required to hold parts in their proper location and alignment for braze welding. In repairing cracks and defects in cast iron parts, fixturing may not be necessary unless the part is broken apart.

Joint Preparation

JOINT DESIGNS FOR braze welds are similar to those for oxyacetylene welding. For thicknesses over 3/32 in. (2 mm), single- or double-V-grooves are prepared with 90 to 120 degrees included angle, to provide large bond areas between base metal and filler metal. Square grooves may be used for thickness less than 3/32 in. (2 mm).

The prepared joint faces and adjacent surfaces of the base metal must be cleaned to remove all oxide, dirt, grease, oil, and other foreign material. On cast iron, the joint faces must also be free of graphite smears caused by prior machining. Graphite smears can be removed by quickly heating the cast iron to a dull red color and then wire brushing it after it cools to black heat. If the casting has been heavily soaked with oil, it should be heated in the range of 600 to 1200°F (320 to 650°C) to burn off the oil. The surfaces should be wire brushed to remove any residue.

In production braze welding of cast iron components, the surfaces to be joined are usually cleaned by immersion in an electrolytic molten salt bath.

Preheating

PREHEATING MAY BE required to prevent cracking from thermally induced stresses in large cast iron parts. Preheating copper reduces the amount of heat required from the brazing torch and the time required to complete the joint.

Preheating may be local or general. The temperature should be 800 to 900°F (425 to 480°C) for cast iron. Higher temperatures can be used for copper. When braze welding is completed on cast iron parts, they should be thermally insulated for slow cooling to room temperature, to minimize the development of thermally induced stresses.

Technique

THE JOINT TO be oxyfuel gas braze welded must be aligned and fixtured in position. Braze welding flux, when required, is applied to preheated filler rod (unless precoated) and also sprinkled on thick joints during heating with the torch. The base metal is heated until the filler metal melts, wets the base metal, and flows onto the joint faces (precoating). The braze welding operation then progresses along the joint, precoating the faces, then filling the groove with one or more passes using operating techniques similar to oxyfuel gas welding. With an oxyacetylene flame, the inner cone should not be directed on copper-zinc alloy filler metals nor on iron or steel base metal.

With electric arc torches the technique is similar to oxyfuel gas braze welding, except that flux is not generally used.

TYPES OF WELDS

GROOVE, FILLET, AND edge welds are used to braze weld assemblies made from sheet and plate, pipe and tubing, rods and bars, castings, and forgings. To obtain good joint strength, adequate bond area between the brazing filler metal and the base metal is required. Weld groove geometry should provide adequate groove face area so that the joint will not fail along the interfaces.

SAFE PRACTICES IN BRAZING

HAZARDS ENCOUNTERED WITH brazing operations are similar to those associated with welding and cutting. At brazing temperatures some elements vaporize, producing toxic gases. Personnel and property need protection against hot materials, gases, fumes, electrical shock, radiation, and chemicals.

Minimum brazing safety requirements are specified in the American National Standard Z49.1, *Safety in Welding and Cutting*,[5] published by the American Welding Society, Miami, Florida. This standard applies to brazing, braze welding, and soldering, as well as other welding and cutting processes.

GENERAL AREA SAFE PRACTICE

BRAZING EQUIPMENT, MACHINES, cables, and other apparatus should be placed so that they present no hazard to personnel in work areas, in passageways, on ladders, or on stairways. Good housekeeping should be maintained.

Precautionary signs conforming to the requirements of ANSI Z535.2, *Environment and Facility Safety Signs*, should be posted designating the applicable hazard(s) and safety requirements.

PERSONNEL PROTECTION

Ventilation

IT IS ESSENTIAL that adequate ventilation be provided so that personnel will not inhale gases and fumes generated while brazing. Some filler metals and base metals contain toxic materials such as cadmium, beryllium, zinc, mercury, or lead, which are vaporized during brazing. Fluxes contain chemical compounds of fluorine, chlorine, and boron, which are harmful if they are inhaled or contact the eyes or skin.

Solvents such as chlorinated hydrocarbons and cleaning compounds, such as acids and alkalies, may be toxic or flammable or cause chemical burn when present in the brazing environment.

To avoid suffocation, care must be taken with atmosphere furnaces to insure that the furnace is purged with air before personnel enter it.

Eye and Face Protection

EYE AND FACE protection shall comply with ANSI Z87.1, *Practices for Occupational and Educational Eye and Face Protection*. Goggles or spectacles with shade number four or five filter lenses should be worn by operators and helpers for torch brazing. Operators of resistance, induction, or salt bath dip brazing equipment and their helpers should use face shields, spectacles, or goggles as appropriate, to protect their faces and eyes.

Protective Clothing

APPROPRIATE PROTECTIVE CLOTHING for brazing should provide sufficient coverage and be made of suitable materials to minimize skin burns caused by spatter or radiation. Heavier material such as woolen or heavy cotton clothing are preferable to lighter materials because they are more difficult to ignite. All clothing shall be free from oil, grease, and combustible solvents. Brazers shall wear protective heat-resistant gloves made of leather or other suitable materials.

Respiratory Protective Equipment

WHEN CONTROLS SUCH as ventilation fail to reduce air contaminants to allowable levels and where the implementation of such controls is not feasible, respiratory protective equipment should be used to protect personnel from hazardous concentrations of airborne contaminants. Only approved respiratory protection equipment should be used. Approvals of respiratory equipment are issued by the National Institute of Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA). Selection of the proper equipment should be in accordance with ANSI Z88.2.

PRECAUTIONARY LABELING AND MATERIAL SAFETY DATA SHEETS

BRAZING OPERATIONS POSE potential hazard from fumes, gases, electric shock, heat, and radiation. Personnel should be warned against these hazards, where applicable, by use of adequate precautionary labeling as defined in ANSI/ASC Z49.1. Examples of labeling are shown in Figures 12.27 through 12.30.

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[5] American National Standards Institute (ANSI) 1430 Broadway, New York, NY 10018.

WARNING: PROTECT yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health.
ARC RAYS can injure eyes and burn skin.
ELECTRIC SHOCK can KILL.

- Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safety practices.
- Keep your head out of the fumes.
- Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases from your breathing zone and the general area.
- Wear correct eye, ear, and body protection.
- Do not touch live electrical parts.
- See American National Standard Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society, 550 N.W. LeJeune Rd., P.O. Box 351040, Miami, Florida 33135; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

DO NOT REMOVE THIS LABEL.

Figure 12.27—Warning Label for Arc Welding Processes and Equipment

WARNING: PROTECT yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health.
HEAT RAYS (INFRARED RADIATION from flame or hot metal) can injure eyes.

- Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safety practices.
- Keep your head out of the fumes.
- Use enough ventilation, exhaust at the flame, or both, to keep fumes and gases from your breathing zone and the general area.
- Wear correct eye, ear, and body protection.
- See American National Standard Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society, 550 N.W. LeJeune Rd., P.O. Box 351040, Miami, Florida 33135; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

DO NOT REMOVE THIS LABEL.

Figure 12.28—Warning Label for Oxyfuel Gas Processes

DANGER: CONTAINS CADMIUM, Protect yourself and others. Read and understand this label.

FUMES ARE POISONOUS AND CAN KILL.

- Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safety practices.
- Do not breathe fumes. Even brief exposure to high concentrations should be avoided.
- Use enough ventilation, exhaust at the work, or both, to keep fumes and gases from your breathing zone and the general area. If this cannot be done, use air supplied respirators.
- Keep children away when using.
- See American National Standard Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society, 550 N.W. LeJeune Rd., P.O. Box 351040, Miami, Florida 33135; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

If chest pain, shortness of breath, cough, or fever develop after use, obtain medical help immediately.

DO NOT REMOVE THIS LABEL.

Figure 12.29–Warning Label for Brazing Filler Metals Containing Cadmium

Resistance and Induction Brazing Processes

AS A MINIMUM, the information shown in Figure 12.27, or its equivalent, shall be placed on stock containers of consumable materials and on major equipment such as power supplies, wire feeders, and controls used in electrical resistance or induction brazing processes. The information shall be readily visible to the worker and may be on a label, tag, or other printed form as defined in ANSI Z535.2 and ANSI Z535.4, *Product Safety Signs and Labels.*

Oxyfuel Gas, Furnace, Dip Brazing Processes

AS A MINIMUM, the information shown in Figure 12.28, or its equivalent, should be placed on stock containers of consumable materials and on major equipment used in oxyfuel gas, furnace (except vacuum), and dip brazing processes. The information should be readily visible to the worker and may be on a label, tag, or other printed form as defined in ANSI Z535.2 and ANSI Z535.4.

Filler Metals Containing Cadmium

AS A MINIMUM, brazing filler metals containing more cadmium than 0.1 percent by weight should carry the information shown in Figure 12.29, or its equivalent on tags, boxes, or other containers, and on any coils or wire or strip not supplied to the user in a labeled container. Label requirements should also conform to ANSI Z535.4.

Brazing Fluxes Containing Fluorides

AS A MINIMUM, brazing fluxes and aluminum salt bath dip brazing salts containing fluorine compounds should have precautionary information as shown in Figure 12.30, or its equivalent, on tags, boxes, jars, or other containers. Labels for other fluxes should conform to the requirements of ANSI Z129.1, *Precautionary Labeling for Hazardous Industrial Chemicals.*

Material Safety Data Sheets (MSDSs)

THE SUPPLIERS OF brazing materials shall provide Material Safety Data Sheets, or equivalent, which identify the hazardous materials, if any, present in their products. The MSDS shall be prepared and distributed to users in accordance with OSHA 29CFR 1910.1200, *Hazard Communications Standard.*

A number of potentially hazardous materials may be present in fluxes, filler metals, coatings, and atmospheres used in brazing processes. When the fumes or gases from a product contain a component whose individual limiting

WARNING: CONTAINS FLUORIDES. Protect yourself and others. Read and understand this label.

FUMES AND GASES CAN BE DANGEROUS TO YOUR HEALTH. BURNS EYES AND SKIN ON CONTACT. CAN BE FATAL IF SWALLOWED.

- Before use, read and understand the manufacturer's instructions, Material Safety Data Sheets (MSDSs), and your employer's safety practices.
- Keep your head out of the fumes.
- Use enough ventilation, exhaust at the work, or both, to keep fumes and gases from your breathing zone and the general area.
- Avoid contact of flux with eyes and skin.
- Do not take internally.
- Keep out of reach of children.
- See American National Standard Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society, 550 N.W. LeJeune Rd., P.O. Box 351040, Miami, Florida 33135; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

First Aid: If flux comes in contact with eyes, flush immediately with clean water for at least 15 minutes. If swallowed, induce vomiting. Never give anything by mouth to an unconscious person. Call a physician.

DO NOT REMOVE THIS LABEL.

Figure 12.30–Warning Label for Brazing and Gas Welding Fluxes Containing Fluorides

value will be exceeded before the general brazing fume limit of 5 mg/m^3 is reached, the component shall be identified on the MSDS. These include, but are not limited to, the low PEL materials listed earlier.

FIRE PREVENTION AND PROTECTION

FOR DETAILED INFORMATION on fire prevention and protection in brazing processes, NFPA 51B, *Fire Protection in Use of Cutting and Welding Processes*, should be consulted.

Brazing should preferably be done in specially designated areas which have been designed and constructed to minimize fire risk. No brazing shall be done unless the atmosphere is either nonflammable or unless gases (such as hydrogen) which can become flammable when mixed with air are confined and prevented from being released into the atmosphere.

Sufficient fire extinguishing equipment shall be ready for use where brazing work is being done. The fire extinguishing equipment may be pails of water or a water hose, buckets of sand, hose, portable extinguishers, or an automatic sprinkler system, depending upon the nature and quantity of combustible material in the adjacent area.

Before brazing is begun in a location not specifically designated for such purposes, inspection and authorization by a responsible person shall be required.

When repairing containers that have held flammable or other hazardous materials, there is the possibility of explosions, fires, and the release of toxic vapors. Brazers must be fully familiar with American Welding Society ANSI/AWS F4.1, *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping That Have Held Hazardous Substances*".

For more information, consult the applicable state, local, and Federal specifications, as well as the AWS *Brazing Manual.*

Brazing Atmospheres

FLAMMABLE GASES ARE sometimes used as atmospheres for furnace brazing operations. These include combusted fuel gas, hydrogen, dissociated ammonia, and nitrogen-hydrogen mixtures. Prior to introducing such atmospheres, the furnace or retort must be purged of air by safe procedures recommended by the furnace manufacturer.

Adequate area ventilation must be provided that will exhaust and discharge to a safe place explosive or toxic gases that may emanate from furnace purging and brazing operations. Local environmental regulations should be consulted when designing the exhaust system.

Steam Hazard From Moist Materials

IN DIP BRAZING and in dip soldering, the parts to be immersed in the bath must be completely dry. Moisture on the parts will cause an instantaneous generation of steam that may expel the contents of the dip pot explosively. Predrying the parts prevents this danger. If supplementary flux must be added, it must be dried to remove both surface moisture and also water of hydration.

ELECTRICAL HAZARDS

ALL ELECTRICAL EQUIPMENT used for brazing should conform to ANSI/NFPA 70, *National Electric Code* (latest edition). The equipment should be installed by qualified personnel under the direction of a competent technical supervisor. Prior to production use, the equipment should be inspected by competent safety personnel to ensure that it is safe to operate.

SUPPLEMENTARY READING LIST

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CHAPTER 13

SOLDERING

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CHAPTER 13

SOLDERING

HISTORY

SOLDERING IS A technology that has been in continuous development from ancient times. Many artifacts discovered in archeological excavations were joined by soldering. The technology seems to have existed for several thousand years with changes as metallurgical knowledge and new metals were discovered.

Copper and lead alloys were the first to be joined. Early metallurgists learned to identify eutectics in binary systems. The use of eutectic alloys permitted soldering to join simple shapes into complex items of jewelry and utensils. The industrial revolution promoted widespread use of soldered joints. Advancements in alloy joining, processing techniques, and applications continue today. Soldering is now used in industrial applications, satellite communications, computers, and the space program.

FUNDAMENTALS

DEFINITION

SOLDERING IS DEFINED as a group of joining processes that produce coalescence of materials by heating them to the soldering temperature and by using a filler metal (solder) having a liquidus not exceeding 840°F (450°C) and below the solidus of the base metals. The solder is distributed between closely fitted faying surfaces of the joint by capillary action.

PRINCIPLES AND PRACTICES IN SOLDERING

THE SOLDERED JOINT is generally considered to be a metallurgical bond between the solder filler metal and the base metals being joined. Strength of the joint can be enhanced by mechanical configuration of the joint. Some solder joints do not have a metallurgical bond, but are held together by adhesion properties of the interfaces.

The metallurgical solder joint is produced by reaction of the base metals and the filler metal. The solder alloy is applied as a liquid metal that wets and spreads in the joint, and generally forms a layer of an intermetallic compound with a small amount of the base metal. Upon solidification, the joint is held together by the same attraction between adjacent atoms that holds a piece of solid metal together.

A sound soldered joint is achieved by the selection and use of proper materials and processes. There are many soldering filler metals, processes, methods, procedures, and equipments, and many metal alloys that are joined. Specific applications require consideration of all these factors to obtain the optimum manufacturing and service results. This chapter is essentially a summary of soldering technology. It covers soldering principles and practices in some detail. Filler metal selection, joint design, metal cleaning, heating methods, fluxes, and joint properties are covered. Temperature ranges of commonly used soldering alloys are compared with base metal melting points in Figure 13.1.

Soldering is an attractive metal joining process. A major factor in its popularity is that such a low temperature process has minimum effect on base-metal properties. The low temperature used for joining requires little energy input and allows precise control of the process. A wide range of heating methods can be adopted, giving flexibility in design and manufacturing procedures. Modern automation produces large numbers of joints in electrical and electronic circuits. High joint reliability can be obtained with carefully controlled procedures. The occasional defective soldered joint can be easily repaired. Soldering technology is an essential technique in modern industry.

PHYSICAL AND CHEMICAL PROPERTIES IN SOLDERING

MANY PHYSICAL SCIENCE principles are involved in the preparation for and execution of the soldered joint. Chem-

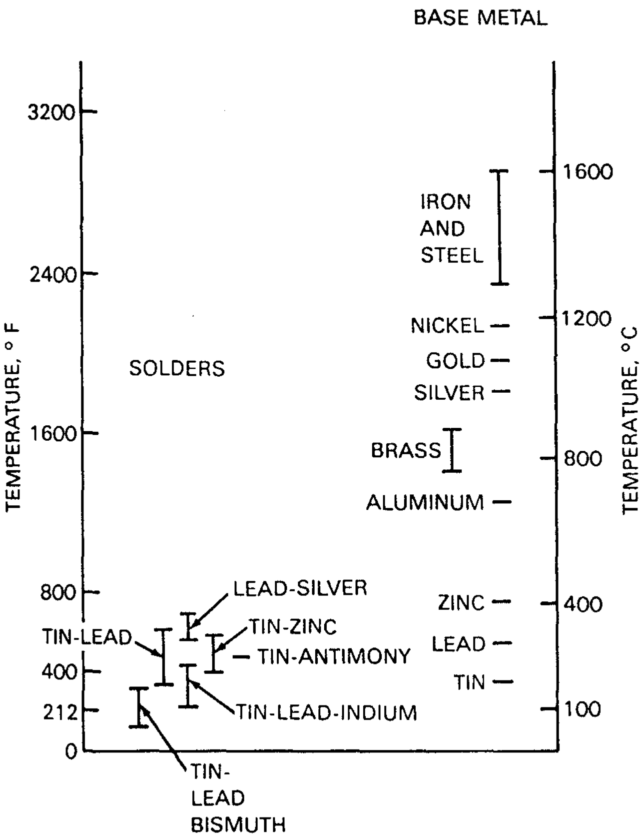

Figure 13.1—Solder Temperature Ranges Compared with Base Metal Melting Points

istry, physics, and metallurgy are the main disciplines involved in solder joining.

Wetting and spreading of solder filler metals on metallic surfaces are conditioned by the surface tension properties of the materials involved and the degree of alloying taking place during the soldering action. Soldering normally requires the presence of a flux. The flux cleans the metal to be joined and lowers the surface tension between the molten metal and the solid substrate. This flux behavior improves the wetting and spreading of the solder metal.

Wetting is said to take place when the solder leaves a continuous permanent film on the base metal surface. Alloying depends on the solubility of the base metal in molten solder metal. A high level of alloying between the base metal and solder metal can retard spreading. Therefore, good solder filler metals usually dissolve only a moderate amount of metal. Intermetallic compounds may form depending upon the metal systems involved.

Many solder joints are designed with gaps that require capillarity between the solder and base metal. Capillary attraction is improved by lowering surface tension, narrowing the gap in the joint, and using a highly compatible displacement type flux.

Principles at work during soldering require that the surfaces of the materials to be joined are cleaned of dirt, oxides, or other contaminants for good soldering to take place. One function of a flux is to provide final cleaning by chemical reaction with the metal surface. This attack should be slight but effective. Covering the surface with flux is no substitute for prior cleaning procedures.

When heated, the flux is activated, cleans contacted surfaces, and protects the cleaned areas from oxidation during soldering. The solder filler metal is applied when the joint has been heated to the soldering temperature. The surfaces are protected by the activated flux during soldering action. When soldered joints have been cooled, some residual flux may be present that needs to be removed to prevent early joint deterioration.

Physical problems affecting wetting, spreading, and capillar action can result in unsatisfactory joints. Unsatisfactory joints generally result from a poor surface condition or improper flux. Some metals, for example chromium, cannot be readily wet by most known solder filler metals. De-wetting is the retraction of solder on an already wetted surface which leaves areas of incomplete coverage. Inadequate cleaning, poor flux selection, and wrong solder composition are the main causes of de-wetting.

BASIC STEPS IN GOOD SOLDERING

BASE METAL SELECTION

BASE METALS ARE usually selected for specific properties that are needed for the component or part design. These include strength, ductility, electrical conductivity, weight, and corrosion resistance. When soldering is required, the solderability of the base materials must also be considered. The selection of flux and surface preparation will be affected by the solderability of the base materials to be joined.

SOLDER SELECTION

THE SOLDER IS selected to provide good flow, penetration, and wettability in the soldering operation, and the desired joint properties in the finished product.

FLUX SELECTION

FLUX IS INTENDED to enhance the wetting of base materials by the solder by removing tarnish films from precleaned surfaces, and by preventing oxidation during the soldering operation. The selection of the type of flux usually depends on the ease with which a material can be soldered. Rosin fluxes are used with base metals in electrical and electronic applications or with metals that are precoated with a solderable finish. Inorganic fluxes are often used in industrial soldering such as plumbing and vehicle radiators. The flux requirements for soldering a number of alloys and metals are indicated in Table 13.1.

JOINT DESIGN

JOINTS SHOULD BE designed to fulfill the requirements of the finished assembly and to permit application of the flux and solder by the soldering process that will be used. Joints should be designed so that proper clearance is maintained during heating. Special fixtures may be necessary, or the components can be crimped, clinched, wrapped, or otherwise held together.

Table 13.1
Flux Requirements for Metals, Alloys, and Coatings

Base Metal, Alloy, or Applied Finish	Rosin	Organic	Inorganic	Special Flux and/or Solder	Soldering Not Recommended*
Aluminum	-	-	-	X	-
Aluminum-bronze	-	-	-	X	-
Beryllium	-	-	-	-	X
Beryllium-copper	-	X	X	-	-
Brass	X	X	X	-	-
Cadmium	X	X	X	-	-
Cast iron	-	-	-	X	-
Chromium	-	-	-	-	X
Copper	X	X	X	-	-
Copper-chromium	-	-	X	-	-
Copper-nickel	X	X	X	-	-
Copper-silicon	-	-	X	-	-
Gold	X	X	X	-	-
Inconel	-	-	-	X	-
Lead	X	X	X	-	-
Magnesium	-	-	-	-	X
Manganese-bronze (high tensile)	-	-	-	-	X
Monel	-	X	X	-	-
Nickel	-	X	X	-	-
Nickel-iron	-	X	X	-	-
Nichrome	-	-	-	X	-
Palladium	X	X	X	-	-
Platinum	X	X	X	-	-
Rhodium	-	-	X	-	-
Silver	X	X	X	-	-
Stainless steel	-	-	X	-	-
Steel	-	-	X	-	-
Tin	X	X	X	-	-
Tin-bronze	X	X	X	-	-
Tin-lead	X	X	X	-	-
Tin-nickel	-	X	X	-	-
Tin-zinc	X	X	X	-	-
Titanium	-	-	-	-	X
Zinc	-	X	X	-	-
Zinc die castings	-	-	-	-	X

* With proper procedures, such as precoating, most metals can be soldered.

PRECLEANING

ALL METAL SURFACES to be soldered should be cleaned before assembly to facilitate wetting of the base metal by the solder. Flux should not be considered as a substitute for precleaning. Precoating may be necessary for base materials that are difficult to solder.

SOLDERING PROCESS

THE SOLDERING PROCESS should be selected to provide the proper soldering temperature, heat distribution, and rate of heating and cooling required for the product being assembled.

Application of the solder and flux will be dictated by the selection of the soldering process.

FLUX RESIDUE TREATMENT

FLUX RESIDUES SHOULD be removed after soldering unless the flux is specifically designed to be consumed during the process.

SOLDERS

SOLDERS HAVE MELTING points or melting ranges generally below 800°F (425°C). There is a wide range of commercially available solder filler metals designed to work with most industrial metals and alloys. These generally flow satisfactorily with the appropriate fluxes, and produce good surface wetting and result in joints with satisfactory properties. Tin-lead alloys are the most widely used solder filler metals. These alloys and other common filler metals are discussed in the following sections.

TIN-LEAD SOLDERS

TIN-LEAD-ALLOY SOLDERS ARE those most widely used in the joining of metals. Most commercial fluxes, cleaning methods, and soldering processes may be used with tin-lead solders.

In describing solders, it is customary to identify the tin content first. As an example, 40/60 solder is 40 percent tin and 60 percent lead.

The behavior of the various tin-lead alloys can best be illustrated by their constitutional diagram. This diagram is shown in Figure 13.2. The following terms are used to describe this diagram:

(1) *Solidus temperature* is the highest temperature at which a metal or alloy is completely solid. This is curve ACEDB of Figure 13.2.

(2) *Liquidus temperature* is the lowest temperature at which a metal or alloy is completely liquid. This is curve AEB of Figure 13.2.

(3) *Eutectic alloy* is an alloy that melts at one temperature and not over a range. The eutectic temperature is the solidus temperature at curve CED of Figure 13.2. The eutectic alloy is the composition noted at point E, Figure 13.2. This alloy is approximately 63 percent tin by weight.

(4) *Melting range* is the temperature between the solidus ACEDB and the liquidus AEB, where the solder is partially melted. As shown in Figure 13.2, pure lead melts at 621°F (327°C) (point A), and pure tin melts at 450°F (232°C) (point B). Solders containing 19.5 percent tin (point C) up to 97.5 percent tin (point D) have the same solidus temperature, namely the eutectic temperature, which is 361°F (183°C). The eutectic composition is completely liquid above 361°F (183°C). Any other composition will contain some solid metal in equilibrium with the liquid. These compositions do not melt completely until above the liquidus temperature. For example, 50/50 solder has a solidus temperature of 361°F (183°C) and a liquidus temperature of 417°F (214°C), which is a melting range covering 56°F (31°C). The melting range is the temperature difference between the solidus and liquidus.

Melting characteristics of specific tin-lead solders are shown in Table 13.2.

The 5/95 tin-lead solder is a relatively high melting temperature solder with a small melting range. Wetting and flow characteristics of 5/95 tin-lead solder are less attractive compared to solders with higher tin contents. Proper wetting and flow of 5/95 tin-lead solder requires extra care in surface preparation. High lead solders have better creep properties at 300°F (149°C) than solders containing more tin. The high soldering temperature limits the use of organic base fluxes, such as rosin or those of the intermediate type. This solder is particularly adaptable to torch, dip, induction, or oven soldering. It is used for sealing precoated containers, for coating and joining metals, and for automotive radiators and other moderately elevated temperature uses.

The 10/90, 15/85, and 20/80 tin-lead solders have lower liquidus and solidus temperatures, but they have wider melting ranges than 5/95 tin-lead solder. Their wetting and flow characteristics are also better with most fluxes. However, to prevent hot tearing, extreme care must be taken to avoid movement of these solders during solidification. These solders are used for sealing cellular automobile heater cores, some radiators, and for the coating and joining of metals.

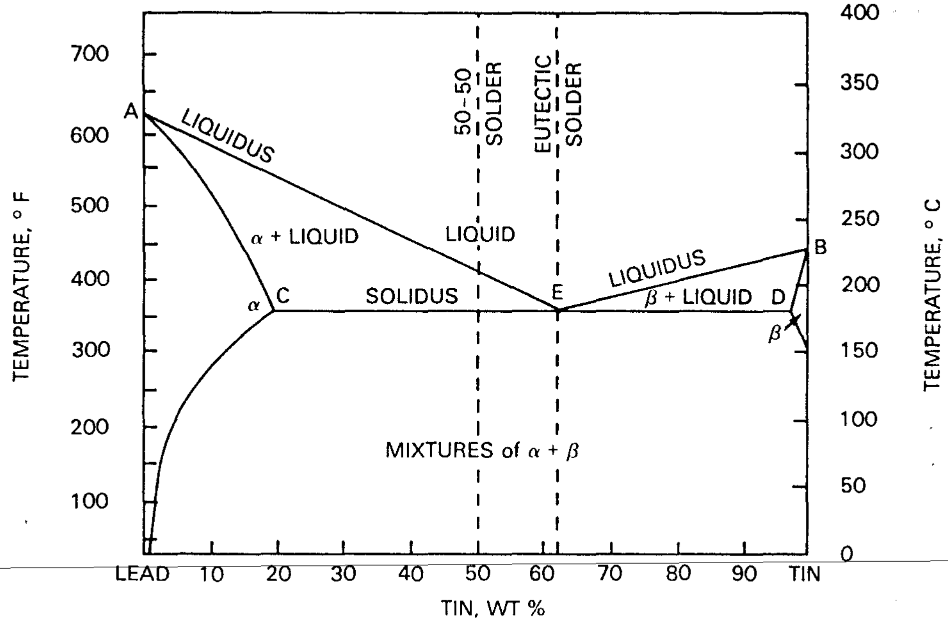

Figure 13.2–Constitutional Diagram for the Tin-Lead Alloy System

The 25/75 and 30/70 tin-lead solders have lower liquidus temperatures than all previously mentioned alloys but have the same solidus temperature as the 20/80 tin-lead solder. Therefore, their melting ranges are narrower than that of the 20/80 solder. All standard cleaning, fluxing, and soldering techniques can be used with these solders. Torch soldering and dipping are widely used. These alloys are used in radiators, radiator repair, and a variety of other industrial applications.

The 35/65, 40/60, and 50/50 tin-lead solders have low liquidus temperatures. The solidus temperature is the same as the 20 percent to 30 percent tin solders, and the melting ranges are narrower. Solders of this group have very good wetting properties, better strength, and economy for electronic applications. Extensive use of these solders is also found in sheet-metal work. The 50/50 combination is used for non-potable water plumbing and piping. These solders are also used as rosin-cored wires and in wave soldering industrial applications.

Table 13.2
Tin-Lead Solder Melting Properties

ASTM Solder Classification*	Composition, wt. %		Solidus		Liquidus		Melting Range	
	Tin	Lead	°F	°C	°F	°C	°F	°C
5	5	95	572	300	596	314	24	14
10	10	90	514	268	573	301	59	33
15	15	85	437	225	553	290	116	65
20	20	80	361	183	535	280	174	97
25	25	75	361	183	511	267	150	84
30	30	70	361	183	491	255	130	72
35	35	65	361	183	477	247	116	64
40	40	60	361	183	455	235	94	52
45	45	55	361	183	441	228	80	65
50	50	50	361	183	421	217	60	34
60	60	40	361	183	374	190	13	7
70	70	30	361	183	378	192	17	9

* See ASTM Specification B32, Standard Specification for Solder Metal

The 60/40 alloy and the 63/37 eutectic tin-lead solder are used when the joint cannot be exposed to high temperatures. Such applications are delicate instruments and electronic assemblies. The 60/40 composition is close enough to that of the eutectic tin-lead alloy to have an extremely narrow melting range. All methods of cleaning, fluxing, and heating may be used with this solder. These solders are widely used for electronic wave soldering, vapor phase processes, and incorporation in solder pastes.

The 70/30 tin-lead solder is a special purpose solder used where a high tin content is required. All soldering techniques are applicable.

IMPURITIES IN TIN-LEAD SOLDERS

IMPURITIES IN TIN-LEAD solders can occur during manufacture of the alloys or may result from contamination during usage. Specifications for solder alloys usually limit the maximum total impurity content, with specific limitations for certain metals. Solder metals covered by ASTM B32, *Standard Specifications for Solder Metals*, are shown in Table 13.3. Individual users sometimes need additional restrictions on impurities for particular applications.

Impurities can cause a reduction in wetting properties, sluggishness of flow within solder joints, an increase in oxidation rate, and changes in melting temperature ranges. Strength properties of joints can be adversely affected, with increased tendencies to cracking of the solder or difficulties with adhesion to the base materials.

Impurity elements affect the appearance and quality of a molten solder. Combined effects can be disastrous in soldered joints. Manufacturing specifications recognize the problem and also take into account the quality of solder needed for different applications. Care should be taken in purchasing solder materials to obtain the appropriate alloy and grade.

Aluminum

ALUMINUM CAN CAUSE grittiness at levels of more than 0.005 percent in the solder. A noticeable deterioration in oxidation of a solder bath surface can be an indication of aluminum contamination.

Antimony

ANTIMONY IS OFTEN used in solders as a desirable addition. This metal tends to reduce wetting and spreading qualities and can cause adhesion problems when present at levels higher than required.

Arsenic

ARSENIC IS A cause of de-wetting with as little as 0.005 percent as present. The problem becomes more severe at higher levels, and therefore less than 0.002 percent in the solder metal is desirable.

Bismuth

LOW LEVELS OF bismuth can be tolerated although it can change metallurgical characteristics of the joints.

Cadmium

THIS METAL AS a contaminant increases the surface tension of solders and can cause such deleterious effects as bridging and icicle formations on printed circuit boards.

Copper

THE AMOUNT OF copper that can be present in a solder without causing problems depends largely upon the application. ASTM specifications limit copper content of tin-lead solders to 0.08 percent. However, copper can be present up to 0.3 percent without any observable reduction in soldering properties.

Iron and Nickel

IRON AND NICKEL are not normally present in solder alloys. Specifications usually limit the iron and nickel content to 0.02 percent maximum. Severe reductions in wetting properties have been observed with higher levels.

Phosphorus and Sulfur

PHOSPHORUS AND SULFUR should be kept at the absolute minimal level to prevent oxidation and grittiness problems.

Zinc

ZINC AFFECTS WETTING and surface tension properties of molten solder. Thus tin-lead solders should contain less than 0.005 percent zinc. De-wetting on copper surfaces has been ascribed to zinc at only 0.01 percent in the alloy.

TIN-ANTIMONY SOLDER

THE 95 PERCENT tin, 5 percent antimony solder has the melting characteristics shown in Table 13.4. It provides a narrow melting range at a temperature higher than the tin-lead eutectic. This solder is used in many plumbing, refrigeration, and air conditioning applications because it has good creep properties.

Table 13.3
Solder Compositions and Melting Properties

Alloy Grade	Composition, % (a, b)											Melting Range (c)			
												Solidus		Liquidus	
	Sn	Pb	Sb	Ag	Cu	Cd	Al	Bi	As	Fe	Zn	°F	°C	°F	°C
Sn96	Rem	0.10	0.12 max	3.4-3.8	0.08	0.005	0.005	0.15	0.01 max	0.02	0.005	430	221	430	221
Sn95	Rem	0.10	0.12	4.4-4.8	0.08	0.005	0.005	0.15	0.01	0.02	0.005	430	221	473	245
Sn94	Rem	0.10	0.12	5.4-5.8	0.08	0.005	0.005	0.15	0.01	0.02	0.005	430	221	536	280
Sn70	69.5-71.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	361	183	377	193
Sn63	62.5-63.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	361	183	361	183
Sn62	61.5-62.5	Rem	0.50	1.75-2.25	0.08	0.001	0.005	0.25	0.03	0.02	0.005	354	179	372	189
Sn60	59.5-61.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.03	0.02	0.005	361	183	374	190
Sn50	49.5-51.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.025	0.02	0.005	361	183	421	216
Sn45	44.5-46.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.025	0.02	0.005	361	183	441	227
Sn40A	39.5-41.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	361	183	460	238
Sn40B	39.5-41.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	365	185	448	231
Sn35A	34.5-36.5	Rem	1.8-2.4	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	361	183	447	247
Sn35B	34.5-36.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	365	185	470	243
Sn30A	29.5-31.5	Rem	1.6-2.0	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	361	183	491	255
Sn30B	29.5-31.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	365	185	482	250
Sn25A	24.5-26.5	Rem	1.1-1.5	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	361	183	511	266
Sn25B	24.5-26.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	365	185	504	263
Sn20A	19.5-21.5	Rem	0.8-1.2	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	361	183	531	277
Sn20B	19.5-21.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	363	184	517	270
Sn15	14.5-16.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	437	225	554	290
Sn10A	9.0-11.0	Rem	0.20	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	514	268	576	302
Sn10B	9.0-11.0	Rem	0.50	1.7-2.4	0.08	0.001	0.005	0.03	0.02	0.02	0.005	514	268	570	299
Sn5	4.5-5.5	Rem	0.50	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	586	308	594	312
Sn2	1.5-2.5	Rem	4.5-5.5	0.015	0.08	0.001	0.005	0.25	0.02	0.02	0.005	601	316	611	322
Sb5	94.0 min	0.20	0.40	0.015	0.08	0.03	0.005	0.15	0.05	0.04	0.005	450	233	464	240
Ag1.5	0.75-1.25	Rem	0.40	1.3-1.7	0.30	0.001	0.005	0.25	0.02	0.02	0.005	588	309	588	309
Ag2.5	0.25	Rem	0.40	2.3-2.7	0.30	0.001	0.005	0.25	0.02	0.02	0.005	580	304	580	304
Ag5.5	0.25	Rem	0.40	5.0-6.0	0.30	0.001	0.005	0.25	0.02	0.02	0.005	580	304	716	380

a. Limits are % max unless shown as a range or stated otherwise.

b. For purposes of determining conformance to these limits, an observed value or calculated value obtained from analysis shall be rounded to the nearest unit in the last right-hand place of figures used in expressing the specified limit, in accordance with rounding method of Recommended Practice E 29.

c. Temperatures given are approximations and for information only.

Table 13.4
Tin-Antimony Solder Melting Properties

Composition, Weight%		Solidus		Liquidus		Melting Range	
Tin	Antimony	°F	°C	°F	°C	°F	°C
95	5	450	232	464	240	14	8

TIN-ANTIMONY-LEAD SOLDERS

ANTIMONY MAY BE added to a tin-lead solder as a substitute for some of the tin. The addition of antimony increases the mechanical properties of the joint with only slight impairment to the soldering characteristics. All standard methods of cleaning and heating may be used. Specialized fluxes are needed for best results with these alloys.

TIN-SILVER, TIN-COPPER-SILVER, AND TIN-LEAD-SILVER SOLDERS

SOLDERS CONTAINING SILVER with their melting characteristics are listed in Table 13.5. The 96 percent tin-4 percent silver solder is free of lead and is often used to join stainless steel for food handling equipment. It has good shear and creep strengths and excellent flow characteristics.

The tin-silver and tin-copper-silver solders are the standard alloys used with copper pipe and tubes in potable water systems. Lead is eliminated for health reasons.

The 62 percent tin-36 percent lead-2 percent silver solder is used when soldering to silver-coated surfaces in electronic applications. The silver addition retards the dissolution of the silver coating during the soldering operation. The addition of silver also increases creep resistance.

High-lead solders containing tin and silver provide higher temperature solders for many applications including automobile radiators. They exhibit good tensile, shear, and creep strengths, and they are recommended for cryogenic applications. Inorganic fluxes are generally recommended for use with these solders.

TIN-ZINC SOLDERS

A LARGE NUMBER of tin-zinc solders, some of which are listed in Table 13.6, have come into use for joining aluminum. Galvanic corrosion of soldered joints in aluminum is minimized if the solder and the base metal are close to each other in the electrochemical series. Alloys containing 70 to 80 percent tin with the balance zinc are recommended for soldering aluminum. The addition of 1 to 2 percent aluminum, or an increase of the zinc content to as high as 40 percent, improves corrosion resistance. However, the liquidus temperature rises correspondingly, and those solders are therefore more difficult to apply. The 91/9 and 60/40 tin-zinc solders may be used at temperatures above 300°F (140°C). The 80/20 and 70/30 tin-zinc solders are more widely used for coating parts before the soldering operation.

CADMIUM-SILVER SOLDER

THE 95 PERCENT-CADMIUM 5 percent silver solder has the melting characteristics shown in Table 13.7. Its primary use is in applications where service temperatures will be higher than permissible with lower melting solders. Butt joints in copper can be made to produce room temperature tensile strengths of 25 000 psi (170 MPa). At 425°F (219°C), the tensile strength is 2600 psi (18 MPa).

Joining aluminum to itself or to other metals is possible with 95 percent cadmium-silver solder. Improper use of solders containing cadmium may lead to health hazards. Therefore, care should be taken in their application, particularly with respect to fume inhalation.

Table 13.5
Tin-Silver and Tin-Lead-Silver Solder Melting Properties

Composition, Weight%			Solidus		Liquidus		Melting Range	
Tin	Lead	Silver	°F	°C	°F	°C	°F	°C
96	-	4	430	221	430	221	0	0
62	36	2	354	180	372	190	18	10
5	94.5	0.5	561	294	574	301	13	7
2.5	97	0.5	577	303	590	310	13	7
1	97.5	1.5	588	309	588	309	0	0

Table 13.6
Tin-Zinc Solder Melting Properties

Composition, Weight%		Solidus		Liquidus		Melting Range	
Tin	Zinc	°F	°C	°F	°C	°F	°C
91	9	390	199	390	199	0	0
80	20	390	199	518	269	128	70
70	30	390	199	592	311	202	112
60	40	390	199	645	340	255	141
30	70	390	199	708	375	318	176

CADMIUM-ZINC SOLDERS

CD-ZN SOLDERS ARE useful for soldering aluminum. Their melting characteristics are given in Table 13.8. The cadmium-zinc solders develop joints with intermediate strength and corrosion resistance, when used with the proper flux. The 40 percent cadmium-60 percent zinc solder has found considerable use for soldering aluminum lamp bases. Improper use of this solder may lead to health hazards, particularly with respect to fume inhalation.

ZINC BASED SOLDERS

ZINC ALUMINUM SOLDER, shown in Table 13.9, is specifically for use on aluminum. It develops joints with high strength and good corrosion resistance. The solidus temperature is high, which limits its use to applications where soldering temperatures in excess of 700°F (371°C) can be tolerated. A major application is in dip soldering the return bends of aluminum air conditioner coils. These coils are also made by flame brazing with fluxes. Ultrasonic solder pots that do not require the use of flux are also employed. In manual soldering operations, the heated aluminum surface is rubbed with the solder stick to promote wetting without a flux.

Table 13.7
Cadmium-Silver Solder Melting Properties

Composition, Weight%		Solidus		Liquidus		Melting Range	
Cadmium	Silver	°F	°C	°F	°C	°F	°C
95	5	640	338	740	393	100	55

Table 13.8
Cadmium-Zinc Solder Melting Properties

Composition, Weight%		Solidus		Liquidus		Melting Range	
Cadmium	Zinc	°F	°C	°F	°C	°F	°C
82.5	17.5	509	265	509	265	0	0
40	60	509	265	635	335	126	70
10	90	509	265	750	399	241	134

Table 13.9
Zinc-Aluminum Solder Melting Properties

Composition, Weight%		Solidus		Liquidus		Melting Range	
Zinc	Aluminum	°F	°C	°F	°C	°F	°C
95	5	720	382	720	382	0	0

Zinc solders with 95 percent zinc and other additions to restrict copper dissolution, and to improve wetting, strength, and corrosion resistance have been developed specifically for automobile radiator application. Melting temperatures in the range of 800°F (425°C) are involved. The solders are used with all heating processes. A series of inorganic fluxes is available for use with these solders.

FUSIBLE ALLOYS

FUSIBLE ALLOYS MAKE substantial use of bismuth and are used in soldering operations where soldering temperatures below 361°F (183°C) are required. The melting characteristics and compositions of a representative group of fusible alloys are shown in Table 13.10.

The following are where low-melting temperature solders apply:

(1) Heat-treated base metals are soldered and higher soldering temperatures would result in softening the part.

(2) Materials adjacent to soldered joints are sensitive to temperature and would deteriorate at higher soldering temperatures.

(3) Step soldering operations are used to avoid destroying a nearby joint that has been made with a higher melting temperature solder.

(4) Temperature-sensing devices, such as fire sprinkler systems, are activated when the fusible alloy melts at relatively low temperature.

Many of these solders, particularly those containing a high percentage of bismuth, are very difficult to use successfully in high-speed soldering operations. Particular attention must be paid to the cleanliness of metal surfaces. Strong, potentially corrosive fluxes must be used to make satisfactory joints on uncoated surfaces of metals, such as copper or steel. If the surface can be plated for soldering with such metals as tin or tin-lead, noncorrosive rosin fluxes may be satisfactory. However, these are not effective below 350°F (177°C).

INDIUM SOLDERS

INDIUM SOLDERS HAVE properties that make them valuable for many electronic and special applications. Melting characteristics and compositions of a representative group of these solders are shown in Table 13.11.

A 50 percent tin-50 percent indium alloy adheres to glass readily and may be used for glass-to-metal and glass-to-glass soldering. The low vapor pressure of this alloy makes it useful for seals in vacuum systems.

High fatigue resistance, especially to thermal cycling, has resulted in increased use of indium alloys, particularly indium-lead and indium-lead-silver solders in electronic systems.

Indium solders do not require special handling techniques. All of the soldering methods, fluxes, and processes used with the tin-lead solders are applicable to indium solders. They are, however, sensitive to corrosion in the presence of chlorides. Joints should be cleaned after soldering. They perform best when covered by conformal coatings or in hermetically sealed conditions.

Table 13.10
Typical Fusible Alloys Melting Properties

Composition, Weight%					Solidus		Liquidus		Melting Range	
Lead	Bismuth	Tin	Other		°F	°C	°F	°C	°F	°C
26.7	50	13.3	10	Cd	158	70	158	70	0	0
25	50	12.5	12.5	Cd	158	70	165	74	7	4
40	52	-	8	Cd	197	91	197	91	0	0
32	52.5	15.5	-	-	203	95	203	95	0	0
28	50	22	-	-	204	96	225	107	25	11
28.5	48	14.5	9	Sb	217	102	440	227	223	125
44.5	55.5	-	-	-	255	124	255	124	0	0

Table 13.11
Typical Indium Solder Melting Properties

Composition, Weight%			Solidus		Liquidus		Melting Range	
Tin	Indium	Lead	°F	°C	°F	°C	°F	°C
50	50	-	243	117	257	125	14	8
37.5	25	37.5	230	138	230	138	0	0
-	50	50	356	180	408	209	52	29

SOLDER SPECIFICATIONS

SPECIFICATIONS FOR SOLDERS are published by the ASTM (ASTM B32, *Standard Specification for Solder Metal*; ASTM B284, *Standard Specification for Rosin Flux-Cored Solder*; and ASTM B486, *Standard Specification for Paste Solder*) and by the United States Government (Federal Specification QQ-S-571, Solders), in addition to various military specifications.

Solders are commercially available in various forms and products which can be grouped into about a dozen classifications. The major groups of solder product forms are listed in Table 13.12. This listing is by no means complete, inasmuch as any desired size, weight, or shape of any form is available on special order.

Table 13.12
Commercial Solder Product Forms

Pig	Available in 50 and 100 lb (25 and 45 kg) pigs
Ingots	Rectangular or circular in shape, weighing 3, 5, and 10 lb (1.4, 2.3, and 4.5 kg)
Bars	Available in numerous cross sections, weights, and lengths
Paste or cream	Available as a mixture of powdered solder and flux
Foil, sheet, or ribbon	Available in various thicknesses and widths
Segment or drop	Triangular bar or wire cut into any desired number of pieces or lengths
Wire, solid	Diameters of 0.010 to 0.250 in. (0.25 to 6.35 mm) on spools
Wire, flux cored	Solder cored with rosin, organic, or inorganic fluxes. Diameters of 0.010 to 0.250 in. (0.25 to 6.35 mm)
Preforms	Unlimited range of sizes and shapes to meet special requirements

FLUXES

THE PURPOSE OF a flux in soldering is to activate a cleaned metal surface, protect that cleaned surface during heating processes, and be available to protect the molten solder at the proper processing temperature. The flux must have sufficient staying power to continue these functions until the joint has been completely soldered.

A soldering flux may be liquid, solid, or gaseous material which, when heated, promotes or accelerates the wetting of metals by solder. A soldering flux should remove and exclude small amounts of oxides and other surface compounds from surfaces being soldered. Anything that interferes with the attainment of uniform contact between the surface of the base metal and the molten solder will prevent the formation of a sound joint. An efficient flux prevents reoxidation of the surfaces during the soldering process and is readily displaced by the molten solder.

A functional method of classifying fluxes is based on their ability to remove metal tarnishes (activity). Fluxes may be classified in three groups: inorganic fluxes (most active), organic fluxes (moderately active), and rosin fluxes (least active).

A generalized metal solderability chart and flux selector guide covering different base materials and flux types is shown in Table 13.13.

INORGANIC FLUXES

THE INORGANIC CLASS of flux as includes inorganic acids and salts. These fluxes are used to best advantage where conditions require rapid and highly active fluxing action. They can be applied as solutions, pastes, or dry salts. They function equally well with torch, oven, resistance, or induction soldering methods, since they do not char or burn. These fluxes can be formulated to provide stability over a wide range of soldering temperatures.

The chloride-based inorganic fluxes have one distinct disadvantage in that the residue remains chemically active after soldering. This residue, if not removed, may cause severe corrosion at the joint. Adjoining areas may also be attacked by residues from the spraying of flux and from flux vapors.

The bromide family of inorganic fluxes is used widely by the automotive radiator industry with and without washing facilities. Certain compositions of these fluxes can be used without washing, and those residues will not cause corrosion of the parts that have been soldered.

The following are typical inorganic flux constituents:

(1) Zinc chloride
(2) Ammonium chloride
(3) Tin chloride
(4) Hydrochloric acid
(5) Phosphoric acid
(6) Other metal chlorides

Table 13.13
Metal Solderability Chart and Flux Selector Guide

		Rosin Fluxes					
Metals	Solderability	Non-Activated	Mildly Activated	Activated	Organic Fluxes (Water Soluble)	Inorganic Fluxes (Water Soluble)	Special Flux and/or Solder
Platinum, gold, copper, silver, cadmium plate, tin (hot dipped), tin plate, solder plate	Easy to solder	Suitable	Suitable	Suitable	Suitable	Not recommended for electrical soldering	. . .
Lead, nickel plate, brass, bronze, rhodium, beryllium copper	Less easy to solder	Not suitable	Not suitable	Not suitable	Suitable	Suitable	. . .
Galvanized iron, tin-nickel, nickel-iron, low-carbon steel	Difficult to solder	Not suitable	Not suitable	Not suitable	Suitable	Suitable	. . .
Chromium, nickel-chromium, nickel-copper, stainless steel	Very difficult to solder	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	. . .
Aluminum, aluminum-bronze	Most difficult to solder	Not suitable	Not suitable	Not suitable	Not suitable	. . .	Suitable
Beryllium, titanium	Not solderable	. . .	. . .	. . .	. . .	. . .	. . .

ORGANIC FLUXES

ORGANIC FLUXES, WHILE less active than the inorganic materials, are effective at soldering temperatures from 200 to 600°F (90 to 320°C). They consist of organic acids and bases and often certain of their derivatives, such as hydrohalides. They are active at soldering temperatures, but the period of activity is short because of their susceptibility to thermal decomposition. Their tendency to volatilize, char, or burn when heated limits their use with torch or flame heating. When properly used, residues from these fluxes are relatively inert and can be removed with water.

Organic fluxes are particularly useful in applications where controlled quantities of flux can be applied and where sufficient heat can be used to fully decompose or volatilize the corrosive constituents. Precaution are necessary to prevent undecomposed flux from spreading onto insulating sleeving. Care must also be taken when soldering in closed systems where corrosive fumes may condense on critical parts of the assembly.

The following are typical organic flux constituents:

(1) Abietic acid
(2) Ethylene diamine
(3) Glutamic acid
(4) Hydrazine hydrobromide
(5) Oleic acid
(6) Stearic acid
(7) A wide range of other acid-based or acid-forming organic chemicals.

ROSIN FLUXES

Nonactive Rosin

WATER-WHITE ROSIN DISSOLVED in a suitable organic solvent is the closest approach to a noncorrosive flux. Rosin fluxes possess important physical and chemical properties which make them particularly suitable for use in the electrical industry. The active constituent, abietic acid, becomes mildly active at soldering temperatures between 350°F (177°C) and 600°F (316°C). The residue is hard, nonhygroscopic, electrically nonconductive, and not corrosive.

Mildly Activated Rosin

BECAUSE OF THE low activity of rosin, mildly activated rosin fluxes have been developed to increase their fluxing action without significantly altering the noncorrosive nature of the residue. These are the preferred fluxes for military, telephone, and other high reliability electronic products.

Activated Rosin

A THIRD AND still more active type of rosin-base flux is called *activated rosin*. These fluxes are widely used in commercial electronics and in high reliability applications where the residue needs to be completely removable after soldering. The activating material can be an organic that reacts to release chlorides, or other halides or a low level of organic acid.

SPECIAL FLUXES

REACTION FLUXES ARE a special group of fluxes that are useful when soldering aluminum. These fluxes are also finding uses with other metals. In practice, the decomposition of the flux cleans and displaces oxides and deposits a metallic film on the metal surface, which allows for wetting and spreading.

FLUXING ACTIONS

A GENERAL FLUX selection guide for various soldering applications including all the above classifications of materials is shown in Table 13.14 to help direct the user towards the most appropriate flux materials.

There are many fluxes available for soldering. These fluxes are designed specifically for the applications involved. Fluxes are available for electronics, plumbing, radiators, different metals, and a wide variation of industrial products. Determination of the appropriate flux is important to assure a successful soldering operation.

Desirable general properties of fluxes include the ability to remove oxides, protect metal surfaces, and melt below the soldering temperature. Desirable post soldering properties include being electrically nonconductive and being corrosion resistant.

Each flux is designed for a heating process and has an optimum processing temperature range for best results.

There is no universal test that can identify all the necessary properties of a flux for an specific application. Therefore, a number of tests have been developed that relate to flux characteristics and value in the fabrication of particular components. Manufacturers should perform a thorough review before selecting a flux. They should not rely entirely on commercially available data that may not be relevant to a particular application.

FLUX FORMS

FLUX IS AVAILABLE as single or multiple cores in wire solder, and in liquids, pastes, and dry powder forms. Not all fluxes are available in each form.

Table 13.14
Typical Fluxing Agents

Type	Composition	Carrier	Uses	Temperature Stability	Ability to Remove Tarnish	Corrosiveness	Recommended Cleaning After Soldering
INORGANIC							
Acids	Hydrochloric, hydrofluoric, orthophosphoric	Water, petrolatum paste	Structural	Good	Very good	High	Hot water rinse and neutralize; organic solvents
Salts	Zinc chloride, ammonium chloride, tin chloride	Water, petrolatum paste, polyethylene glycol	Sturctural	Excellent	Very good	High	Hot water rinse and neutralize; 2% HCl solution; hot water rinse and neutralize; organic solvents
ORGANIC							
Acids	Lactic, oleic, stearic glutamic, phthalic	Water, organic solvents, petrolatum paste, polyethylene glycol	Structural, electrical	Fairly good	Fairly good	Moderate	Hot water rinse and neutralize; organic solvents
Halogens	Aniline hydrochloride, glutamic hydrochloride, bromide derivatives of palmitic acid, hydrazine hydrochloride (or hydrobromide)	Same as organic acids	Sturctural, electrical	Fairly good	Fairly good	Moderate	Same as organic acids
Amines and amides . . .	Urea, ethylene diamine	Water, organic solvents, petrolatum paste, polyethylene glycol	Structural, electrical	Fair	Fair	Noncorrosive normally	Hot water rinse and neutralize; organic solvents
Activated rosin	Water-white rosin	Isopropyl alcohol, organic solvents, polyethylene glycol	Electrical	Poor	FairFair	Noncorrosive normally	Water-based detergents; isopropyl alcohol; organic solvents
Water-white rosin	Rosin only	Same as activated	Electrical	Poor	Poor	None	Same as activated water white rosin but does not normally require post-cleaning

JOINT DESIGN

THE SELECTION OF a joint design for a specific application will depend largely on the service requirements of the assembly. It may also depend on such factors as the heating method to be used, the fabrication techniques prior to soldering, the number of items to be soldered, and the method of applying the solder.

When service requirements of a joint are severe, it is generally necessary to design the joint so that it does not limit the function of the assembly. Solders have low strength compared to the metals that are usually soldered; therefore, the soldered joint should be designed to avoid dependence on the strength of the solder. The necessary strength can be provided by shaping the parts to be joined so that they engage or interlock, requiring the solder only to seal and stiffen the assembly.

There are industrial uses of soldering where the solder joint itself must carry the joint load. A typical example is pipe joints in plumbing systems, where lap joints are used with no additional mechanical support. In these cases, the properties of the solder alloy and the joint as manufactured are important to the service operation involved.

There are two basic types of joint design used for soldering: the lap joint and the lock seam joint. Typical joint designs frequently used in soldering are illustrated in Figure 13.3. Butt joints are not often used.

The lap or lock seam type of joint should be employed whenever possible, since they offer the best possibility of obtaining joints with maximum strength.

An important factor in joint design is the manner in which the solder will be applied to the joint. The designer must consider the number of joints per assembly and the number of assemblies to be manufactured. For limited production, using a manual soldering process, the solder may be face-fed into the joint with little or no problems. However, for large numbers of assemblies containing multiple joints, an automated process such as wave soldering may be advantageous. In this case, the design must provide accessible joints suitable for automated fluxing, soldering, and cleaning.

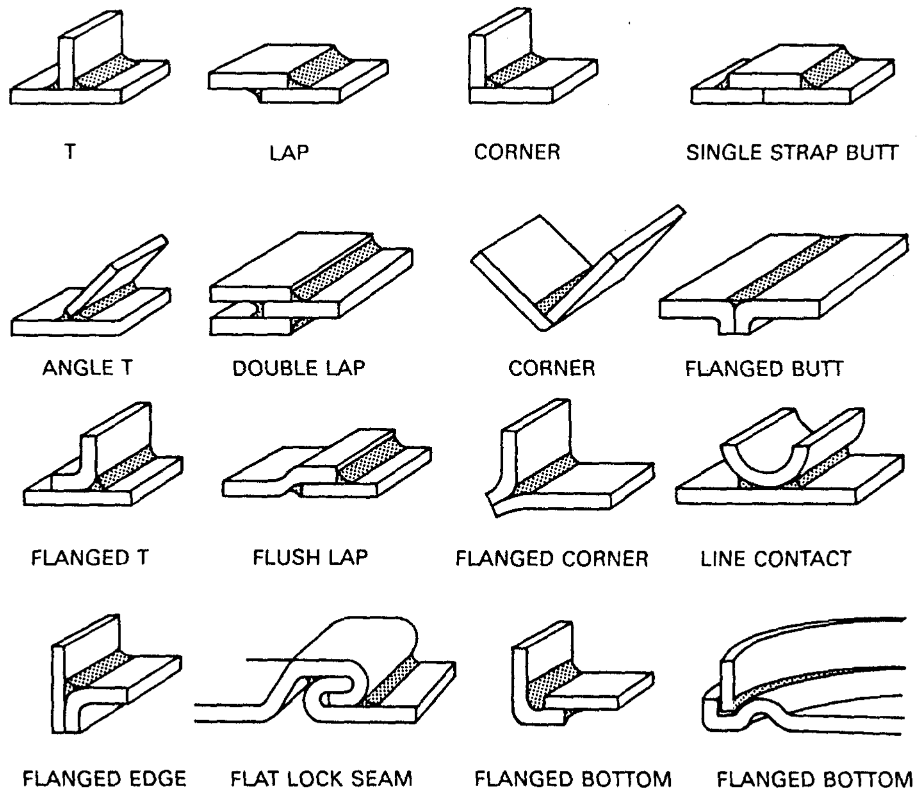

Figure 13.3–Joint Designs Frequently Used in Soldering

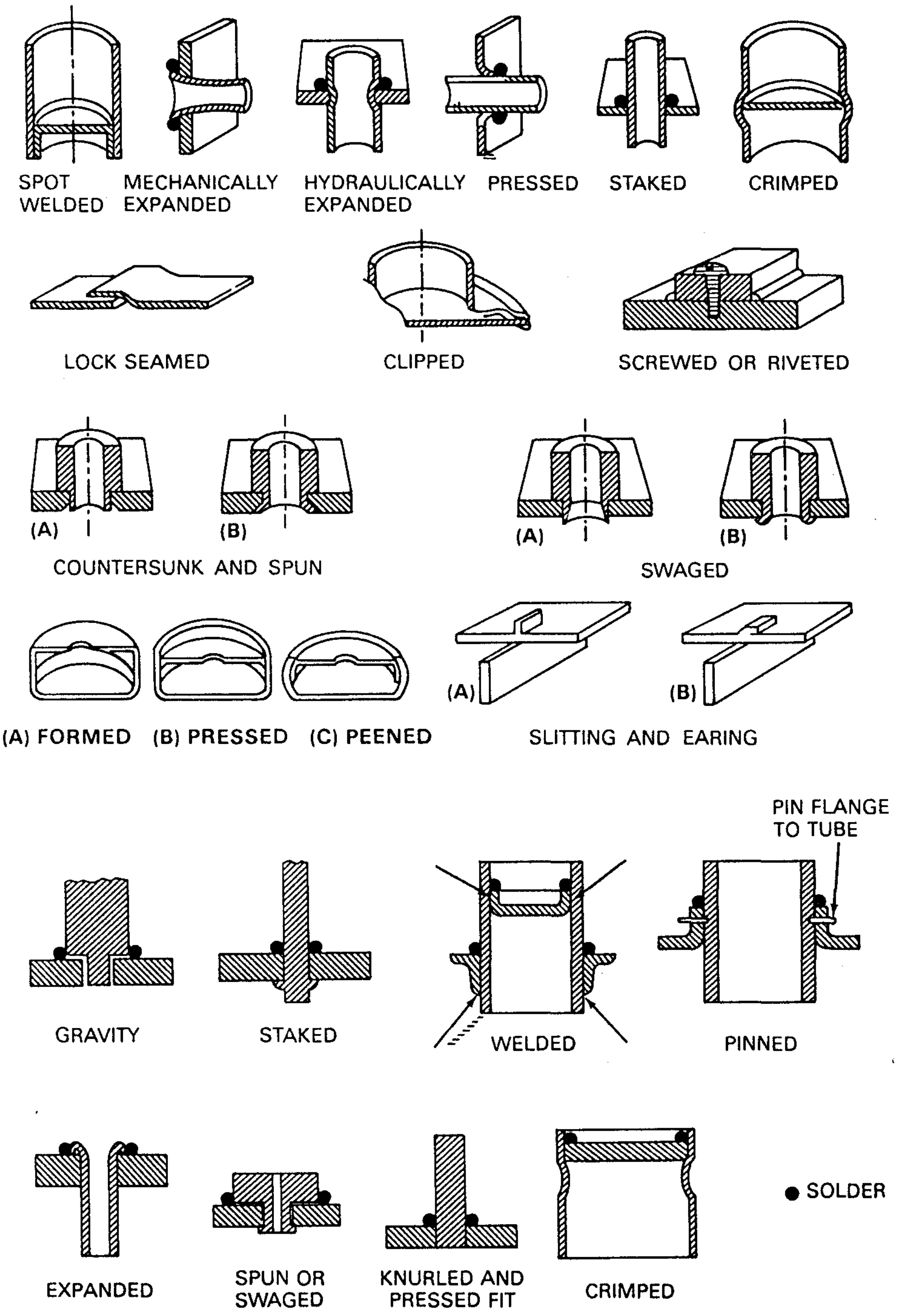

Figure 13.4—Self-Jigging Solder Joint Designs

Clearance between the parts to be joined should allow the solder to be drawn into the space between them by capillary action, but not so wide that the solder cannot fill the gap. Joint clearances up to 0.003 in. (0.075 mm) are preferred for optimum strength, but variations are allowable in specific instances. For example, when soldering precoated metals, a clearance as low as 0.001 in. (0.025 mm) is possible.

Twenty-one designs for self-jigging solder joints are illustrated in Figure 13.4. Various means of improving the strength of joints in printed circuits are shown in Figure 13.5.

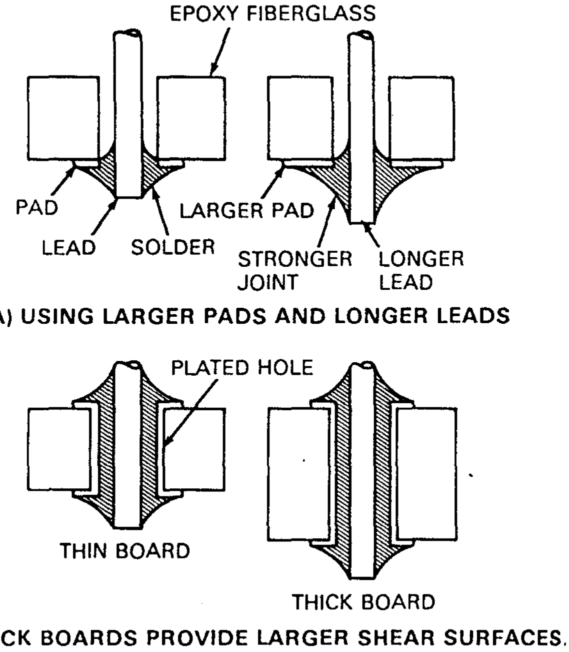

Figure 13.5–Methods of Improving Joint Strength

PRECLEANING AND SURFACE PREPARATION

AN UNCLEAN SURFACE prevents the solder from flowing and makes soldering difficult or impossible. Materials such as oil, grease, paint, pencil markings, drawing and cutting lubricants, general atmospheric dirt, oxides, and rust films should be removed before soldering. To insure sound soldered joints, the importance of cleanliness cannot be overemphasized.

DEGREASING

SOLVENT OR ALKALINE degreasing is recommended for cleaning oily or greasy surfaces. Of the solvent degreasing methods, the vapor condensation type solvents leave the least residual film on the surface. In the absence of vapor degreasing apparatus, immersion in liquid solvents or in detergent solutions is a suitable procedure. Hot alkali detergents are widely used for degreasing. All cleaning solutions must be thoroughly removed before soldering. Residues from hard-water rinses may later interfere with soldering.

Cleaning methods are often designed for a specific soldering operation, hence their suitability for a critical application should be investigated thoroughly.

PICKLING

THE PURPOSE OF pickling or acid cleaning is to remove rust, scale, and oxides or sulfides from the metal to provide a clean surface for soldering. The inorganic acids (hydrochloric, sulfuric, phosphoric, nitric, and hydrofluoric), singly or mixed, all fulfill this function, although hydrochloric and sulfuric are the most widely used. The pieces should be washed thoroughly in hot water after pickling and dried as quickly as possible.

MECHANICAL CLEANING

MECHANICAL CLEANING INCLUDES the following methods:

(1) Mechanical sanding or grinding
(2) Hand filing or sanding
(3) Cleaning with steel wool
(4) Wire brushing or scraping
(5) Grit or shotblasting

Soft metals such as copper are best cleaned by gentle wire brushing or sanding, or with steel wool on plumbing materials. Mechanical cleaning is best avoided for electronic components. Aluminum can be soldered better after oxides are removed by mechanical means; wire brushing or scraping is best. Steel or stainless steel can be brushed or blasted. Shot blasting is preferable to sanding because it avoids embedding silica particles. Stainless steel shot should be used for stainless surfaces. For best results, cleaning should extend beyond the joint area.

PRECOATING

COATING OF BASE metal surfaces with a more solderable metal or alloy prior to the soldering operation is sometimes desirable to facilitate soldering. Coatings of tin, copper, silver, cadmium, iron, nickel, and alloys of tin-lead, tin-zinc, tin-copper, and tin-nickel are used for this purpose. The advantages of precoating are twofold: (1) soldering becomes more rapid and uniform, and (2) strong acidic fluxes can be avoided during soldering. The precoating of metals that have tenacious oxide films, such as aluminum, aluminum bronzes, highly alloyed steels, and cast iron, is almost mandatory. Precoating of steel, brass, and copper can sometimes be useful.

Precoating of the metal surfaces may be accomplished by a number of different methods. Solder or tin may be applied with a soldering iron or an abrasive wheel, by ultrasonic soldering, by immersion in molten metal, by electrodeposition, or by chemical displacement.

Hot dipping may be accomplished by fluxing and dipping the parts in molten tin or solder. Small parts are often placed in wire baskets, cleaned, fluxed, dipped in the molten metal, and centrifuged to remove excess metal. Coating by hot dipping is applicable to carbon steel, alloy steel, cast iron, copper, and certain copper alloys. Prolonged immersion in molten tin or solder should be avoided to prevent excessive formation of intermetallic compounds at the interface between the coating and the base metal.

Precoating by electrodeposition may be done in stationary tanks, in conveyorized plating units, or in barrels. These methods are applicable to all steels, copper alloys, and nickel alloys. The coating metals are not limited to tin and solder. Copper, cadmium, silver, precious metals, nickel, iron, and alloy platings such as tin-copper, tin-zinc, and tin-nickel are also in common use.

Certain combinations of electrodeposited metals (duplex coatings), where one metal is plated over another, are becoming more popular as an aid to soldering. A coating of 0.0002 in (0.005 mm) of copper plus 0.0003 in. (0.008 mm) of tin is particularly useful for brass. The solderability of aluminum is assisted by a coating of 0.0005 in. (0.013 mm) of nickel followed by 0.0003 in. (0.008 mm) of tin, or by a combination of zincate (zinc), 0.0002 in. (0.005 mm) copper, and tin. An iron plating followed by tin plating is extremely useful over a cast iron surface.

Immersion coatings or chemical displacement coatings of tin, silver, or nickel may be applied to some of the common base metals. These coatings are usually very thin and generally have a poor shelf life.

The shelf life of a coating is defined as the ability of the coating to withstand storage conditions without impairment of solderability. Hot tinned and flow brightened electrotinned coatings have an excellent shelf life; inadequate thicknesses of electrotinned or immersion tinned coatings have a limited shelf life. Coating thicknesses of 0.0001 in. (0.003 mm) to 0.0003 in. (0.008 mm) of tin or solder are recommended to assure maximum solderability after prolonged storage.

SOLDERING PROCESS CONSIDERATIONS

SOLDERING IS CARRIED out by many methods covered in the next section. There are common conditions that occur in all soldering practices that should be carefully considered in deciding which process or method is best for a particular job.

The basic stages in soldering are joint preparation, cleaning, fluxing, preheating, soldering, and final cleaning. Soldering is a low-temperature joining method so that fluxes used need to have good activation and reaction at these low temperatures. Each choice of a solder and flux has a process that provides the best results.

Solderability tests are widely used on materials. These tests give important information but do not cover such effects as future storage, variation in materials, or the ability to clean already prepared components.

Soldering often must be done in close proximity to other heat sensitive materials or metals that have been given a specific heat treatment. Coldworked metals can become softened or relaxed during the soldering process. This should be taken into account in designing a finished part. Soldering requires the maintenance of close tolerances to ensure quality joints. It is often advisable to make sample parts with the intended process and subject them to destructive testing to be sure that production parts will be satisfactory. Soldering processes can be highly automated when all the material and processing variables have been evaluated and are carefully controlled. In contrast, soldering can also be carried out successfully and efficiently with individual parts or small lots using hand-held soldering torches.

SOLDERING METHODS AND EQUIPMENT

PROPER APPLICATION OF heat is of paramount importance in any soldering operation. The heat should be applied in such a manner that the solder melts while the surface is heated to permit the molten solder to wet and flow over the surface. A number of tools and methods are available as heat sources.

SOLDERING IRONS

THE TRADITIONAL SOLDERING tool is the soldering iron with a copper tip which may be heated electrically or by oil, coke, or gas burners. To lengthen the usable life of a copper tip, a coating of solder-wettable metal, such as iron, with or without additional coatings, is applied to the surface of the copper. The rate of dissolution of the iron coating in molten solder is substantially less than the rate for copper. The iron coating also shows less wear, oxidation, and pitting than uncoated copper.

The selection of soldering irons can be simplified by classifying them into four groups: (1) soldering irons for servicemen, (2) transformer type, low-voltage pencil irons; (3) special quick-heating and plier-type irons, and (4) heavy-duty industrial irons. A selection of the more common types of soldering irons is shown in Table 13.15.

Regardless of the heating method, the tip performs the following functions:

(1) Stores and conducts heat from the heat source to the parts being soldered
(2) Stores molten solder
(3) Conveys molten solder
(4) Withdraws surplus molten solder

The performance of electrical industrial irons cannot be measured solely by the wattage rating of the heating element. The materials used and the design of the iron affect the heat reserve and temperature recovery of the copper tip.

The angle at which the copper tip is applied to the work is important in delivering the maximum heat to the work. The flat side of the tip should be applied to the work to obtain the maximum area of contact. Flux cored solders should not be melted on the soldering tip because this destroys the effectiveness of the flux. The cored solder should be touched to the soldering tip to initiate good heat transfer, and then the solder should be melted on the work parts to complete the solder joint.

Modern hand-soldering irons are manufactured with closely controlled temperatures in the tip, in a wide range of tip sizes especially designed to work with certain solder wire diameters and to maintain the required soldering temperatures.

TORCH SOLDERING

THE SELECTION OF a gas torch for soldering should match the size, mass, and configuration of the assembly to be soldered. Flame temperature is controlled by the nature of the gas or gases used. Fuel gas, when burned with oxygen, will provide higher flame temperatures than when burned with air. The highest flame temperatures are attained with acetylene and lower temperatures with propane, butane, natural gas, and manufactured (city) gas, roughly in the order given. The flame of a fuel gas burned with oxygen will be sharply defined; with air, the flame will be bushy and flared.

Multiple flame tips, or burners, of shapes suitable to the work are frequently used. They may be designed to operate on oxygen and fuel gas, compressed air and fuel gas, or bunsen-type torches.

In adjusting tips or torches, care should be taken to avoid adjustment which results in a "sooty" flame; the carbon deposited on the work will prevent the flow of solder.

Complex automated torch systems with many flames are used in some industrial applications.

Table 13.15
Selection of Soldering Irons

Work to be Done	Tip Diameter Range in.	Tip Diameter Range mm	Power Range, Watts
Miniature printed circuits, thin substrates, temperature-sensitive components	1/32 - 1/8	1-3	10-20
Intermittent light assembly work, printed circuits, instruments, jewelry	1/8 - 3/16	3-5	20-35
Repetitive assembly work, telephone and applicances, art glass	3/16 - 1/4	5-6	40-60
High speed production soldering, light tinware, general duty, medium electrical, light plumbing	1/4 - 1/2	6-13	70-150
Medium tinware, light roofing, shipboard repair, heavy electrical, heavy plumbing	1/2 - 1-1/2	13-38	170-350
Heavy tinware, roofing, radiators, armatures, transformer cans	1-1/2 - 2	38-53	350-1250

DIP SOLDERING

THIS SOLDERING METHOD uses a molten bath of solder to supply both the heat and the solder necessary to join the workpieces.

Two techniques of dip soldering are illustrated in Figure 13.6(A). When conducted properly, this method is useful and economical in that an entire unit comprising any number of joints can be soldered in one operation. Fixtures are usually required to hold the parts and maintain joint clearances during solidification of the solder.

The soldering pot should be large enough to maintain the rate of production. Parts being dipped should not appreciably lower the temperature of the solder bath. Pots of adequate size can be held at lower operating temperatures and still supply sufficient heat to solder the dipped joints.

WAVE SOLDERING

IN WAVE SOLDERING, as shown in Figure 13.6(B), the solder is pumped out of a narrow slot above the solder pot to produce a wave or series of waves. The work conveyor can pass over the waves at a small angle to the horizontal, to assist in draining the solder, and double waves or special wave forms may also be used for this purpose. Wave-solder systems are excellent for oxide-free solder surfaces.

A alternate technique of wave soldering is cascade soldering, as illustrated in Figure 13.6(C). The solder flows down a trough by gravity and is returned by pump to the upper reservoir.

Integrated wave-soldering systems for printed circuit assemblies provide units that can apply the flux, dry and preheat the board, solder components, and clean the completed assembly. Some of these systems have special features where the flux is applied by passing through a wave, by spraying, by rolling, or by dipping. Several systems employ oil mixed with the solder to aid in the elimination of icicles (also called *bridging*) between conductor paths.

Another system features dual waves with the solder alloy flowing in the direction opposite to the board travel.

VAPOR PHASE SOLDERING (CONDENSATION)

THIS METHOD USES the latent heat of vaporization of a condensing saturated liquid to provide the heat required for soldering work with preplaced flux and solder. A reservoir of saturated vapor over a boiling liquid provides a constant controlled temperature with rapid heat transfer that is useful for soldering large assemblies as well as temperature-sensitive parts. Commercial equipment uses conveyors to provide an in-line continuous process for electronics manufacturing. Condensing fluids are fluorinated organic compounds with boiling points between 420 and 490°F (215 and 253°C).

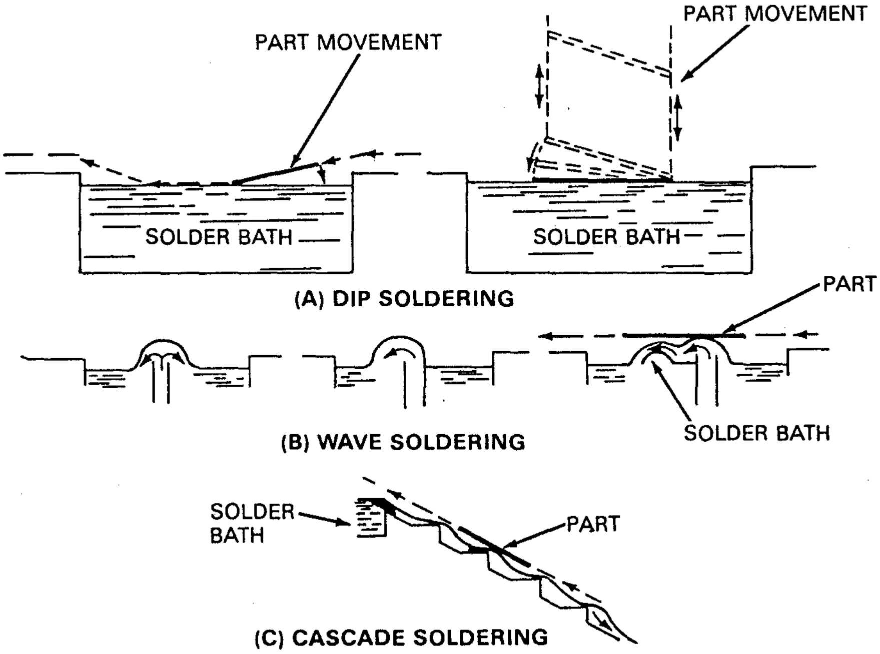

Figure 13.6—Several Soldering Techniques Used for Large Production Runs

OVEN OR FURNACE SOLDERING

THERE ARE MANY applications, especially in high-volume soldering, where furnace soldering produces consistent and satisfactory results.

Oven heating should be considered under the following circumstances:

(1) When entire assemblies can be brought to the soldering temperature without damage to any of the components

(2) When production is sufficiently great to allow expenditure for jigs and fixtures to hold the parts during soldering

(3) When the assembly is complicated, making other heating methods impractical

Proper clamping fixtures are important during oven or furnace soldering. Movement of the joint during solidification of the solder may result in a poor joint.

Oven or furnace soldering is usually carried out with inorganic fluxes because of the temperature and time requirements. The use of a reducing atmosphere in the oven allows joints to be made with less aggressive types of fluxes, depending on the metal and solder combination. The use of inert atmospheres will prevent further oxidation of the parts but still requires adequate and appropriate fluxing.

It is often advantageous to accelerate the cooling of the parts on their removal from the oven. An air blast has been found satisfactory.

Furnaces should be equipped with adequate temperature controls since the flow of solder has an optimum temperature range, depending upon the flux used. The optimum heating condition exists when the heating capacity of the oven is sufficient to heat the parts rapidly under controlled flux application.

RESISTANCE SOLDERING

RESISTANCE SOLDERING REQUIRES the work to be placed either between a ground and a movable electrode or between two movable electrodes to complete an electrical circuit. Heat is applied to the joint both by the electrical resistance of the metal being soldered and by conduction from the moving electrode, which is usually carbon.

Production assemblies may use multiple electrodes, rolling electrodes, or special electrodes, whichever will be advantageous with regard to soldering speed, localized heating, and power consumption.

Resistance soldering electrode tips cannot be tinned, and the solder must be fed into the joint or supplied by preforms or solder coatings on the parts.

INDUCTION SOLDERING

THE MATERIAL THAT is to be induction soldered must be an electrical conductor. The rate of heating is dependent upon the induced current flow, while the distribution of heat obtained with induction heating is a function of the induced wave frequency. Higher frequencies concentrate the heat at the surface. Types of equipment available for induction heating include the vacuum tube oscillator, the resonant-spark gap system, motor-generator units, and solid-state electrical supplies.

Induction soldering is generally chosen for the following:

(1) Large scale production
(2) Application of heat to a localized area
(3) Minimum oxidation of surface adjacent to the joint
(4) Good appearance and consistently high joint quality
(5) Simple joint design, which lends itself to mechanization

The induction technique requires that parts being joined have clean surfaces and accurate joint clearances. High-grade solders spread rapidly and produce good capillary flow. Preforms often are the best means of supplying the correct amount of solder and flux to the joint.

When soldering dissimilar metals by induction, particularly joints composed of both magnetic and nonmagnetic components, attention must be given to the design of the induction coil in order to bring both parts to approximately the same temperature.

INFRARED SOLDERING

OPTICAL SOLDERING SYSTEMS are available based on focusing infrared light (radiant energy) on the joint by means of a lens. Lamps ranging from 45 to 1500 watts can be used for different applications. The devices can be programmed through a solid-state controlled power supply with an internal timer.

HOT GAS SOLDERING

HOT GAS SOLDERING uses a fine jet of inert gas, heated to above the liquidus of the solder. The gas acts as a heat transfer medium and as a shield to reduce access of air to the joint.

ULTRASONIC SOLDERING

EQUIPMENT IS AVAILABLE for ultrasonic dip soldering and hand-soldering operations. An ultrasonic transducer produces high-frequency vibrations which break up tenacious oxide films on base metals. The freshly exposed base metal is readily wet action without the use of flux, or with a less aggressive flux. Ultrasonic units are useful in soldering return bends to the sockets of aluminum air conditioner coils. Ultrasonic soldering is also used to apply solderable coatings on difficult-to-solder metals.

SPRAY GUN SOLDERING

THIS METHOD IS generally selected when the contour of the part is difficult to handle with more conventional techniques.

Gas fired or electrically heated guns are available, each designed to spray molten or semimolten solder on the work from a continuously fed solid solder wire.

Gas fired guns use propane with oxygen, or natural gas with air, to heat and spray a continuously-fed solid solder wire, approximately 1/8 in. (3.2 mm) in diameter. About 90 percent of the solder wire is melted by the flame of the gun. The solder strikes the workpiece in a semiliquid form. The workpiece, heated also by the flame, then supplies the balance of the heat required to melt and flow the solder. Adjustments can be made within the spray gun to control the solder spray.

Electrically heated guns are similar to the gas fired guns except that they use a heating element to melt the solder. Compressed air is then used to spray the molten solder on the workpiece.

FLUX RESIDUE TREATMENT

AFTER THE JOINT is soldered, flux residues which may corrode the base metal or otherwise prove harmful to the effectiveness of the joint must be removed. The removal of flux residues is especially important where joints are subjected to humid environments.

Zinc chloride based fluxes leave a fused residue that will absorb water from the atmosphere. Removal is best accomplished by thorough washing in hot water containing two percent of concentrated hydrochloric acid, followed by a hot water rinse. The acidified water removes the white crust of zinc oxy-chloride, which is insoluble in water alone. Complete removal can also be accomplished by further washing in hot water which contains some washing soda (sodium carbonate), followed by a clear water rinse. Occasionally some mechanical scrubbing may also be required.

The inorganic type flux residues containing inorganic salts and acids should be removed completely. Residues from the organic type fluxes that are composed of very mild organic acids, such as stearic acid, oleic acid, and ordinary tallow, or the highly corrosive combinations of urea plus various organic hydrochlorides, should also be removed.

To determine whether all of the salts have been removed, the joint should be washed with warm water containing a few drops of silver nitrate. If any chloride salts are present the wash will turn milky with the precipitation of silver chloride.

Residues from the organic fluxes are usually quite soluble in hot water. Double rinsing in warm water is always advisable.

Generally, rosin flux residues may be left on the joint unless appearance is the prime factor, or if the joint area is to be painted or subsequently coated. Activated rosin fluxes may be treated in the same manner, but they should be removed for critical electronic applications.

If rosin residues must be removed, alcohol or chlorinated hydrocarbons may be used. Certain rosin activators are insoluble in water but soluble in organic solvents. These flux residues require removal by organic solvents, followed by a water rinse.

The residues from reaction type fluxes used on aluminum are usually removed with a rinse in warm water. If this does not remove all traces of residue, the joint may be scrubbed with a brush and then immersed in two percent sulfuric acid, followed by immersion in one percent nitric acid. A final warm-water rinse is then required.

Soldering pastes for plumbing systems are usually emulsions of petroleum jelly and a water solution of zinc ammonium chloride. Because of the corrosive nature of the acid salts contained in the flux, residues must be removed to prevent corrosion of the soldered joints and the copper pipes. Oily or greasy flux paste residues are generally removed with an organic solvent.

INSPECTION AND TESTING

VISUAL INSPECTION

VISUAL INSPECTION IS normally adequate for soldered joints. Soldered joints should be smooth and free of obvious voids, holes, or porosity. The profile between the soldered joint and the material being joined should show a smooth transition with a relatively low angle of contact between the solder and the base metal. Examination for any areas that have not been successfully wetted should be made. Non-wetting can be seen where the metal retains its original color. De-wetting occurs where solder has originally flowed across the joining surfaces and then pulled back into globules, leaving a discolored, dirty-looking surface. These defects are usually related to poor surface precleaning or use of an inappropriate flux.

Solder joints can be readily overheated or underheated. Overheated joints can be detected by the presence of burned fluxes and oxides on the solder joint. Underheated joints generally show poor flow characteristics, and the solder lumps appear stuck to the surface. These features indicate that no metallurgical bonding has occurred.

Soldered printed circuit boards produce a set of defects peculiar to that product. Bridging of solder may occur between electrical connections that are closely spaced, and should be insulated from each other. Bridging can be caused by the alloy composition or the processing conditions. Another defect unique to circuit boards is called *icicling*, which produces spikes of solder beneath the board. This may cause electrical interference in the finished product. Icicling is promoted by impurities such as cadmium or zinc and by lack of flux activity.

Some types of porosity can be caused by the design or the material of the printed circuit board.

All of these defects can be found by visual inspection.

OTHER INSPECTION METHODS

OTHER METHODS OF nondestructive testing are used to inspect some soldered products. Pressure-vacuum fluid-seal testing and leakage-rate testing can be used on closed systems. Examples are plumbing systems checked by water pressure tests, vehicle radiators checked by air pressure tests, food cans checked by vacuum tests, and gas-filled systems checked by halogen-leak testing.

Radiography can be used for pipe joints or other applications where large surface areas of lead solder joints are present.

Laser inspection techniques are finding use in electronic fabrications. Heat generated by the laser provides an indication of solder joint quality. Surface dimensions may also be checked.

Acoustic emission testing is useful, but this process may affect the joint quality.

Normal destructive testing techniques, including mechanical tests, corrosion evaluation, and metallurgical analysis, are applied to soldered joints in all areas of their application.

PROPERTIES OF SOLDERS AND SOLDER JOINTS

THE PHYSICAL AND mechanical properties of solders are usually provided by the supplier and are used in specifications to ensure the consistent quality of filler metals. Typical properties reported by filler metal manufacturers may not apply to commercial products and applications. Therefore, users should conduct tests on their manufactured products to determine the suitability of the filler metal and the solder process. The reported properties of these alloys serve only to provide a basis to choose among several available solder filler metals.

Soldered joints are used mainly in shear as lap joints, or in peel as lock seam or material-supported joints. The test method must be appropriate to the product for mechanical property evaluation. Short-time tensile tests are good for manufacturing quality control and for comparisons. Most solder joints are subject to some stress in service, and therefore results of creep, stress-rupture, and fatigue tests are important indicators of product performance. Ultimately, the total soldered product must be tested to closely simulate actual service, otherwise serious deficiencies can occur by premature joint failures. Mechanical properties of soldered products are very much dependent upon the product design, alloy selection, manufacturing process, and service conditions. Each individual product should be studied for all these factors so that an optimum balance can be obtained between costs and utility. Additional information can be found in the Supplementary Reading List at the end of the chapter.

SAFETY PRACTICES IN SOLDERING

SOLDERING OPERATIONS SHOULD be carried out under safe conditions. Care must be taken to read all labels on the solder filler wires and fluxes supplied to ensure freedom from handling problems, to recognize any potential for toxic metals or chemicals, and to use these materials only for the purposes intended. All handsoldering operations should be carried out in a ventilated area with working surfaces kept clean of solder droplets, particles, and residual fluxes. Workers using solders and fluxes should always wash exposed skin areas before consuming food.

Industrial soldering operations often require electrical supplies at relatively high levels of power. All soldering irons and equipment should be properly grounded. Where electrical heaters are used for dip soldering operations, current leakage safety devices should be used for worker protection.

Overheated solder pots can give off toxic metal vapors and fumes. Ventilation systems should be installed to eliminate these fumes.

Employees should be kept aware of all factors involved in soldering that could have an influence on their health and safety.

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CHAPTER 14

OXYGEN CUTTING

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CHAPTER 14

OXYGEN CUTTING

INTRODUCTION

OXYGEN CUTTING (OC) describes a group of cutting processes used to sever or remove metals by high-temperature exothermic reaction of oxygen with the base metal. With some oxidation-resistant metals, the reaction can be aided by the use of a chemical flux or metal powder. Typical oxygen cutting processes are oxyfuel gas, oxygen arc, oxygen lance, chemical flux, and metal powder cutting.

OXYFUEL GAS CUTTING

FUNDAMENTALS OF THE PROCESS

Definition and General Description

OXYFUEL GAS CUTTING (OFC) processes sever or remove metal by the chemical reaction of oxygen with the metal at elevated temperatures. The necessary temperature is maintained by a flame of fuel gas burning in oxygen. In the case of oxidation resistant metals, the reaction is aided by adding chemical fluxes or metal powders to the cutting oxygen stream.

The process has been called various other names, such as as burning, flame cutting, and flame machining. The actual cutting operation is performed by the oxygen stream. The oxygen-fuel gas flame is the mechanism used to raise the base metal to an acceptable preheat temperature range and to maintain the cutting operation.

The OFC torch is a versatile tool that can be readily taken to the work site. It is used to cut plates up to 7 ft (2 m) thick. Because the cutting oxygen jet has a 360° "cutting edge", it provides a rapid means of cutting both straight edges and curved shapes to required dimensions without expensive handling equipment. Cutting direction can be continuously changed during operation.

Principles of Operation

THE OXYFUEL GAS cutting process employs a torch with a tip (nozzle). The functions of the torch are to produce preheat flames by mixing the gas and the oxygen in the correct proportions and to supply a concentrated stream of high-purity oxygen to the reaction zone. The oxygen oxidizes the hot metal and also blows the molten reaction products from the joint. Features of cutting torches are shown in Figures 14.1 and 14.2. The cutting torch mixes the fuel and oxygen for the preheating flames and aims the oxygen jet into the cut. The torch cutting tip contains a number of preheat flame ports and a center passage for the cutting oxygen.

The preheat flames are used to heat the metal to a temperature where the metal will react with the cutting oxygen. The oxygen jet rapidly oxidizes most of the metal in a narrow section to make the cut. Metal oxides and molten metal are expelled from the cut by the kinetic energy of the oxygen stream. Moving the torch across the workpiece at a proper rate produces a continuous cutting action. The torch may be moved manually or by a mechanized carriage.

The accuracy of a manual operation depends largely on the skill of the operator. Mechanized operation generally improves the accuracy and speed of the cut and the finish of the cut surfaces.

Kerf. When a piece is cut by an OC process, a narrow width of metal is progressively removed. The width of the cut is called a *kerf*, as shown in Figure 14.3. Control of the kerf is important in cutting operations where dimensional accuracy of the part and squareness of the cut edges are significant factors in quality control. With the OFC process, kerf width is a function of the size of oxygen port, type of tip used, speed of cutting, and flow rates of cutting oxygen and preheating gases. As material thickness in-

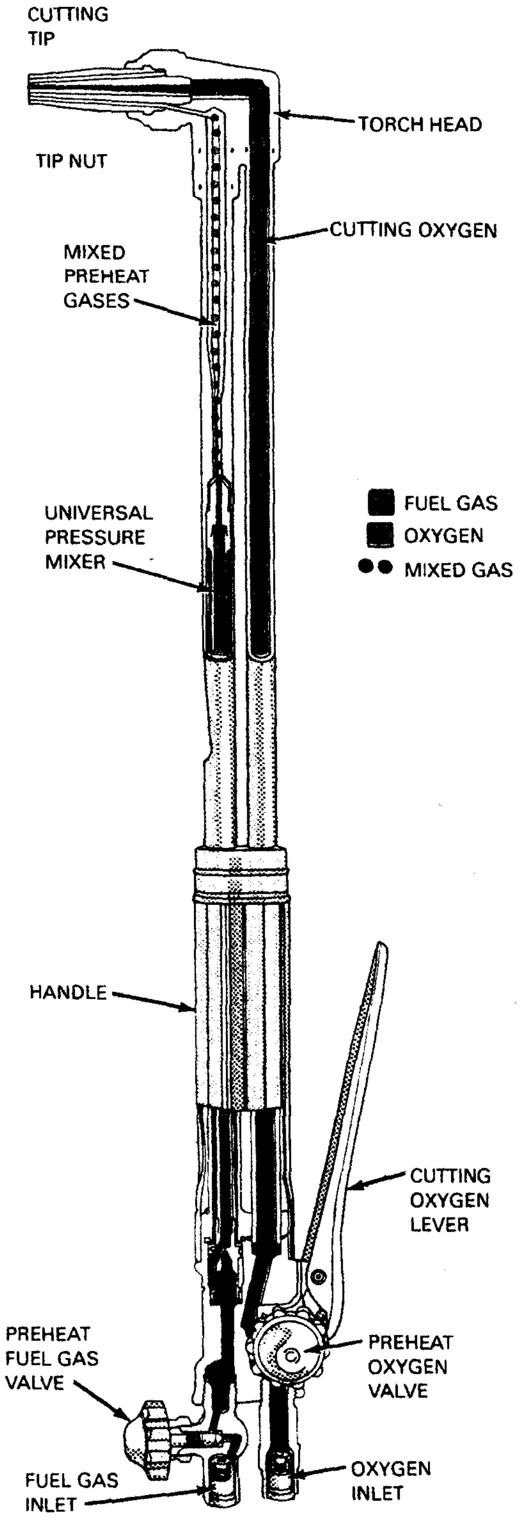


Figure 14.1–Typical Premixing-Type Cutting Torch

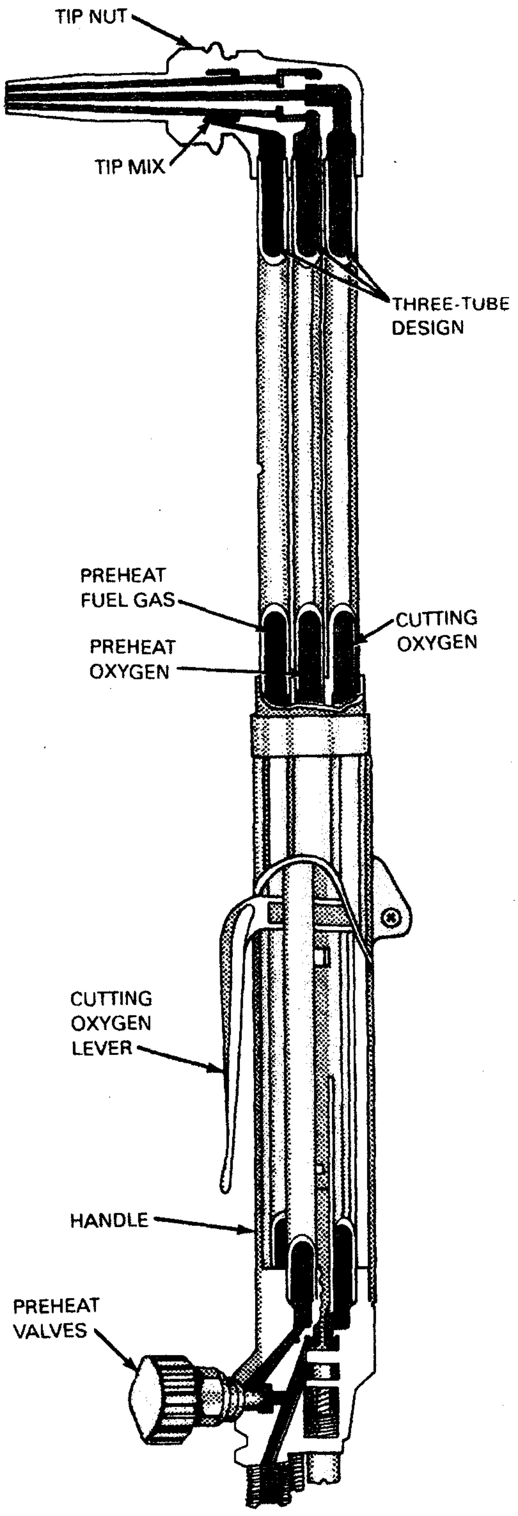


Figure 14.2–Typical Tip Mix Cutting Torch

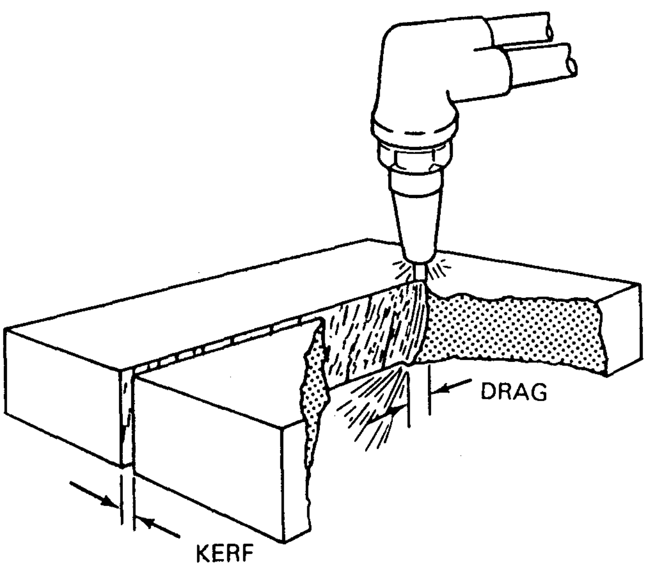


Figure 14.3–Kerf and Drag in Oxyfuel Gas Cutting

creases, oxygen flow rates must usually be increased. Cutting tips with larger cutting oxygen ports are required to handle the higher flow rates. Consequently, the width of the kerf increases as the material thickness being cut increases.

Kerf width is especially important in shape cutting. Compensation must be made for kerf width in the layout of the work, or the design of the template. Generally, on materials up to 2 in, (50 mm) thick, kerf width can be maintained within +1/64 in. (+0.4 mm).

Drag. When the speed of the cutting torch is adjusted so that the oxygen stream enters the top of the kerf and exits from the bottom of the kerf along the axis of the tip, the cut will have zero drag. If the speed of cutting is increased, or if the oxygen flow is decreased, the oxygen available in the lower regions of the cut decreases. With less oxygen available, the oxidation reaction rate decreases, and also the oxygen jet has less energy to carry the reaction products out of the kerf. As a result, the most distant part of the cutting stream lags behind the portion nearest to the torch tip. The length of this lag, measured along the line of cut, is referred to as the *drag*. This is shown in Figure 14.3.

Drag may also be expressed as a percentage of the cut thickness. A ten percent drag means that the far side of the cut lags the near side of the cut by a distance equal to ten percent of the material thickness.

An increase in cutting speed with no increase in oxygen flow usually results in a larger drag. This may cause a decrease in cut quality. There is also a strong possibility of loss of cut at excessive speeds. Reverse drag may occur when the cutting oxygen flow is too high or the travel speed is too low. Under these conditions, poor-quality cuts usually result. Cutting stream lag caused by incorrect torch alignment is not considered to be drag.

Cutting speeds below those recommended for best quality cuts usually result in irregularities in the kerf. The oxygen stream inconsistently oxidizes and washes away additional material from each side of the cut. Excessive preheat flame results in undesirable melting and widening of the kerf at the top.

Chemistry of Oxygen Cutting

THE PROCESS OF oxygen cutting is based on the ability of high-purity oxygen to combine rapidly with iron when it is heated to its ignition temperature, above 1600°F (870°C). The iron is rapidly oxidized by the high-purity oxygen and heat is liberated by several reactions.

The balanced chemical equations for these reactions are the following:

(1) $Fe + O \rightarrow FeO$ + heat (267 kJ), first reaction
(2) $3Fe + 2O_2 \rightarrow Fe_3O_4$ + heat (1120 kJ) second reaction
(3) $2Fe + 1.5O_2 \rightarrow Fe_2O_3$ + heat (825 kJ), third reaction

The tremendous heat release of the second reaction predominates over that of the first reaction, which is supplementary in most cutting applications. The third reaction occurs to some extent in heavier cutting applications. Stoichiometrically, 104 ft^3 (0.29 m^3) of oxygen will oxidize 2.2 lb (1 kg) of iron to Fe_3O_4.

In actual operations, the consumption of cutting oxygen per unit mass of iron varies with the thickness of the metal. Oxygen consumption per unit mass is higher than the ideal stoichiometric reaction for thicknesses less than approximately 1-1/2 in. (40 mm), and it is lower for greater thicknesses. For thicker sections, the oxygen consumption is lower than the ideal stoichiometric reaction because only part of the iron is completely oxidized to Fe_3O_4. Some unoxidized or partly oxidized iron is removed by the kinetic energy of the rapidly moving oxygen stream.

Chemical analysis has shown that, in some instances, over 30 percent of the slag is unoxidized metal. The heat generated by the rapid oxidation of iron melts some of the iron adjacent to the reaction surface. This molten iron is swept away with the iron oxide by the motion of the oxygen stream. The concurrent oxidizing reaction heats the layer of iron at the active cutting front.

The heat generated by the iron-oxygen reaction at the focal point of the cutting reaction (the hot spot) must be sufficient to continuously preheat the material to the ignition temperature. Allowing for the loss of heat by radiation and conduction, there is ample heat to sustain the reaction. In actual practice, the top surface of the material is frequently covered by mill scale or rust. That layer must be melted away by the preheating flames to expose a clean metal surface to the oxygen stream. Preheating flames help to sustain the cutting reaction by providing heat to the surface. They also shield the oxygen stream from turbulent interaction with air.

The alloying elements normally found in carbon steels are oxidized or dissolved in the slag without markedly interfering with the cutting process. When alloying elements are present in steel in appreciable amounts, their effect on the cutting process must be considered. Steels containing minor additions of oxidation resistant elements, such as nickel and chromium, can still be oxygen cut. However, when oxidation resistant elements are present in large quantities, modifications to the cutting technique are required to sustain the cutting action. This is true for stainless steels.

OXYGEN

OXYGEN USED FOR cutting operations should have a purity of 99.5 percent or higher. Lower purity reduces the efficiency of the cutting operation. A one percent decrease in oxygen purity to 98.5 percent will result in a decrease in cutting speed of approximately 15 percent, and an increase of about 25 percent in consumption of cutting oxygen. The quality of the cut will be impaired, and the amount and tenacity of the adhering slag will increase. With oxygen purities below 95 percent, the familiar cutting action disappears, and it becomes a melt-and-wash action that is usually unacceptable.

PREHEATING FUELS

FUNCTIONS OF THE preheat flames in the cutting operation are the following:

(1) Raise the temperature of the steel to the ignition point
(2) Add heat energy to the work to maintain the cutting reaction
(3) Provide a protective shield between the cutting oxygen stream and the atmosphere
(4) Dislodge from the upper surface of the steel any rust, scale, paint, or other foreign substance that would stop or retard the normal forward progress of the cutting action

A preheat intensity that raises the steel to the ignition temperature rapidly will usually be adequate to maintain cutting action at high travel speeds. However, the quality of the cut will not be the best. High-quality cutting can be carried out at considerably lower preheat intensities that those normally required for rapid heating. On most larger cutting machines, dual range gas controls are provided that limit high-intensity preheating to the starting operation. Then the preheat flames are reduced to lower intensity during the cutting operation, to save fuel and oxygen and provide a better cut surface.

A number of commercially available fuel gases are used with oxygen to provide the preheating flames. Some have proprietary compositions. Fuel gases are generally selected because of availability and cost. Properties of some commonly used fuel gases are listed in Table 14.1. To understand the significance of the information in this table, it is necessary to understand some of the terms and concepts involved in the burning of fuel gas. These terms and concepts are discussed in Chapter 11. Combustion intensity or specific flame output for various fuel gases is also covered in that chapter. This property is an important consideration in fuel gas selection.

Fuel Selection

THE FOLLOWING ARE some general factors for consideration when selecting a preheat fuel:

(1) Time required for preheating when starting cuts on square edges and rounded corners, and also when piercing holes for cut starts
(2) Effect on cutting speeds for straight line, shape, and bevel cutting
(3) Effect of the above factors on work output
(4) Cost and availability of the fuel in cylinder, bulk, and pipeline volumes
(5) Cost of the preheat oxygen required to burn the fuel gas efficiently
(6) Ability to use the fuel efficiently for other operations, such as welding, heating, and brazing, if required
(7) Safety in transporting and handling the fuel gas containers

For best performance and safety, the torches and tips should be designed for the particular fuel selected.

Acetylene

ACETYLENE IS WIDELY used as a fuel gas for oxygen cutting and also for welding. Its chief advantages are availability, high flame temperature, and widespread familiarity of users with its flame characteristics.

Combustion of acetylene with oxygen produces a hot, short flame with a bright inner cone at each preheat port. The hottest point is at the end of this inner cone. Combustion is completed in the long outer flame.

The sharp distinction between the two flames helps to adjust the oxygen-to-acetylene ratio for the desired flame characteristics.

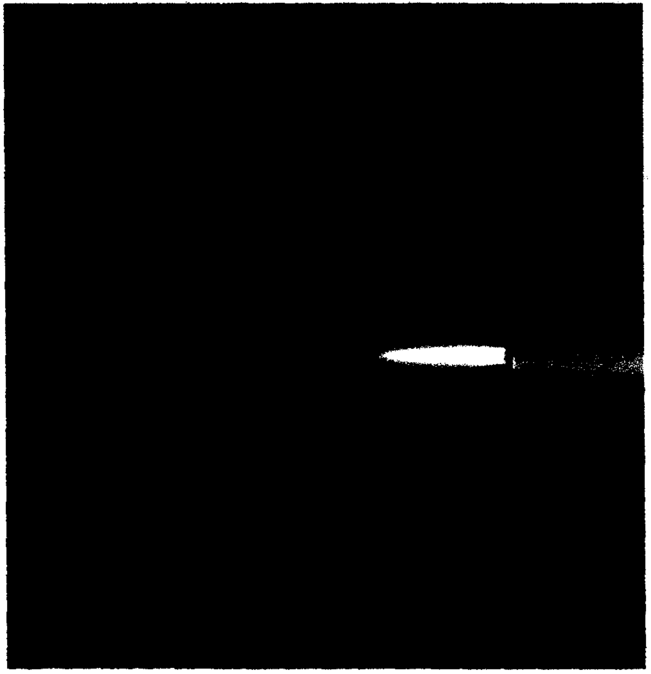
Depending on this ratio, the flame may to be adjusted to reducing (carburizing), neutral, or oxidizing, as shown in Figure 14.4. The neutral flame, obtained with a ratio of approximately one part oxygen to one part acetylene, is used for manual cutting. As the oxygen flow is decreased, a bright streamer begins to appear. This indicates a reducing flame, which is sometimes used to rough-cut cast iron.

Table 14.1
Properties of Common Fuel Gases

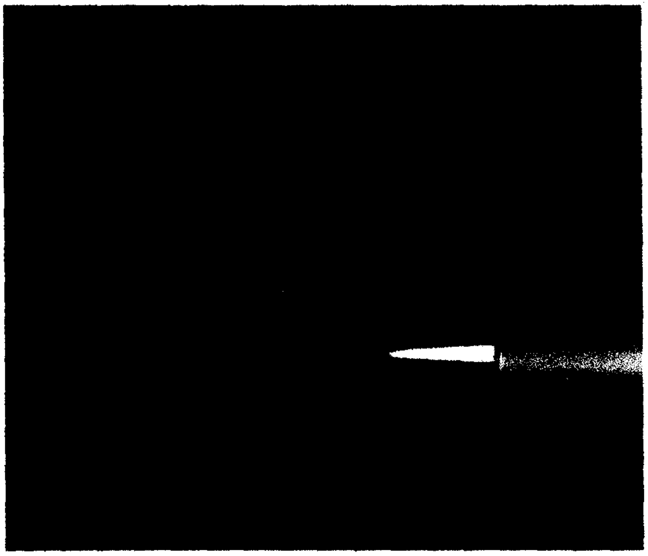
	Acetylene	Propane	Propylene	Methyl-acetylene-propadiene (MPS)	Natural Gas
Chemical Formula	C_2H_2	C_8H_8	C_3H_6	C_3H_4 (Methylacetylene, propadiene)	CH_4 (Methane)
Neutral flame temperature					
°F	5600	4580	5200	5200	4600
°C	3100	2520	2870	2870	2540
Primary flame heat emission					
btu/ft^3	507	255	433	517	11
MJ/m^3	19	10	16	20	0.4
Secondary flame heat emission					
btu/ft^3	963	2243	1938	1889	989
MJ/m^3	36	94	72	70	37
Total heat value (after vaporization)					
btu/ft^3	1470	2498	2371	2406	1000
MJ/m^3	55	104	88	90	37
Total heat value (after vaporization)					
btu/lb	21 500	21 800	21 100	21 100	23 900
kJ/kg	50 000	51 000	49 000	49 000	56 000
Total oxygen required (neutral flame)					
vol. O_2/vol. fuel	2.5	5.0	4.5	4.0	2.0
Oxygen supplied through torch (neutral flame)					
vol. O_2/vol. fuel	1.1	3.5	2.6	2.5	1.5
ft^3 oxygen/lb fuel (60°F)	16.0	30.3	23.0	22.1	35.4
m^3 oxygen/kg (15.6°C)	1.0	1.9	1.4	1.4	2.2
Maximum allowable regulator pressure					
psi	15	150	150	150	Line
kPa	103	1030	1030	1030	
Explosive limits in air: percent	2.5-80	2.3-9.5	2.0-10	3.4-10.8	5.3-14
Volume-to-weight ratio					
ft^3/lb (60°F)	14.6	8.66	8.9	8.85	23.6
m^3/kg (15.6°C)	0.91	0.54	0.55	0.55	1.4
Specific gravity of gas (60°F, 15.6°C) Air = 1	0.906	1.52	1.48	1.48	0.62

When excess oxygen is supplied, the inner flame cone shortens and becomes more intense. The flame temperature increases to a maximum at an oxygen-to-acetylene ratio of about 1.5 to 1. An oxidizing flame is used for short preheating times and for cutting very thick sections.

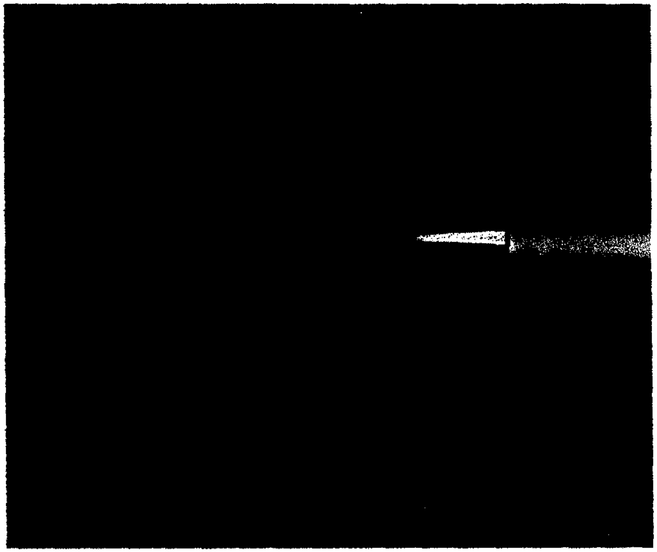
The high flame temperature and heat transfer characteristics of the oxyacetylene flame are particularly important for bevel cutting. They are also an advantage for operations in which the preheat time is an appreciable fraction of the total time for cutting, such as short cuts.



(A) CARBURIZING FLAME



(B) NEUTRAL FLAME



(C) OXIDIZING FLAME

Figure 14.4—Types of Oxyacetylene Flames

Figure 14.4—Types of Oxyacetylene Flames

Acetylene in the free state should not be used at pressures higher than 15 psi (103 kPa) gage, or 30 psi (207 kPa) absolute pressure. At higher pressures, it may decompose with explosive force when exposed to heat or shock.

Chapter 11 contains additional information on acetylene, its production and storage, and on the oxyacetylene flame.

Methylacetylene-Propadiene Stabilized (MPS)

MPS IS A liquefied, stabilized acetylenelike fuel that can be stored and handled similarly to liquid propane. MPS is a mixture of several hydrocarbons, including propadiene (allene), propane, butane, butadiene, and methylacetylene. Methylacetylene, like acetylene, is an unstable, high-energy, triple-bond compound. The other compounds in MPS dilute the methylacetylene sufficiently to make the mixture safe for handling. The mixture burns hotter than either propane or natural gas. It also affords a high release of energy in the primary flame cone, another characteristic similar to acetylene. The outer flame gives relatively high heat release, like propane and propylene. The overall heat distribution in the flame is the most even of any of the gases.

A neutral flame is achieved at a ratio of 2.5 parts of torch-supplied oxygen to 1 part MPS. Its maximum flame temperature is reached at a ratio of 3.5 parts of oxygen to 1 part of MPS. These ratios are used for the same applications as the acetylene flame.

Although MPS gas is similar in many characteristics to acetylene, it requires about twice the volume of oxygen per volume of fuel for a neutral preheat flame. Thus, oxygen cost will be higher when MPS gas is used in place of acetylene for a specific job. To be competitive, the cost of MPS gas must be lower than acetylene for the job.

MPS gas does have an advantage over acetylene for underwater cutting in deep water. Because acetylene outlet pressure is limited to 30 psi (207 kPa) absolute, it usually is not applicable at depths below 20 ft (6m) of water. MPS can be used there and at greater depths, as can hydrogen. For a particular underwater application, MPS, acetylene, and hydrogen should be evaluated for preheat fuel.

Natural Gas

THE COMPOSITION OF natural gas varies depending on its source. Its main component is methane (CH_4). The ratio of torch supplied oxygen to natural gas is 1.5 to 1 for a neutral flame. The flame temperature with natural gas is lower than with acetylene. It is also more diffused and less intense. The characteristics of the flame for carburizing, neutral, or oxidizing conditions are not as distinct as with the oxyacetylene flame.

Because of the lower flame temperature and the resulting lower heating efficiency, significantly greater quantities of natural gas and oxygen are required to produce heating rates equivalent to those of oxygen and acetylene. To compete with acetylene, the cost and availability of natural gas and oxygen, their higher gas consumptions, and their longer preheat times must be considered. The use of tips designed to provide a heavy preheat flame, or cutting machines that allow a high-low preheat setting, may compensate for deficiencies in the lower heat output of natural gas.

The torch and tip designs for natural gas are different from those for acetylene. The delivery pressure for natural gas is generally low and the combustion ratios are different (see Table 14.1)

Propane

PROPANE IS USED regularly for oxygen cutting in a number of plants because of its availability and its much higher total heat value (MJ/m^3) than natural gas (see Table 14.1). For proper combustion during cutting, propane requires 4 to 4 1/2 times its volume of preheat oxygen. This requirement is offset somewhat by its higher heat value. It is stored in liquid form and is easily transported to the work site.

Propylene

PROPYLENE, UNDER MANY different brand names, is used as fuel gas for oxygen cutting. One volume of propylene requires 2.6 volumes of torch supplied oxygen for a neutral flame and 3.6 volumes for maximum flame temperature. Cutting tips are similar to those used for MPS.

ADVANTAGES AND DISADVANTAGES

OXYFUEL GAS CUTTING has a number of advantages and disadvantages compared to other metal cutting operations, such as sawing, milling, and arc cutting.

Advantages

SEVERAL ADVANTAGES OF OFC are as follows:

(1) Steels can generally be cut faster by OFC than by mechanical chip removal processes.

(2) Section shapes and thicknesses that are difficult to produce by mechanical means can be severed economically by OFC.

(3) Basic manual OFC equipment costs are low compared to machine tools.

(4) Manual OFC equipment is very portable and can be used in the field.

(5) Cutting direction can be changed rapidly on a small radius during operation.

(6) Large plates can be cut rapidly in place by moving the OFC torch rather than the plate.

(7) OFC is an economical method of plate edge preparation for bevel and groove weld joint designs.

Disadvantages

THERE ARE A number of disadvantages with oxyfuel gas cutting of metals. Several important ones are as follows:

(1) Dimensional tolerances are significantly poorer than machine tool capabilities.

(2) The process is essentially limited commercially to cutting steels and cast iron, although other readily oxidized metals, such as titanium, can be cut.

(3) The preheat flames and expelled red hot slag present fire and burn hazards to plant and personnel.

(4) Fuel combustion and oxidation of the metal require proper fume control and adequate ventilation.

(5) Hardenable steels may require preheat, postheat, or both to control their metallurgical structures and mechanical properties adjacent to the cut edges.

(6) Special process modifications are needed for OFC of high alloy steels and cast irons.

EQUIPMENT

THERE ARE TWO basic types of OFC equipment: manual and machine. The manual equipment is used primarily for maintenance, for scrap cutting, cutting risers off castings, and other operations that do not require a high degree of accuracy or a high quality cut surface. Machine cutting equipment is used for accurate, high quality work, and for large volume cutting, such as in steel fabricating shops. Both types of equipment operate on the same principle.

No one should attempt to operate any oxyfuel apparatus until trained in its proper use or under competent supervision. It is important to follow closely the manufacturer's recommendations and operating instructions for safe use. See Volume I, Chapter 16, for more information on safe practices.

Manual Equipment

A SETUP FOR manual OFC requires the following:

(1) One or more cutting torches suitable for the preheat fuel gas to be used and the range of material thicknesses to be cut
(2) Required torch cutting tips to cut a range of material thicknesses
(3) Oxygen and fuel gas hoses
(4) Oxygen and fuel gas pressure regulators
(5) Sources of oxygen and fuel gases to be used
(6) Flame strikers, eye protection, flame and heat resistant gloves and clothing, and safety devices
(7) Equipment operating instructions from the manufacturer

Torches. The functions of an OFC torch are as follows:

(1) To control the flow and mixture of fuel gas and preheat oxygen
(2) To control the flow of cutting oxygen
(3) To discharge the gases through the cutting tip at the proper velocities and volumetric flow rates for preheating and cutting

These functions are partially controlled by the operator, by the pressures of incoming gases, and by the design of the torch and cutting tips.

For manual cutting, a torch that can be readily manipulated by the operator is preferred. Manual oxygen cutting torches are available in various sizes. Torch and tip selection generally depend on the thickness range of the steel to be cut. Tips used in manual cutting equipment have varied designs, depending on the fuel gas and type of work to be done. For example, for cutting rusty or scaly steel, a tip furnishing a great amount of preheat should be selected.

There are two basic types of OFC torches: (1) the tip mixing type, in which the fuel and oxygen for preheating flames are mixed in the tip; and (2) the premixing type, in which the mixing takes place within the torch. Premixing-type torches are further designated as equal (positive) pressure design, or injector (low pressure) design. The positive-pressure-type torches are used where there is sufficient fuel gas pressure to supply the torch mixer with the required volume of gas. The injector-type torches are used where the fuel gas pressure (usually natural gas at less than 2 psig) is such that the fuel gas must be drawn into the torch by the venturi action of the injector mixer. The two types of torches are shown in Figures 14.1 and 14.2 respectively. Some manufactures offer a mixer design that will operate effectively at both low and high fuel pressures. This design is referred to as a universal pressure mixer.

Manual Cutting Tips. Cutting tips are precision machined copper-alloy parts of various designs and sizes. They are held in the cutting torch by a tip nut. All oxygen cutting tips have preheat flame ports, usually arranged in a circle around a central cutting oxygen orifice. The preheat flame ports and the cutting oxygen orifice are sized for the thickness range of metal that the tip is designed to cut. Cutting tips are designated as standard or high speed. Standard tips have a straight bore oxygen port, and they are usually used with oxygen pressures from 30 to 60 psi (205 to 415 kPa). High-speed tips differ from standard tips in that the exit end of the oxygen orifice flares out or diverges. The divergence allows the use of higher oxygen pressures, typically 60 to 100 psi (415 to 690 kPa), while maintaining a uniform oxygen jet at supersonic velocities. High-speed tips are ordinarily used for machine cutting only. They usually permit cutting at speeds approximately 20 percent greater than speeds available with standard tips. Both types of tips are shown in Figure 14.5.

Cutting oxygen orifice size and design are not usually affected by the type of fuel used. However, preheat flame port design does depend on the fuel. Various fuel gases require different volumes of oxygen and fuel, and they burn at different velocities. Therefore, the preheat flame port size and number are designed to provide both a stable flame and adequate preheat for applications with the particular fuel gas being used. Acetylene tips are usually one piece with drilled or swaged flame ports. They are flat on the flame end. Tips for use with other fuel gases are either one piece, similar to acetylene tips, or two pieces with

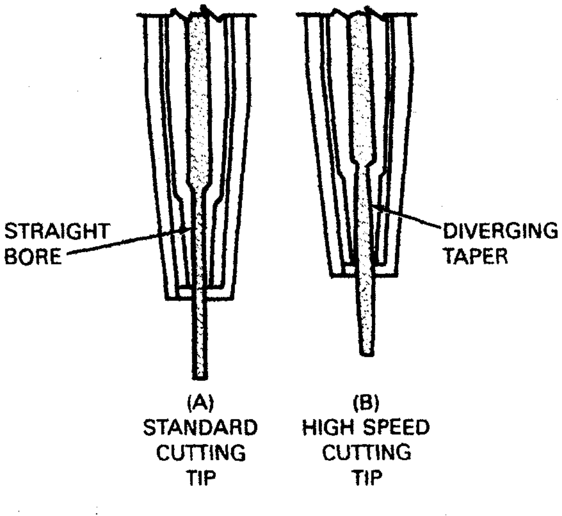


Figure 14.5–Oxyfuel Gas Cutting Tips

milled splines on the inner member, as illustrated in Figure 14.6.

Tips for MPS have a flat surface on the flame end. Most propylene tips have a slight recess, and natural gas and propane tips usually have a deeper recess or cupped end.

(A) ONE PIECE TIPS

(B) TWO PIECE TIPS

Figure 14.6—Cross Section View of One Piece and Two Piece Tips Used for Fuel Gases Other Than Acetylene

Cutting tips, although considered consumable items, are precision tools. The tip is considered to have the greatest influence on cutting performance. Proper maintenance of tips can greatly extend their useful life and provide continued high-quality performance.

The accumulation of slag in and around the preheat and cutting oxygen passages disturbs the preheat flame and oxygen stream characteristics. This can result in an obvious reduction in performance and quality of cut. When it happens, the tip should be taken out of service and either restored to a good working condition or replaced.

Gas Pressure Regulators. The ability to make a successful cut requires not only the proper choice of cutting torch and tip for the fuel gas selected, but also a means of precisely regulating the proper gas pressures and volumes. Regulators are pressure control devices used to reduce high source pressures to required working pressures by manually adjusted pressure valves. They vary in design, performance, and convenience features. Gas pressure regulators are designed for use with specific types of gases and for definite pressure ranges.

Gas pressure regulators used for OFC are generally similar in design to those used for oxyfuel gas welding (OFW),which are discussed in Chapter 11. Regulators for most other fuel gases are similar in design to acetylene regulators. For OFC, regulators with higher capacities and delivery pressure ranges than those used for OFW may be required for multitorch operations and heavy cutting.

Hoses. Oxygen and fuel gas hoses used for OFC are the same as those used for OFW. They are discussed in Chapter 11.

Other Equipment. Tinted goggles or other appropriate eye protection devices are available in a number of different shades. Tip cleaners, wrenches, strikers, and all appropriate safety devices including protective clothing should be used.

Mechanized Equipment

MECHANIZED OFC WILL require additional facilities depending on the application:

(1) A machine to move one or more torches in the required cutting pattern
(2) Torch mounting and adjusting arrangements on the machine
(3) A cutting table to support the work
(4) Means for loading and unloading the cutting table
(5) Automatic preheat ignition devices for multiple torch machines

Mechanized OFC equipment can vary in complexity from simple hand-guided machines to very sophisticated numerically-controlled units. The mechanized equipment is analogous to the manual equipment in principle, but differs in design to accommodate higher fuel pressures, faster cutting speeds, and means for starting the cut. Many machines are designed for special purposes, such as those for making vertical cuts, edge preparation for welding, and pipe cutting and beveling. Many variations of mechanized cutting systems are commercially available.

Machine Torches. A typical machine cutting torch consists of a barrel, similar to a manual torch but with heavier construction, and a cutting tip. See Figure 14.7. The torch body and barrel encase the oxygen and fuel gas tubes, which carry the gases to the end where the cutting tip is secured by a tip nut. The body of the torch may have a rack for indexing the tip to a desired position from the work surface. A machine torch will have either two or three gas (hose) inlets. Torches with two gas inlet fittings have a fuel-line connection and one oxygen connection with two valves. Torches with three inlet fittings have separate connections for fuel gas, preheat oxygen, and cutting oxygen. Three inlet torches permit separate regulation of preheat and cutting oxygen. They are generally recommended when remote control operation is desired.

Machine Cutting Tips. Machine cutting tips are designed to operate at higher oxygen and fuel pressures than those normally used for manual cutting. The two-piece divergent tip is one type used for operation at high cutting speeds [see Figure 14.5(B)]. Divergent cutting tips are based on the principles of gas flow through a venturi. High velocities are reached as the gas emerges from the venturi nozzle. Divergent cutting tips are precision machined to minimize any distortion of the gases when they exit from the nozzle. They are used for the majority of machine cutting applications because of their superior cutting characterics for materials up to 6 in. (150 mm) thick. They are not recommended for cutting materials over 10 in. (250 mm) thick.

Regulators. When natural gas or propane is used as a preheat fuel in machine cutting, fuel and oxygen can be conserved by using combination high-low pressure regulating systems. Because these fuels burn at lower heat transfer intensities than acetylene, high flow rates of fuel and preheat oxygen are required to heat the metal to ignition temperature in a reasonable time. Once the cut is started, less heat is needed to maintain cutting action with an appropriate savings in gas costs.

High-low pressure regulating systems permit the starting gas flow rates to be reduced to a predetermined level when the flow of cutting oxygen is initiated. This reduction may be done manually or automatically, depending on the regulator and control system design.

Cutting Machines. Oxyfuel gas cutting machines are either portable or stationary. Portable machines are usu-

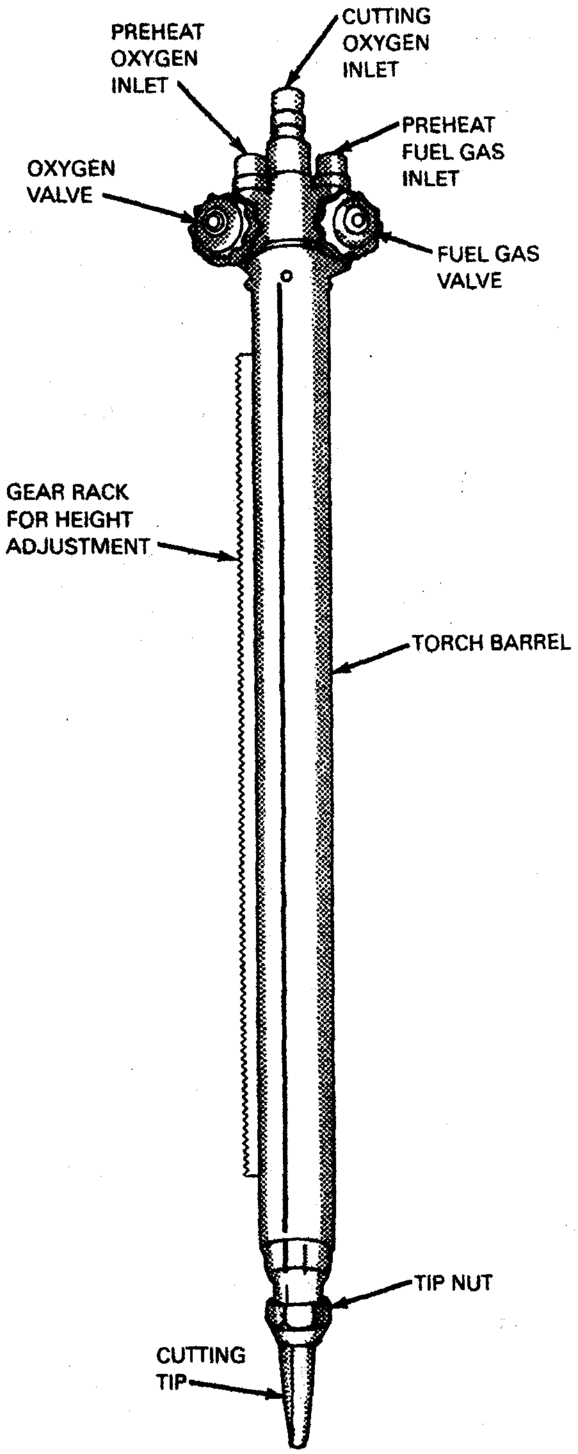


Figure 14.7–Three Hose Machine Cutting Torch

ally moved to the work. Stationary machines are fixed in location and the work is moved to the machine.

Portable Machines. Portable cutting machines are primarily used for straight line cutting, although they can be adapted to cut circles and shapes. Portable machines usually consist of a motor driven carriage with an adjustable mounting for the cutting torch. See Figure 14.8. In most cases, the machine travels on a track, which performs the function of guiding the torch. The carriage speed is adjustable over a wide range. The degree of cutting precision depends upon both the accuracy of the track, or guide, and the fit between the track and the driving wheels of the carriage. Portable machines are of various weights and sizes, depending on the type of work to be done. The smallest machines weigh only a few pounds. They are limited to carrying light-duty torches for cutting thin materials. Large, portable cutting machines are heavy and rugged. They can carry one or more heavy-duty torches and the necessary auxiliary equipment for cutting thick sections.

Generally, the operator must follow the carriage to make adjustments, as required, to produce good quality cuts. The operator ignites the torch, positions it at the starting point, and initiates the cutting oxygen flow and carriage travel. The operator adjusts torch height to maintain the preheat flames at the correct distance from the work surface. At the completion of the cut, the operator shuts off the cutting torch and carriage.

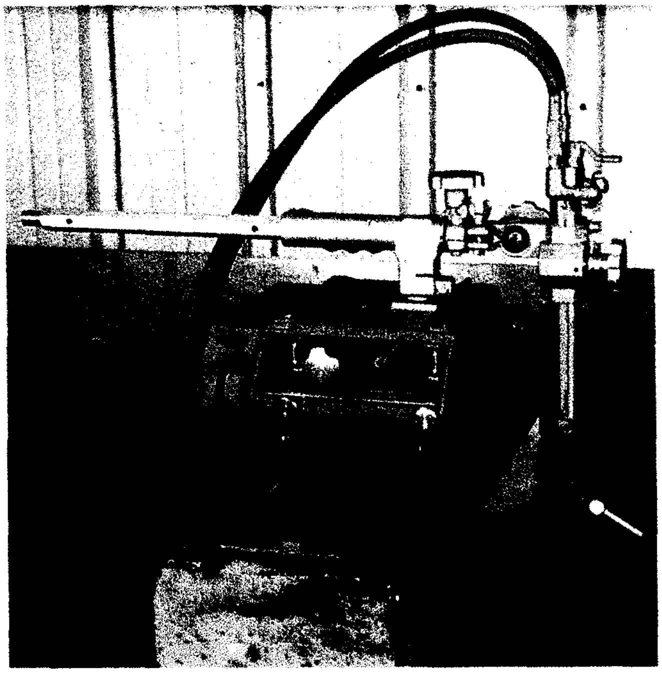


Figure 14.8–Machine Cutting Torch Mounted on a Portable Carriage

Stationary Machines. Stationary machines are designed to remain in a single location. The raw material is moved to the machine, and the cut shapes are transported away. The work station is composed of the machine, a system to supply the oxygen and preheat fuel to the machine, and a material handling system.

The torch support carriage runs on tracks. The structure either spans the work with a gantry-type bridge across the tracks or it is cantilevered off to one side of the tracks. These types of equipment are shown in Figures 14.9 and 14.10 respectively. They are usually classified according to the width of plate that can be cut (transverse motion). The length that can be cut is the travel distance on the tracks. The maximum cutting length is dictated by physical limitations of gas and electric power supply lines. An operator station with consolidated controls for gas flow, torch movement, and machine travel is generally a part of the machine.

A number of torches can be mounted on a shape cutting machine, depending on the size of the machine. The machine can cut shapes of nearly any complexity and size. In multiple torch operations, several identical shapes can be cut simultaneously. The number depends on the part size, plate size, and the number of available torches.

A rectilinear or coordinate drive-type machine often has a sine-cosine potentiometer to coordinate separate drive motors for longitudinal and transverse motion of the torch. The carriage and the cross arm, each with its own driving motor, are driven in the proper directions, and the linear speed of the torch remains at a constant preselected value. This type of construction permits the design and manufacture of cutting machines with sufficient rigidity to carry all modern control equipment.

It is possible to feed information to the electric drive motors of the carriage and cross arm from any suitable control. One method uses a photoelectric cell tracer that can follow line drawings or silhouettes. Numerical control machines use profile programs placed on punched or magnetic tapes or computer disks. These storage devices, in turn, control the shape cutting by appropriate signals to the cutting machine drive motors.

GENERAL PROCESS APPLICATIONS

MANUAL OFC IS widely used for the severing of steel and some other iron alloys. Portability permits taking the equipment to the job site. Structural shapes, pipe, rod, and similar materials can be cut to length for construction and maintenance, or cut up in scrap and salvage operations. In a steel mill or foundry, extraneous projections, such as caps, gates, and risers, are quickly severed from billets and castings. Mechanical fastenings, such as bolts, rivets, and

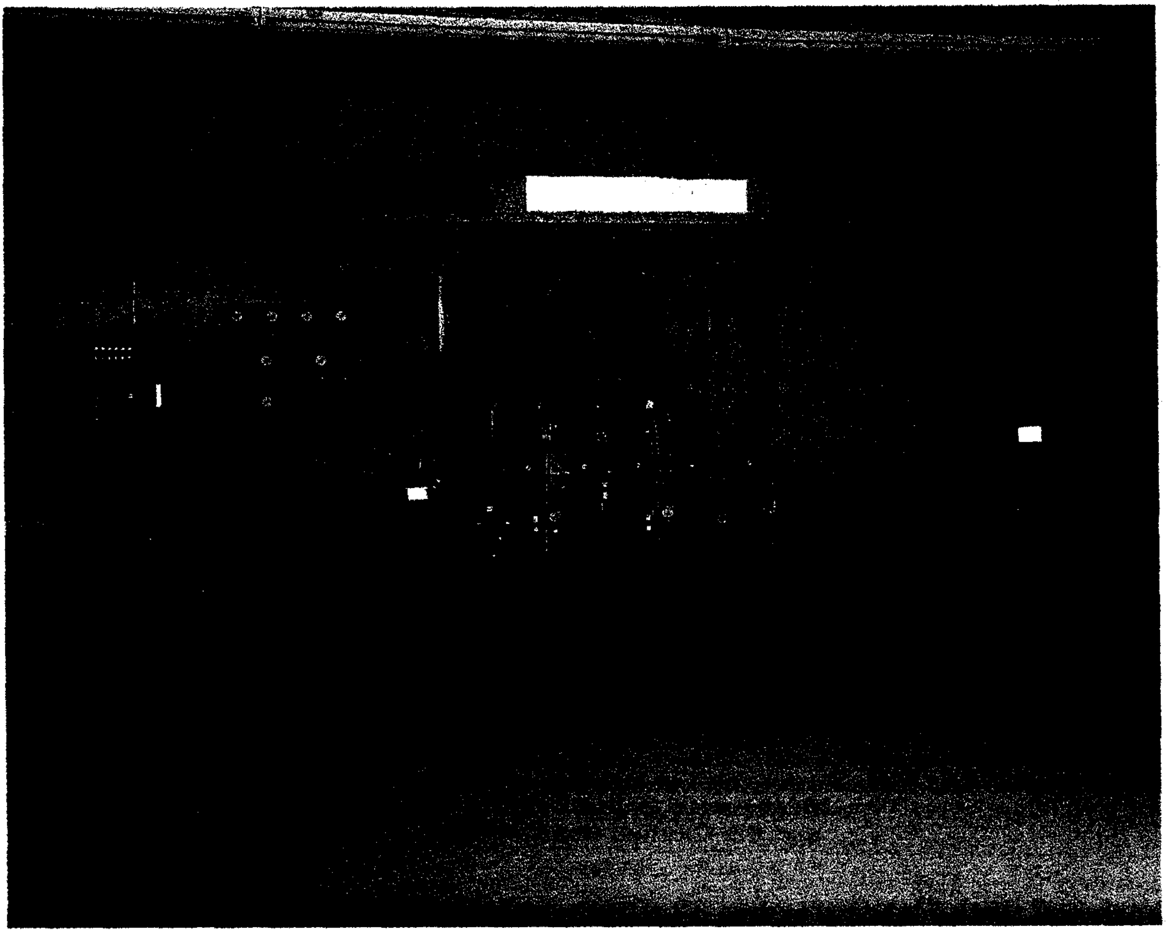


Figure 14.9–Gantry Type Shape Cutting Machine with Computer Numerical Control Drive

pins, are rapidly severed for disassembly using OFC. Holes can be made rapidly in steel components by piercing and cutting.

Machine OFC is used in many industries and steel warehouses to cut steel plate to size, to cut various shapes from plate, and to prepare plate edges for welding. Many machine parts such as gears, clevises, frames, and tools are made by oxygen-cutting procedures.

Machines capable of cutting to tolerances of 1/32 to 1/16 in. (0.8 to 1.6 mm) are used to produce parts that can be assembled into final product form without intermediate machining. They are also used for rapid material removal prior to machining to close tolerances.

Oxyfuel gas cutting is used to cut a wide range of steel thicknesses from approximately 1/8 to 84 in. (3 to 2100 mm). Thicknesses over approximately 20 in. (500 mm) are not generally cut except in steel mill operations, where the pieces are cut while still at high temperatures.

OPERATING PROCEDURES

IN THE OPERATION of OFC equipment, the recommendations of the equipment manufacturer in assembling and using the equipment should always be closely followed. This will prevent damage to the equipment and also insure its proper and safe use.

Regulators

THE OXYGEN AND fuel gas regulators must be clean and in good working condition. If there is oil, grease, or foreign material on a regulator or other equipment, or if the equipment is damaged, it must not be used prior to being properly cleaned or serviced by a qualified repair technician. Hoses must be in good condition and of appropriate size to provide adequate volume and pressure of both oxygen and fuel gas to the cutting torch.

Figure 14.10–Cantilever Type Mechanized Shape Cutting Machine Equipped with Photocell Tracer and Six Oxyfuel Gas Cutting Torches

Flashback and Back Fire

A FLASHBACK IS the burning of the flame in or behind the torch mixing chamber. It is a serious condition, and corrective action must be taken to extinguish it. The torch oxygen valve should be turned off immediately and then the fuel gas valve. One cause of flashback is failure to purge the hose lines before lighting the torch; another cause is the overheating of the torch tip.

A backfire is the momentary recession of the flame into the torch tip followed by immediate reappearance or complete extinguishing of the flame. After this condition, the torch is still workable. If backfiring continues, the torch or tips, or both, should be removed from service for cleaning and possible repair.

Operating the Torch

THE MANUFACTURER'S RECOMMENDATIONS for lighting, testing, and using the equipment should always be followed. Only a spark lighter or other recommended lighting device should be used. Shaded or tinted eye protection and other appropriate clothes must be worn.

The most widely accepted manner to light the torch is to open the fuel-gas valve slightly, and light the gas with a spark lighter. Adjust the fuel gas until a stable flame is maintained at the end of the tip. Open the oxygen preheat valve slowly and increase the flow until the desired flame is attained. The intensity of the flame may be adjusted by slightly increasing or decreasing the volumes of both gases.

Flame Adjustment

FLAME ADJUSTMENT IS a critical factor in attaining satisfactory torch operation. The amount of heat produced by the flame depends on the intensity and type of flame used. Three types of flames can be set by properly adjusting the torch valves. See Figure 14.4.

A carburizing flame with acetylene, MPS, or propylene is indicated by trailing feathers on the primary flame cone or by long yellow-orange streamers in the secondary flame envelope. Propylene-based fuels, propane, and natural gas have a long, rounded primary flame cone. A carburizing flame is often used for the best finish and for stack cutting of thin material.

A neutral flame with acetylene, MPS, or propylene is indicated by a sharply defined, dark primary flame cone and a pale blue secondary flame envelope. Propane and propylene base fuels and natural gas have a short and sharply defined cone. This flame is obtained by adding oxygen to a carburizing flame. It is the flame most frequently used for cutting.

An oxidizing flame for acetylene or MPS has a light color primary cone and a smaller secondary flame shroud. It also generally burns with a harsh whistling sound. With propane and propylene base fuels and natural gas, the primary flame cones are longer, less sharply defined, and have a lighter color. This flame is obtained by adding some oxygen to the neutral flame. This type of flame is frequently used for fast, low-quality cutting, and selectively in piercing and quality beveling.

CUTTING PROCEDURES

Manual Cutting

SEVERAL METHODS CAN be used to start a cut on an edge. The most common method is to place the preheat flames halfway over the edge, holding the end of the flame cones 1/16 to 1/8 in. (1.5 to 3 mm) above the surface of the material to be cut. The tip axis should be aligned with the plate edge. When the top corner reaches a reddish yellow color, the cutting oxygen valve is opened and the cutting process starts. Torch movement is started after the cutting action reaches the far side of the edge.

Another starting method is to hold the torch halfway over the edge, with the cutting oxygen turned on, but not touching the edge of the material. When the metal reaches a reddish yellow color, the torch is moved onto the material and cutting starts. This method wastes oxygen, and starting is more difficult than with the first method. It should only be used for cutting thin material where preheat times are very short.

A third method is to put the tip entirely over the material to be cut. The preheat flame is held there until the metal reaches its kindling temperature. The tip is then moved to the edge of the plate so the oxygen stream will just clear the metal. With the cutting oxygen on, the cut is initiated. This method has the advantage of producing sharper corners at the beginning of the cut.

Once the cut has been started, the torch is moved along the line of cut with a smooth, steady motion. The operator should maintain as constant a tip-to-work distance as possible. The torch should be moved at a speed that produces a light ripping sound and a smooth spark stream.

For plate thicknesses of 1/2 in. (13 mm) or more, the cutting tip should be held perpendicular to the plate. For the thin plate, the tip can be tilted in the direction of the cut. Tilting increases the cutting speed and helps prevent slag from freezing across the kerf. When cutting material in a vertical position, start on the lower edge of the material and cut upward.

It is often necessary to start a cut at some point other than on the edge of a piece of metal. This technique is known as *piercing*. Piercing usually requires a somewhat larger preheat flame than the one used for an edge start. In addition, the flame should be adjusted to slightly oxidizing to increase the heat energy. The area where the pierce cut is to begin should be located in a scrap area. Hold the torch tip in one spot until the steel surface turns a yellowish red and a few sparks appear from the surface of the metal. The tip should be angled and lifted up as the cutting oxygen valve is opened. The torch is held stationary until the cutting jet pierces through the plate.

Torch motion is then initiated along the cut line. If the cutting oxygen is turned on too quickly and the torch is not lifted, slag may be blown into the tip and may plug the gas ports.

Machine Cutting

OPERATING CONDITIONS FOR mechanized oxygen cutting will vary depending on the fuel gas and the style of cutting torch being used. Tip size designations, tip design, and operating data can be obtained from the torch manufacturer.

Start up and shutdown procedures for machine OFC are essentially the same as those previously given for hand torch operation. However, proper adjustment of operating conditions is more critical if high-speed, high-quality cuts are to be obtained. The manufacturer's or supplier's cutting chart should be used to select the proper tip size for the material thickness to be cut. In addition to the tip size, initial fuel and oxygen pressure settings and travel speeds should be selected from the chart. Frequently the chart will also list gas flow rates, drill size of the oxygen orifice, preheat cone lengths, and kerf width. Operating conditions should then be adjusted to give the desired cut quality.

Proper tip size and cutting oxygen pressure are important in making a quality machine cut. If the proper tip size is not used, maximum cutting speed and the best quality of cut will not be achieved. The cutting oxygen pressure setting is an essential condition; deviations from the recommended setting will greatly affect cut quality. For this reason, some manufacturers specify setting the pressure at the regulator and operating with a given length of hose. When longer or shorter hoses are used, an adjustment in pressure should be made. An alternative is to measure oxygen pressure at the torch inlet. Pressure settings for cutting oxygen are then adjusted to obtain the recommended pressure at the torch inlet, rather than at the regulator outlet.

Other adjustments, such as the preheat fuel and oxygen pressure settings and the travel speed, are also important. Once the regulators have been adjusted, the torch valves are used to throttle gas flows to give the desired preheat flame. If sufficient flow rates are not obtained, pressure settings at the regulator can be increased to compensate. Cleanliness of the nozzle, type of base metal, purity of cutting oxygen, and other factors have a direct effect on performance.

Manufacturers differ in their recommended travel speeds. Some give a range of speeds for specific thicknesses, while others list a single speed. In either case, the settings are intended only as a guide. In determining the proper speed for an application, begin the cut at a slower speed than that recommended. Gradually increase the speed until cut quality falls below the required level. Then reduce the speed until the cut quality is restored, and continue to operate at that speed.

Typical data for cutting low carbon steel, using commonly available fuel gases, are shown in Table 14.2. The gas flow rates and cutting speeds are to be considered only as guides for determining more precise settings for a particular job. When a new material is being cut, a few trial cuts should be made to obtain the most efficient operating conditions.

Heavy Cutting

HEAVY CUTTING IS considered the cutting of steel over approximately 12 in. (300 mm) thick. The basic reactions that permit oxygen cutting of thick steel are the same as

Table 14.2
Data for Manual and Machine Cutting of Clean Low Carbon Steel Without Preheat

U.S. Customary Units

Thickness of Steel in.	Diameter of cutting Orifice, in.	Cutting Speed in./min.	Gas Flow, ft^3/h Cutting Oxygen	Acetylene	MPS	Natural Gas	Propane
1/8	0.020-0.040	16-32	15-45	3-9	2-10	9-25	3-10
1/4	0.030-0.060	16-26	30-55	3-9	4-10	9-25	5-12
3/8	0.030-0.060	15-24	40-70	6-12	4-10	10-25	5-15
1/2	0.040-0.060	12-23	55-85	6-12	6-10	15-30	5-15
3/4	0.045-0.060	12-21	100-150	7-14	8-15	15-30	6-18
1	0.045-0.060	9-18	110-160	7-14	8-15	18-35	6-18
1-1/2	0.060-0.080	6-14	110-175	8-16	8-15	18-35	8-20
2	0.060-0.080	6-13	130-190	8-16	8-20	20-40	8-20
3	0.065-0.085	4-11	190-300	9-20	8-20	20-40	9-22
4	0.080-0.090	4-10	240-360	9-20	10-20	20-40	9-24
5	0.080-0.095	4-8	270-360	10-25	10-20	25-50	10-25
6	0.095-0.105	3-7	260-500	10-25	20-40	25-50	10-30
8	0.095-0.110	3-5	460-620	15-30	20-40	30-55	15-32
10	0.095-0.110	2-4	580-700	15-35	30-60	35-70	15-35
12	0.110-0.130	2-4	720-850	20-40	30-60	45-95	20-45

SI Units

Thickness of Steel mm	Diameter of cutting Orifice, mm	Cutting Speed mm/s	Gas Flow, L/min Cutting Oxygen	Acetylene	MPS	Natural Gas	Propane
3.2	0.51-1.02	6.8 -13.5	7.2- 21.2	2- 4	2- 4	4-12	2- 5
6.4	0.76-1.52	6.8 -11.0	14.2- 26.0	2- 4	2- 5	4-12	2- 6
9.5	0.76-1.52	6.4 -10.1	18.9- 33.0	3- 5	2- 5	5-12	3- 7
13	1.02-1.52	5.1 - 9.7	26.0- 40.0	3- 5	2- 5	7-14	3- 8
19	1.14-1.52	5.1 - 8.9	47.2- 70.9	3- 6	3- 5	7-14	3- 9
25	1.14-1.52	3.8 - 7.6	51.9- 75.5	4- 7	4- 7	8-17	4- 9
38	1.52-2.03	2.5 - 5.9	51.9- 82.6	4- 8	4- 8	9-17	4-10
51	1.52-2.03	2.5 - 5.5	61.4- 89.6	4- 8	4- 8	9-19	4-10
76	1.65-2.16	1.7 - 4.7	89.6-142	4- 9	4-10	10-19	5-11
102	2.03-2.29	1.7 - 4.2	113 -170	5-10	4-10	10-19	5-11
127	2.03-2.41	1.7 - 3.4	127 -170	5-10	5-10	12-24	5-12
152	2.41-2.67	1.3 - 3.0	123 -236	5-12	5-12	12-24	6-19
203	2.41-2.79	1.3 - 2.1	217 -293	7-14	10-19	14-30	7-15
254	2.41-2.79	0.85 - 1.7	274 -331	7-17	10-19	16-33	7-15
305	2.79-3.30	0.85 - 1.7	340 -401	9-19	15-29	20-75	10-22

Notes:

1. Preheat oxygen consumptions: Preheat oxygen for acetylene = 1.1 to 1.25 x acetylene flow ft^3/h; preheat oxygen for natural gas = 1.5 to 2.5 natural gas flow ft^3/h; preheat oxygen for propane = 3.5 to 5 x propane flow ft^3/h.

2. Operating notes: Higher gas flows and lower speeds are generally associated with manual cutting, whereas lower gas flows and higher speeds apply machine cutting. When cutting heavily scaled or rusted plate, use high gas flow and low speeds. Maximum indicated speeds apply to straight line cuttin for intricate shape cutting and best quality, lower speeds will be required.

those for the cutting of thinner sections. Thicknesses ranging from 12 to 60 in. (300 to 1525 mm) may be cut using heavy-duty torches. Preheat and cutting oxygen flows increase, and cutting speed decreases, as thickness increases.

For heavy cutting, the most important factor is oxygen flow. Tip size and operating pressure must provide the necessary cutting oxygen flow required for the thickness being cut. Oxygen cutting pressures in the range of 10 to 55 psi (70 to 380 kPa), measured at the cutting torch, have been found adequate for the heaviest cutting using the proper tip size and equipment. The oxygen flow at the torch entry is of paramount importance when comparing results of different cutting operations. By relating performance to oxygen flow rate rather than pressure, heavy cutting data can be plotted as a continuous curve.

In terms of flow, it is possible to arrive at an approximate demand constant that will be useful as a guide in selecting equipment suitable for a given job. These demand constants may vary, but in terms of thickness, they usually fall within the approximate range of 80 to 125 ft^3 of oxygen per in. (89 to 139L of oxygen per mm) of thickness. Table 14.3 gives the range of operating conditions that cover normal heavy cutting operations.

Heavy cutting covers a wide variety of operations, such as ingot cropping, scrap cutting, and riser cutting. The data in Table 14.3 may not be entirely suitable for all heavy cutting operations, although the values given have been used successfully. They may be used as a guide in selecting the correct equipment and operating conditions. The actual values for most efficient operation of a specific cutting application are always best found by trial cuts.

When heavy cutting is performed with the torch in a horizontal position, the cutting oxygen pressure may need to be increased to aid in removing slag from the kerf.

Recommended travel speeds are not included in Table 14.3, but speeds from 2 to 6 in./min (0.85 to 2.5 mm/s) are used in the range of thicknesses covered. A speed of 3 in./min (1.3 mm/s) is possible for thicknesses up to at least 36 in. (910 mm). The correct speed is obtained by observing the operating conditions carefully and making suitable adjustments while actual cutting is in progress.

Because heavy pieces usually have a scale covered surface, techniques of starting the cut differ from those used with clean, thin material. The start is made more slowly on the rougher edges. Figure 14.11 indicates correct and incorrect starting procedures. Figure 14.11(A) shows the desirable starting position with the preheat flames on the top corner and extending down the face of the material. The cutting reaction starts at the top corner. It proceeds down the face of the material to the bottom as the torch moves forward. Figures 14.11(B), (C), (D), (E), and (F) show problems occurring from incorrect procedures.

When the cut proceeds properly with correct oxygen flow and forward speed, the reaction will proceed to the end of the cut without leaving a skipped corner. Figure 14.12 illustrates various correct and incorrect terminating conditions and also proper drag conditions. Conditions producing a drop cut are depicted in Figure 14.12(A).

In general, the following conditions are required for successful heavy cutting on a production basis:

(1) Adequate gas supply sufficient to complete the cut; this is necessary because a lost cut on heavy materials is extremely difficult, if not impossible, to restart.

(2) Equipment of sufficient size structurally to maintain rigidity and to carry the equipment needed, and of sufficient capacity to handle the range of speeds and gas flows required.

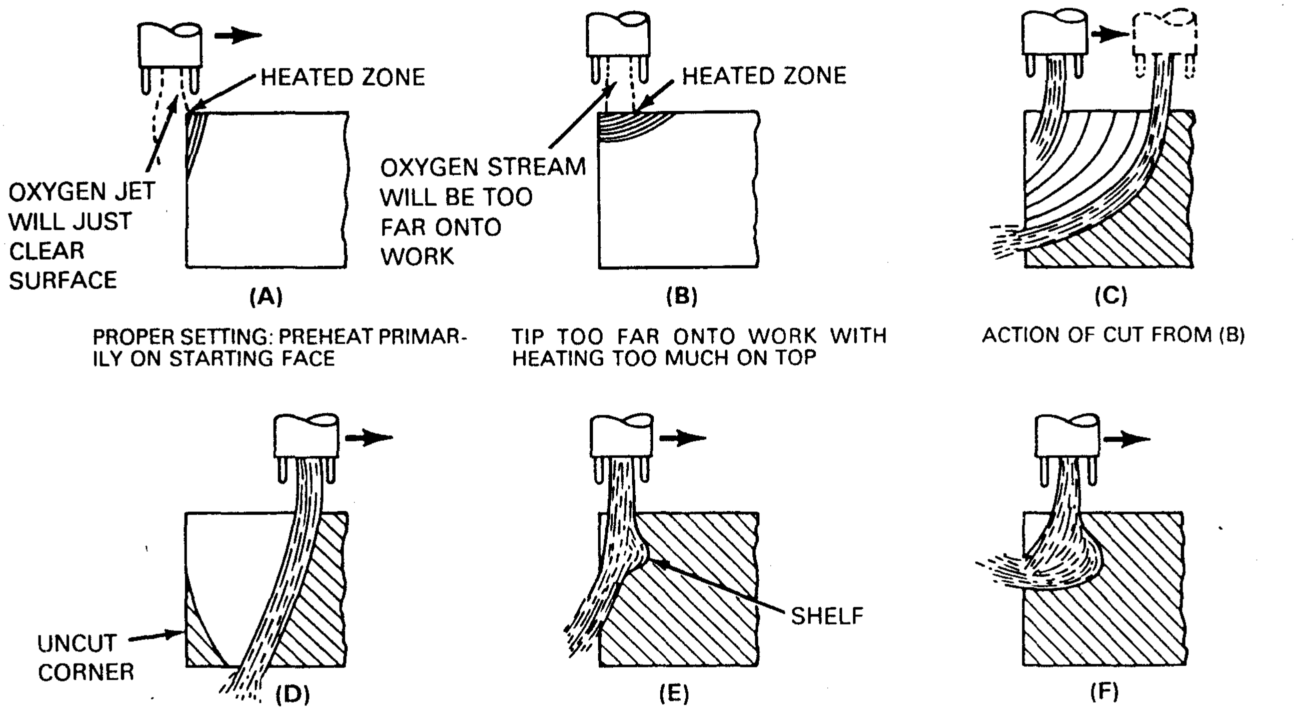
(3) Skilled personnel that are trained in proper heavy cutting techniques.

Stack Cutting

IF DATA ON machine OFC speeds and gas requirements are plotted against the material thickness, the requirements are not directly proportional to material thickness, "t". Gas consumption per unit of thickness, "t", decreases as the thickness, "t", increases. Consequently, cutting costs

Table 14.3
Data for Oxyfuel Gas Cutting of Thick Low Carbon Steel

Material Thickness		Cutting Oxygen					
		Orifice Diameter		Flow Rate		Pressure at Torch	
in.	mm	in.	mm	ft^3/h	L/min	psi	kPa
12	305	0.147-0.221	3.74- 5.61	1000-1500	472- 708	56-33	386-228
16	406	0.170-0.290	4.32- 7.36	1300-2000	614- 944	54-25	372-172
20	508	0.194-0.332	4.93- 8.44	1700-2500	803-1180	52-22	359-152
24	610	0.221-0.332	5.61- 8.44	2000-3000	944-1416	48-29	331-200
28	711	0.250-0.375	6.35- 9.53	2300-3500	1087-1652	41-26	283-179
32	813	0.250-0.375	6.35- 9.53	2700-4000	1274-1888	51-30	352-207
36	914	0.290-0.422	7.37-10.72	3000-4500	1416-2120	40-26	276-179
40	1016	0.290-0.422	7.37-10.72	3400-5000	1605-2360	46-30	317-207
44	1118	0.290-0.468	7.37-11.90	3800-5500	1792-2600	51-26	352-179
48	1219	0.332-0.468	8.44-11.90	4000-6000	1888-2830	40-28	276-193



PROPER SETTING: PREHEAT PRIMARILY ON STARTING FACE

TIP TOO FAR ONTO WORK WITH HEATING TOO MUCH ON TOP

ACTION OF CUT FROM (B)

TYPICAL RESULT FROM (B)

EXCESSIVE OXYGEN PRESSURE OR INADEQUATE TRAVEL SPEED

INSUFFICIENT OXYGEN PRESSURE OR EXCESSIVE TRAVEL SPEED

Figure 14.11–Starting Procedures for Heavy Cutting

per "t" may decrease as "t" increases when "t" is below a specific value, depending on the material being cut. Stacking of material for cutting can be more economical than cutting individual pieces, particularly when the material thickness is under 1/4 in. (6 mm). Stack cutting is limited to sheet and plate up to 1/2 in. (13 mm) thick because of the difficulty in clamping heavier material in a tight stack. A stack cutting operation is shown in Figure 14.13.

Stack cutting is also a means of cutting sheet material that is too thin for ordinary OFC methods. Sheet thicknesses of 20 gage (0.9 mm) and over are the most practical. Stack cutting is used in place of shearing or stamping, particularly where volume does not justify expensive dies. The flame cut sheet edges are square with no burrs.

Successful stack cutting requires clean, flat sheet or plate. Dirt, mill scale, rust, and paint may interrupt the cut and reduce cut quality. The stack must be securely clamped, particularly at the cut location, with the edges aligned at the point where the cut is to start.

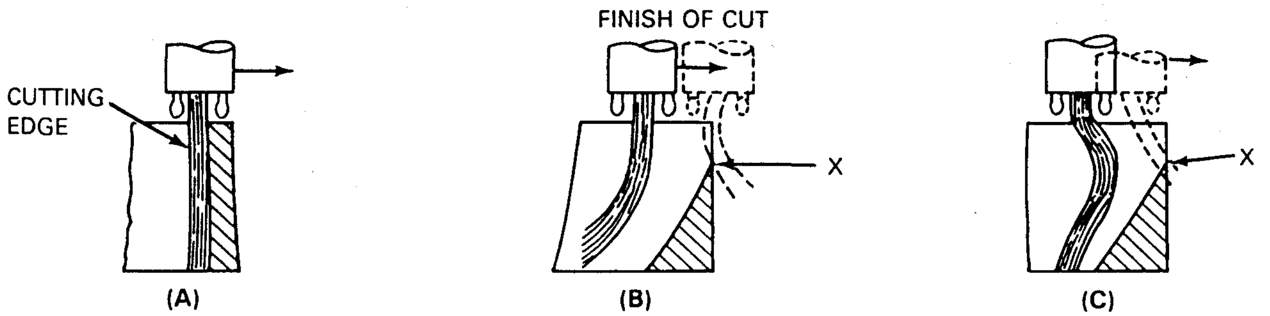
Piercing of stacks with the OF torch to start a cut is impractical. Holes must be drilled though the stacks to start an interior cut.

The total thickness of the stack is determined by the cutting tolerance requirement and the thickness of the top piece. With a cutting tolerance of 1/32 in. (0.8 mm), stack height should not exceed 2 in. (50 mm); with a 1/16 in. (1.6 mm) tolerance, the thickness may be up to 4 in. (100 mm). The maximum practical limit of thickness is about 6 in. (150 mm).

When stack cutting material less than 3/16 in. (5 mm) thick, a waster plate 1/4 in. (6 mm) thick is used on top. It insures better starting, a sharper edge on the top production piece, and no buckling of the top sheet.

Starting the cut must be done with extreme care so that it will extend through the stack. One method of starting is to align the sheet edges exactly in a vertical line. A vertical strip along the aligned face is preheated with a hand torch to ignition temperature. The machine torch is quickly positioned at the starting point and cutting initiated. Another procedure is to position each sheet so that its edge projects slightly over the edge below. This is advantageous for sheared sheet stacked with the burr down. Cutting is initiated on the top plate (waster plate) and progresses from one sheet to the other through the stack. A third method is to run a vertical weld bead down the stack to form a continuous strip of metal. The cut is started through the weld bead and progresses into the stack.

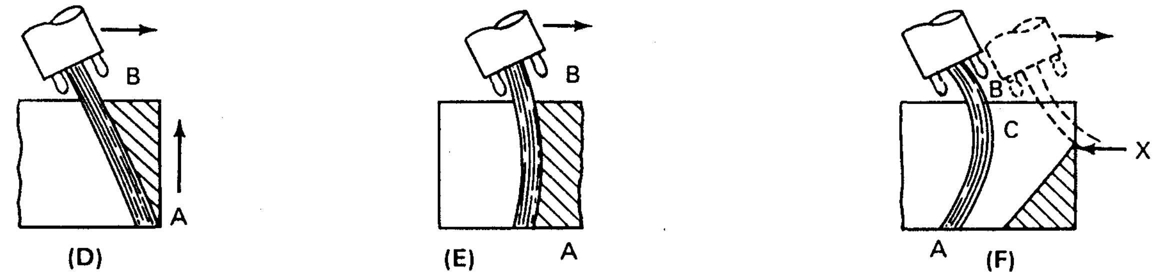
Even when extreme care has been exercised, there is always the possibility of an interruption of cutting with possible loss of the entire stack. The application of flux cut-



NO DRAG PERMITS STREAM TO BREAK THROUGH FACE UNIFORMLY AT ALL POINTS. TYPICAL OF BALANCED CONDITIONS

DRAG CAUSES ACTION TO CARRY THROUGH AT X AND AND TO PASS BEYOND MATERIAL, LEAVING UNCUT CORNER. TYPICAL OF INSUFFICIENT OXYGEN OR EXCESSIVE SPEED

FORWARD DRAG CAUSES STREAM TO BREAK THROUGH AT X AND BECOME DEFLECTED, LEAVING UNCUT CORNER. TYPICAL OF HIGH CUTTING OXYGEN PRESSURE OR TOO LITTLE SPEED



IF CUTTING FACE IS SUCH THAT BREAKTHROUGH AT BOTTOM, A, LIES AHEAD OF ENTRY POINT, B, AND AT NO POINT DOES FACE EXTEND BEYOND A, ACTION WILL SEVER FROM A, UPWARD

ANGULAR TIP DISPOSITION SIMILAR TO (D) SHOWING LIMIT OF EFFECTIVENESS. SIMILAR TO (A)

IF CONDITIONS ARE SUCH THAT A AND B ARE IN LINE OR OTHERWISE DISPOSED, BUT C LIES AHEAD OF A, STREAM WILL BREAK AT X, LEAVING UNCUT CORNER, SIMILAR TO (C)

Figure 14.12–Terminating Conditions for Heavy Cutting — A, B, and C With Torch Vertical; D, E, and F With Torch Angled in Direction of Cutting

ting and powder cutting processes greatly minimizes this hazard. These methods assist in propagating the oxidation reaction within the cut. Appreciable air gaps that otherwise might inhibit cutting can be tolerated between plates. The use of divergent tips with high velocity cutting jets also appears to aid this transfer action.

Regardless of the procedure employed, the economy of a stack cutting operation must be carefully compared with the total costs involved, including such items as material preparation, stack makeup, clamping devices, and increased skill and care requirements.

Plate Edge Preparation

BEVEL, V-, AND U-groove joint joint designs are used for welding steel components together. The preparation of the edges to be welded together can be done by oxygen cutting or gouging. Single and double bevels are produced using standard cutting tips and torches, usually mechanized, for straight-line beveling. Oxygen gouging is done by using specially designed cutting tips to produce U-groove joints.

Plate Beveling. The beveling of plate edges before welding is necessary in many applications to insure proper dimensions and fit, and also to accommodate standard welding techniques. Beveling may be done by using a single torch or multiple torches operating simultaneously. Although single beveling can be done manually, beveling is best done by machine for accurate control of the cutting variables. When cutting bevels with two or three torches, plate riding devices should be used to insure constant tip position above the plate, as shown in Figure 14.14.

In single-torch beveling, the amount and type of torch preheat is a dominant factor. With bevel angles of less than 15°, the loss of preheat efficiency is small. When the bevel

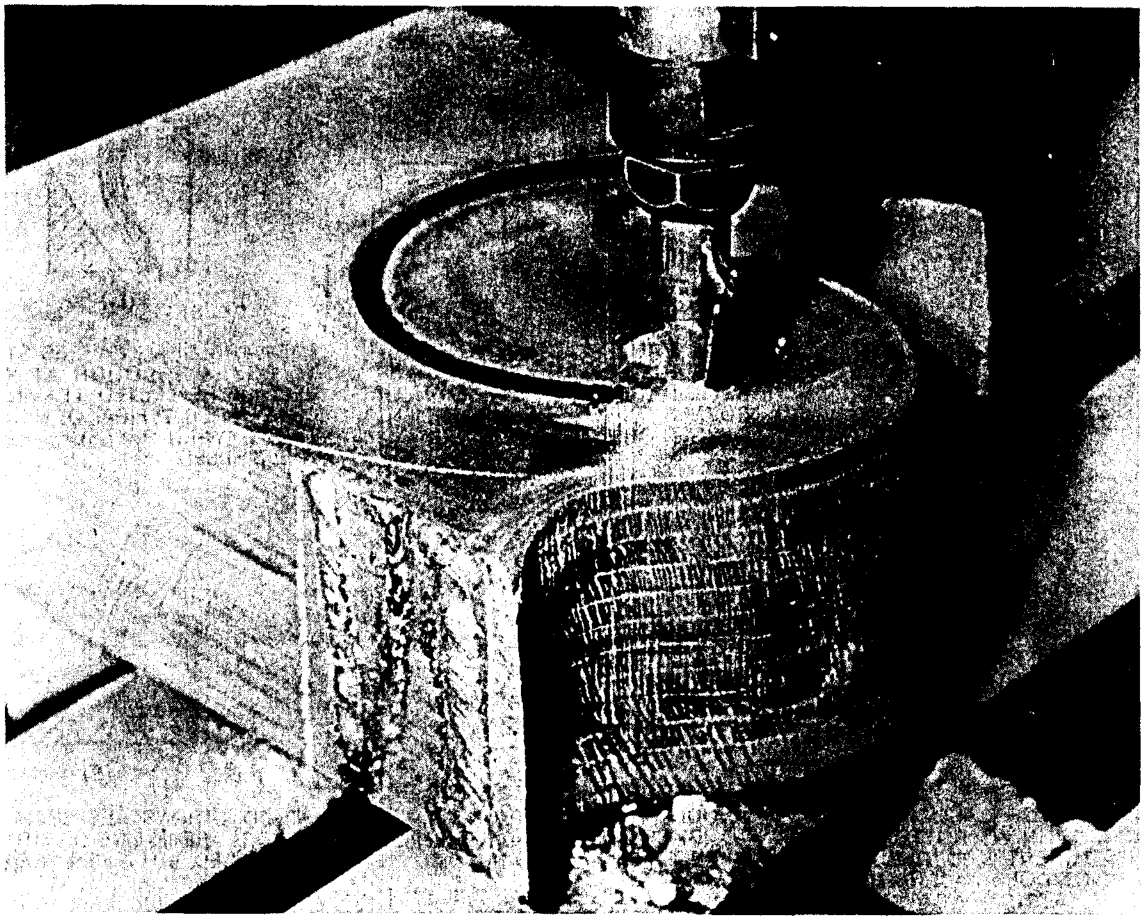


Figure 14.13–Typical Stack Cutting Operation With the Plates Clamped by Vertical Welds

angle is above 15°, the heat transferred from the preheat flames to the plate decreases rapidly as the bevel angle increases. Considerably greater preheat input is required, particularly for thicknesses up to 1 in. (25 mm). Best results are obtained by positioning the tip very close to the work and using high oxygen to fuel ratios. For bevels greater than 30°, or on heavy plate, special bevel tips will provide the additional preheat capacity required.

An auxiliary torch (with only preheat flames burning) mounted perpendicular to the work or an auxiliary adapter, which divides the preheat and applies a portion of it at right angles to the work, may be used to obtain faster beveling speeds. Either method actually consumes less total preheat gas than a single angled tip.

The best quality of cut face is usually not obtained at the highest cutting speed. The cut face finish can usually be improved by operating at lower speeds. When speed is reduced to obtain improved surface finish, the preheat flames should be decreased to prevent excessive meltdown of the top edge of the faces.

Figures 14.15, 14.16, and 14.17 illustrate the torch positions to cut the three basic beveled edges. In each case, torch position spacings A and B are governed by plate thickness, tip size, and speed of cutting. The cutting torches are positioned at spacings that are practical without interrupting the cutting action of any of the three cutting oxygen streams. When the lengths of A or B or both are too great, the cutting action of the trailing torch does not span the kerf of the leading torch. This causes the oxygen stream to be deflected into the kerf of the leading torch, and it gouges the cut face. This produces a rough surface and usually a light slag adhering to the underside of the prepared edge.

The positioning of the torches in a lateral direction for multibevel cutting is usually accomplished by trial and error. However, this can be costly and result in lengthy reworking or possible scrap. A simple machined template, which is typical of the desired edge geometry, is quite useful for torch alignment. A kerf-centering device is attached to each cutting tip, as shown in Figure 14.18. The torches

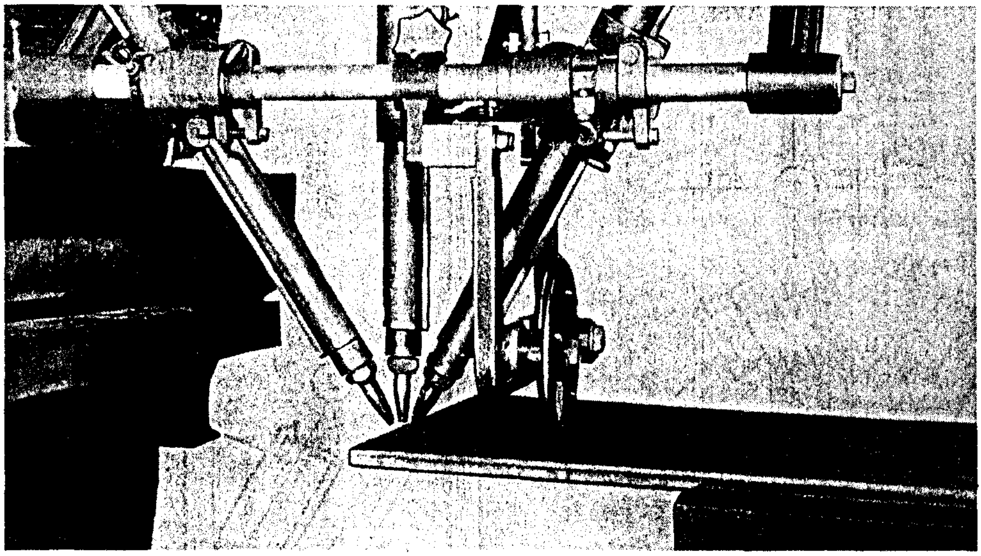


Figure 14.14—Mechanized Cutting Arrangement for Beveling a Plate Edge

are then properly angled and adjusted to the edge template. The multiple torch cutting head is now ready to duplicate the template profile.

To obtain close dimensional tolerance when preparing plate edges, precise torch-conveying equipment is necessary. For reproducibility, accuracy, and maximum efficiency, large gantry and rail-type cutting machines are used. Such apparatus may be classified in the same category as a machine tool. A plate is placed on a flat cutting table between the rails of a three-gantry type cutting machine, as shown in Figure 14.19. The machine can prepare all four edges of the plate without repositioning it. It can also cut the plate into smaller segments at the same time.

Gouging. Gouging of steel plate using the OFC processes is usually limited to steel plate thicknesses up to 1 in. (25 mm). The process is frequently used on the underside of a welded joint to remove defects that are in the original root pass. OFC gouging is also frequently used to remove defective weld joints or cracks when repairing previously fabricated metal.

The gouging process usually requires a special gouging tip with extra-heavy preheat capacity and a central oxygen orifice that causes a high level of turbulence in the oxygen stream. This turbulence causes a wide flow of oxygen that can be controlled by the operator to achieve the desired width and depth of gouge. Other factors used to determine the shape of the gouge are speed, tip angle, pressure, amount of preheat, and tip size. One of the significant advantages of oxyfuel gouging is that no additional equipment other than that already used in the OFC process is required.

UNDERWATER CUTTING

UNDERWATER CUTTING IS used for salvage work and for cutting below the water line on piers, dry docks, and ships. The two methods most widely used are oxyfuel gas cutting and oxygen arc cutting.

The technique for underwater cutting with OFC is not materially different from that used in cutting steel in open air. An underwater OFC torch embodies the same features as a standard OFC torch with the additional feature of supplying its own ambient atmosphere. In the underwater cutting torch, fuel and oxygen are mixed together and and burned to produce the preheat flame. Cutting oxygen is provided through the tip to sever the steel. In addition, the torch provides an air bubble around the cutting tip. The air bubble is maintained by a flow of compressed air around the tip, as shown in Figure 14.20. The air shield stabilizes the preheat flame and at the same time displaces the water from the cutting area.

The underwater cutting torch has connections for three hoses to supply compressed air, fuel gas, and oxygen. A combination shield and spacer device is attached at the cutting end of the torch. The adjustable shield controls the formation of the air bubble. The shield is adjusted so that the preheat flame is positioned at the correct distance from the work. The feature is essential for underwater work because of poor visibility and reduced operator mobility caused by cumbersome diving suits. Slots in the shield allow the burned gases to escape. A short torch is used to reduce the reaction force produced by the compressed air and cutting oxygen pushing against the surrounding water.

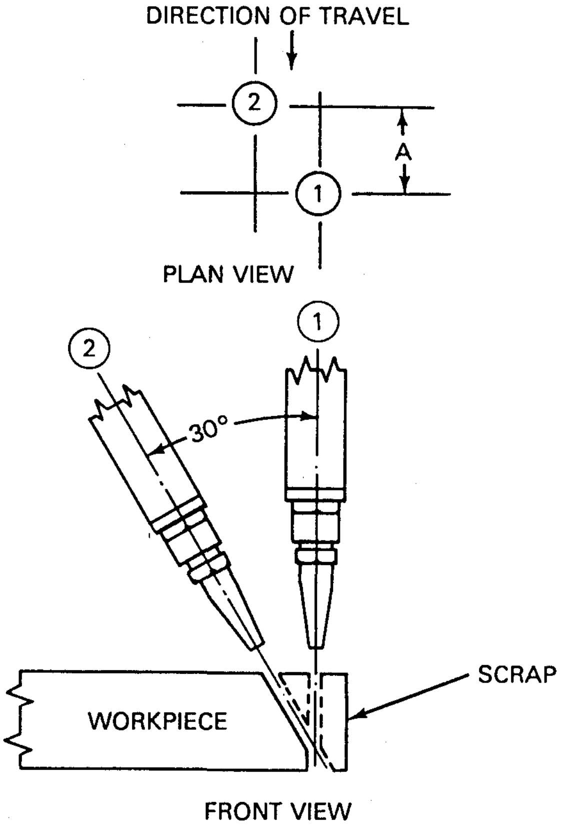


Figure 14.15–Cutting a Single Bevel Edge Preparation With a Root Face

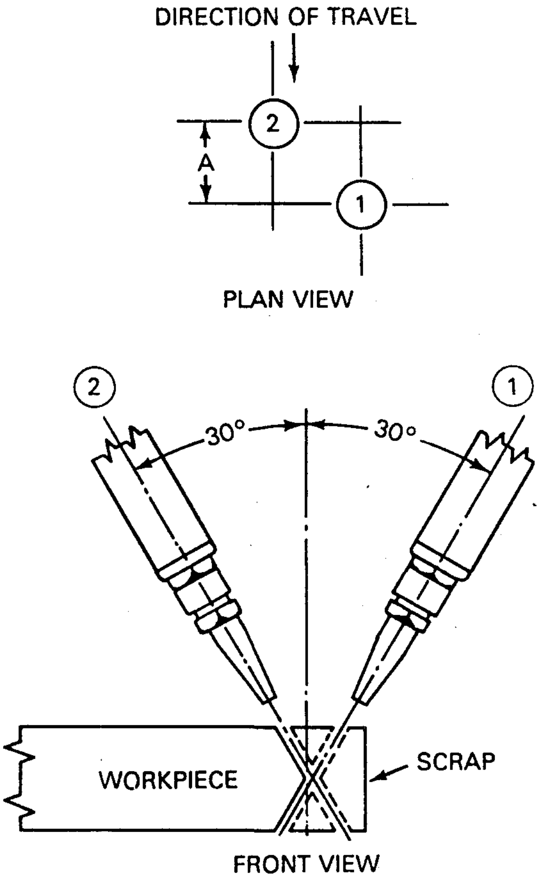


Figure 14.16–Cutting a Double Bevel Edge Preparation With No Root Face

As the depth at which the cutting is being done increases, the gas pressures must be increased to overcome both the added water pressure and the frictional losses in the longer hoses. Approximately 1/2 psi (3.5 kPa) for each 12 in. (300 mm) of depth must be added to the basic gas pressure requirements used in air for the thickness being cut.

MPS, propylene, and hydrogen are the best all-purpose preheat gases, because they can be used at any depths to which divers can descend and perform satisfactorily. Acetylene must not be used at depths greater than approximately 20 ft (6 m), because its maximum safe operating pressure is 15 psi (100 kPa) gage.

The oxyfuel gas cutting torch experiences no great difficulty underwater in severing steel plate in thicknesses from 1/2 in. (13 mm) to approximately 4 in. (101 mm). Under 1/2 in. (13 mm) thickness, the constant quenching effect of the surrounding water lowers the efficiency of preheating. This requires much larger preheating flames and preheat gas flows. Cutting oxygen orifice size is considerably larger for underwater cutting than for cutting in air. A special apparatus for lighting the preheat flames under water is also needed.

Some manufacturers have developed a spacing sleeve to be used for underwater cutting with a standard cutting torch. This device clamps over the cutting tip and provides a guide for the proper tip-to-work distance. A source of compressed air is not required for this unit.

The recommendations of the manufacturer should be followed for setting up and operating underwater OFC equipment.

QUALITY OF CUTTING

ACCEPTABLE QUALITY OF OFC depends on the job requirements. Salvage operations and severing members for scrap do not require high-quality cutting. Oxygen cutting is used to rapidly complete the operations with little regard to the quality of the cut surfaces.

When the cut materials are used in fabrications with no other processing of the cut surfaces, the quality of the sur-

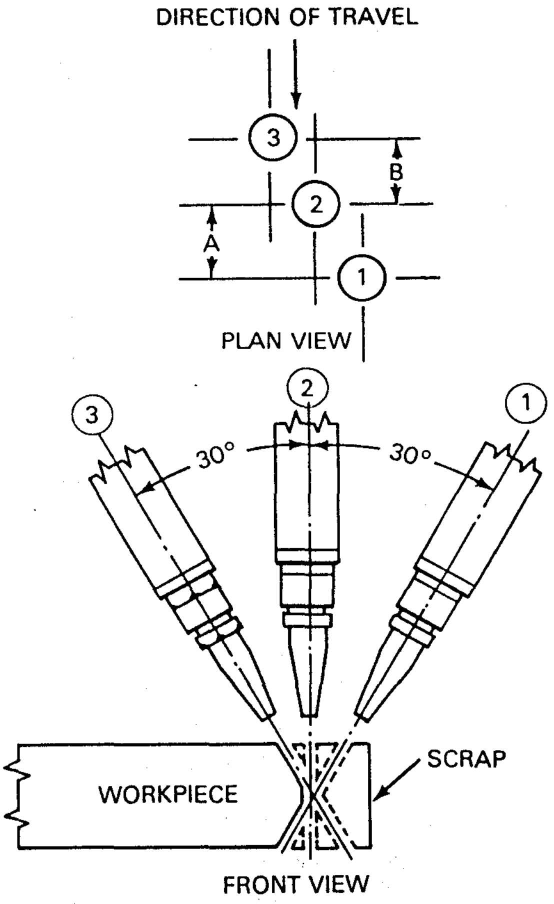


Figure 14.17–Cutting a Double Bevel Edge Preparation With a Root Face

faces may be significant. Cutting quality may include such things as:

(1) Proper angle of the cut surface with adjacent surfaces
(2) Flatness of the surface
(3) Sharpness of the cut preheat edge
(4) Dimensional tolerances of the cut shape
(5) Adherence of tenacious slag
(6) Cut surface defects, such as cracks and pockets

Close control of these items is generally confined to machine OFC. Good control of torch position, initiation of the cut, travel speed, and template stability are required for high-quality cutting. Also, consistent maintenance and cleanliness of the equipment is needed.

With the proper equipment in good condition, a well-trained operator, and reasonably clean and well-supported work, shapes can be cut to tolerances of 1/32 to 1/16 in. (0.8 to 1.6 mm) from material not more than 2 in. (51 mm) thick. Correct cutting tip, preheat flame adjustment, cutting oxygen pressure and flow, and travel speed must be used.

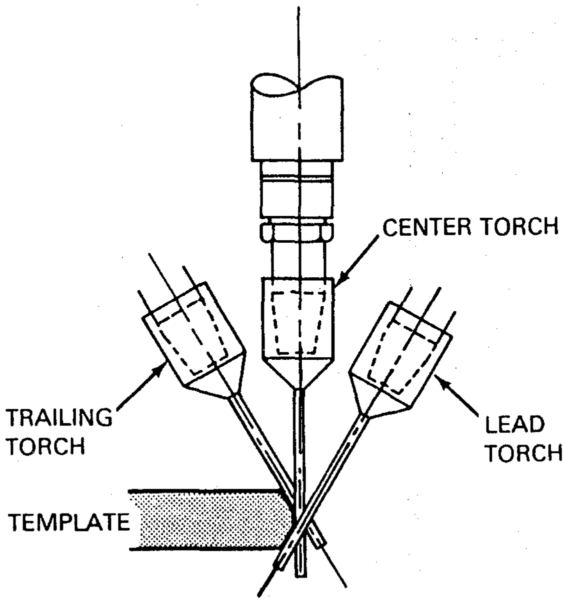


Figure 14.18–Kerf Centering and Bevel Angle Setting Method

Regardless of operating conditions, drag lines are inherent to oxygen cutting. They are the lines that appear on the cut surface, shown in Figure 14.21, resulting from the way that the iron oxidizes in the kerf. Light drag lines on the cut surface are not considered detrimental. The amount of drag is important. If it is too great, the corner at the end of the cut may not be completely severed and the part will not drop.

Cut surface quality is dependent on many variables, the most significant being the following:

(1) Type of steel
(2) Thickness of the material
(3) Quality of steel (freedom from segregations, inclusions, etc.)
(4) Condition of the steel surface
(5) Intensity of the preheat flames and the preheat oxy-fuel gas ratio
(6) Size and shape of the cutting oxygen orifice
(7) Purity of the cutting oxygen
(8) Cutting oxygen flow rate
(9) Cleanliness and flatness of the exit end of the nozzle
(10) Cutting speed

For any given cut, the variables listed should be evaluated so that the required quality of cut may be obtained

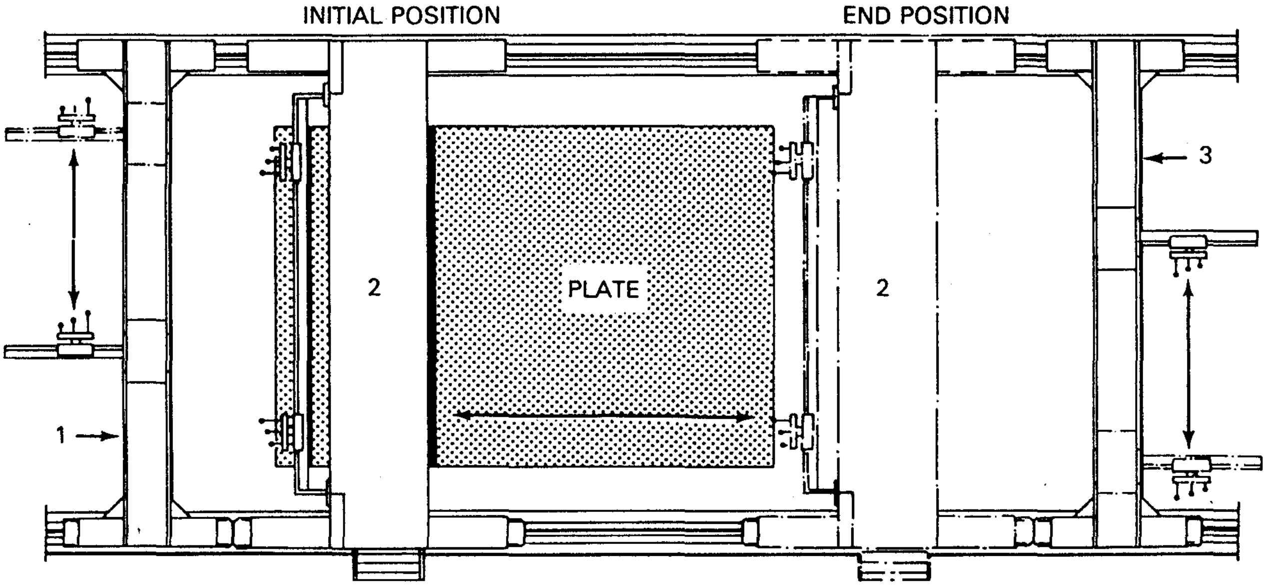


Figure 14.19—Plan View of a Three-Gantry Cutting Machine

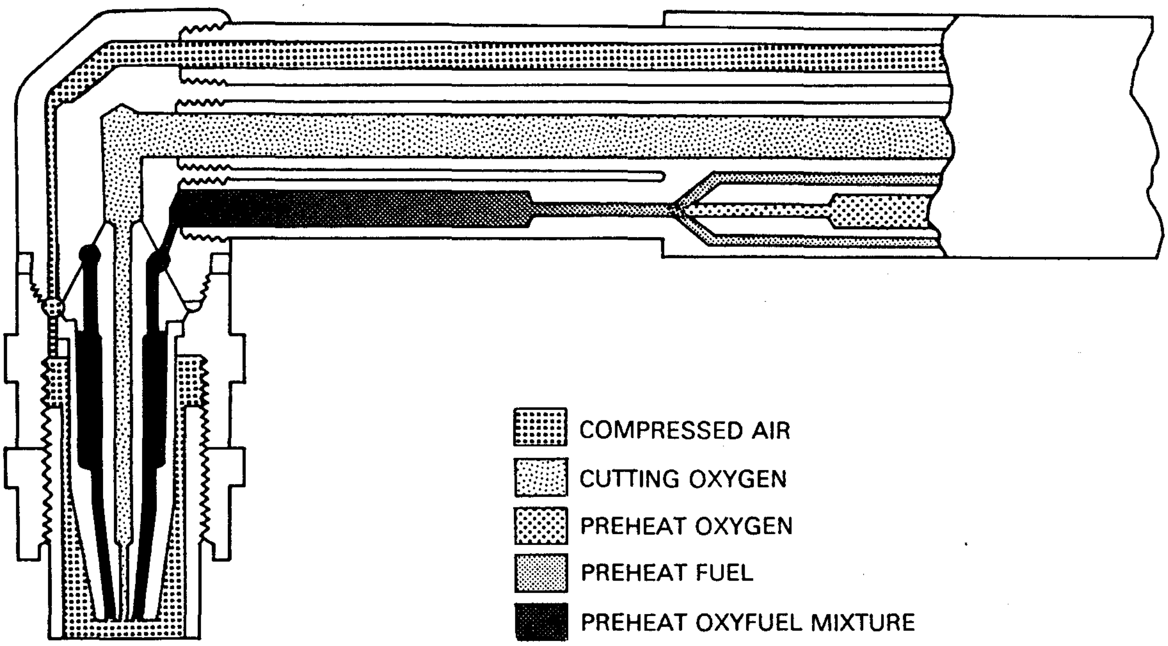


Figure 14.20—Basic Design of an Underwater Oxyfuel Gas Cutting Torch

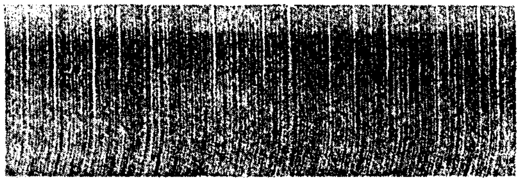


Figure 14.21–Drag Lines on the Kerf Wall Resulting From Oxygen Cutting

with the minimum aggregate cost in oxygen, fuel gas, labor, and overhead. Figures 14.22 and 14.23 show typical edge conditions resulting from variations in the cutting procedure for material of uniform type and thickness.

Dimensional tolerance and surface roughness must be considered together when judging the quality of a cut, because they are somewhat dependent on each other. Most specifications include dimensional tolerances. These include straightness of edge, squareness of edge, and permissible variation in plate width. All of these are primarily a function of the cutting equipment and its mechanical operation. When the torch is held rigidly and advanced at a constant speed, as in machine OFC, dimensional tolerances can be maintained within reasonable limits. The degree of longitudinal precision of a machine cut depends primarily on such factors as the condition of the equipment, trueness of guide rails, clearances in the operating mechanism, and the uniformity of speed control of the drive unit. In addition to equipment, dimensional accuracy is dependent on the control of thermal expansion of the material being cut. Lack of dimensional tolerance may re-

Figure 14.22–Typical Edge Conditions Resulting From Oxyfuel Gas Cutting Operations: (1) Good Cut in 1 in. (25 mm) Plate - the Edge is Square, and the Drag Lines are Essentially Vertical and Not Too Pronounced; (2) Preheat Flames Were Too Small for This Cut, and the Cutting Speed Was Too Slow, Causing Bad Gouging at the Bottom; (3) Preheating Flames Were Too Long, With the Result That the Top Surface Melted Over, the Cut Edge is Irregular, and There is an Excessive Amount of Adhering Slag; (4) Oxygen Pressure Was Too Low, With the Result That the Top Edge Melted Over Because of the Slow Cutting Speed; (5) Oxygen Pressure Was Too High and the Nozzle Size Too Small, With the Result That Control of the Cut Was Lost

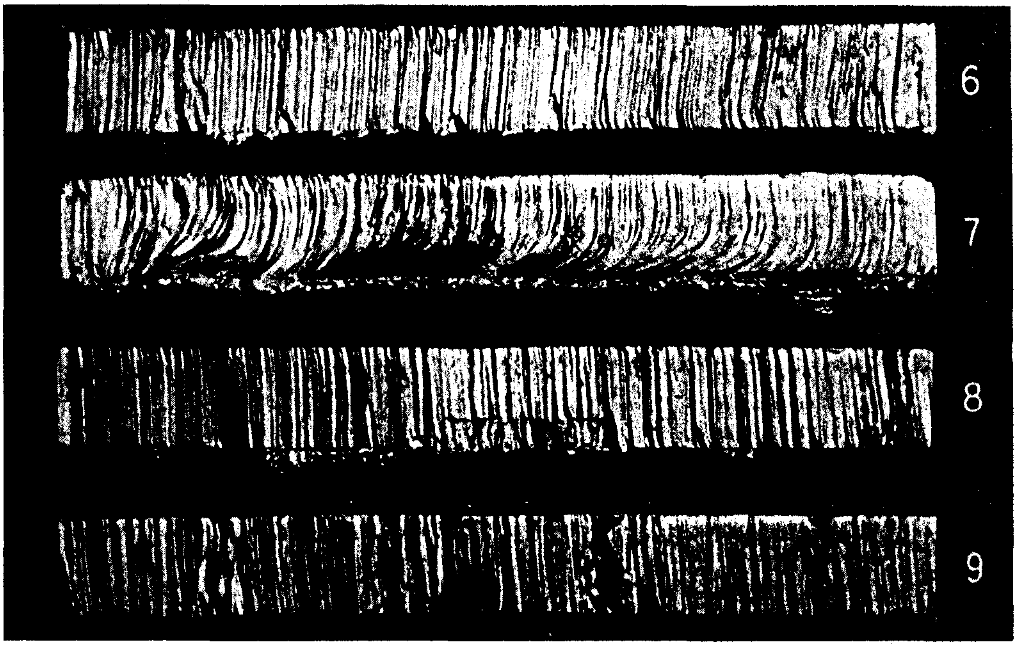


Figure 14.23–Typical Edge Conditions Resulting From Oxyfuel Gas Cutting Operations: (6) Cutting Speed Was Too Slow, With the Result That the Irregularities of the Drag Lines are Emphasized; (7) Cutting Speed Was Too Fast, With the Result That There is a Pronounced Break in the Dragline, and the Cut Edge is Irregular; (8) Torch Travel Was Unsteady, With the Result That the Cut Edge is Wavy and Irregular; (9) Cut was Lost and Not Carefully Restarted, Causing Bad Gouges at the Restarting Point

sult from buckling of the material (thin plate or sheet), warpage resulting from the heat being applied to one edge, or shifting of the material while it is being cut.

The OFC operation should be planned carefully to minimize the effect of the variables on dimensional accuracy. For instance, when trimming opposite edges of a plate, warpage will be minimized if both cuts are made simultaneously in the same direction. Distortion can often be controlled when cutting irregular shapes from plates by inserting wedges in the kerf following the cutting torch, to limit movement of the metal from thermal expansion and contraction. In cutting openings in the middle of a plate, distortion may be limited by making a series of unconnected cuts. The section is left attached to the plate in a number of places until cutting is almost completed, then connecting locations are finally cut though. The intermittent cutting will reduce cut quality somewhat.

Thin material is often stack cut to eliminate warping and buckling. Another technique is to cut the thin plate while it is partially submerged in water to remove the heat.

MATERIALS CUT

FOR MOST STEEL cutting, standard oxygen cutting equipment is satisfactory. For high alloy and stainless steel cutting, it may be necessary to use a special OFC process, such as flux injection or powder cutting, or one of the arc cutting processes. The cutting process and type of operation (manual or mechanized) selected depend on the material that is being cut, production requirements, and the ultimate use of the product.

CARBON AND LOW ALLOY STEELS

CARBON STEELS ARE readily cut by the OFC process. Low carbon steels are cut without difficulty using standard procedures. Typical data for cutting low carbon steel, using commonly available fuel gases, are shown in Table 14.2. The gas flow rates and cutting speeds listed are to be considered as guides for determining more precise settings for a particular job. When a new material is being cut, a few trial cuts should be made to obtain the most efficient operating conditions.

It should be noted that the tables end at 12 in. (300 mm), which is the maximum thickness normally encountered for shape cutting in production shops. The division has been made arbitrarily. The cutting of steel plate over approximately 12 in. (300 mm) thick is considered heavy cutting. The characteristics of heavy cutting are discussed later.

Effects Of Alloying Elements

ALLOYING ELEMENTS HAVE two possible effects on the oxygen cutting of steel. They may make the steel more difficult to cut, or they may give rise to hardened or heat-checked cut surfaces,or both. The effects of alloying elements are roughly evaluated in Table 14.4.

A large quantity of heat energy is liberated in the kerf when steel is cut with an oxygen jet. Much of this energy is transferred to the sides of the kerf, where it raises the temperature of the steel adjacent to the kerf above its critical temperature. Since the torch is moving forward, the source of heat quickly moves on. The mass of cold metal near the kerf acts as a quenching medium, rapidly cooling the hot steel. This quenching action may harden the cut surfaces of high carbon and alloy steels.

The depth of the heat-affected zone depends on the carbon and alloy contents, on the thickness of the base metal, and the cutting speed employed. Hardening of the heat-affected zones of steels containing up to 0.25 percent carbon is not critical in the thicknesses usually cut. Higher carbon steels and some alloy steels are hardened to a degree that the thickness may become critical.

Typical depths of the heat-affected zones in oxygen cut steel are shown in Table 14.5. For most applications of oxygen cutting, the affected metal need not be removed. However, if it is removed, removal should be by mechanical means.

Preheating and Postheating

THE MATERIAL BEING cut may be preheated to provide desired mechanical and metallurgical characteristics or to improve the cutting operation.

Preheating the work can accomplish several useful purposes:

(1) It can increase the efficiency of the cutting operation by permitting higher travel speed. Higher travel speed will reduce the total amount of oxygen and fuel gas required to make the cut.

(2) It will reduce the temperature gradient in the steel during the cutting operation. This in turn, will reduce or give more favorable distribution to thermally induced stresses and prevent the formation of quenching or cooling cracks. Distortion will also be reduced.

Table 14.4
Effect of Alloying Elements on Resistance of Steel to Oxygen Cutting

Element	Effect of Element on Oxygen Cutting
Carbon	Steels up to 0.25% carbon can be cut without difficulty. Higher carbon steels should be preheated to prevent hardening and cracking. Graphite and cementite (Fe_3C) are detrimental, but cast irons containing 4% carbon can be cut by special techniques.
Manganese	Steels with about 14% manganese and 1.5% carbon are difficult to cut and should be preheated for best results.
Silicon	Silicon, in amounts usually present, has no effect. Transformer irons containing as much as 4% silicon are being cut. Silicon steel containing large amounts of carbon and manganese must be carefully preheated and postannealed to avoid air hardening and possible surface fissures.
Chromium	Steels with up to 5% chromium are cut without much difficulty when the surface is clean. Higher chromium steels, such as 10% chromium steels, require special techniques (see the section Oxidation Resistant Steels), and the cuts are rough when the usual oxyacetylene cutting process is used. In general, carburizing preheat flames are desirable when cutting this type of steel. The flux injection and iron powder cutting processes enable cuts to be readily made in the common straight chromium irons and steels as well as in stainless steel.
Nickel	Steels containing up to 3% nickel may be cut by the normal oxygen cutting processes; up to about 7% nickel content, cuts are very satisfactory. Cuts of excellent quality may be made in the common stainless steels (18-8 to about 35-15 as the upper limit) by the flux injection or iron powder cutting processes.
Molybdenum	This element affects cutting about the same as chromium. Aircraft quality chrome-molybdenum steel offers no difficulties. High molybdenum-tungsten steels, however, may be cut only by special techniques.
Tungsten	The usual alloys with up to 14% tungsten may be cut very readily, but cutting is difficult with a higher percentage of tungsten. The limit seems to be about 20% tungsten.
Copper	In amounts up to about 2%, copper has no effect.
Aluminum	Unless present in large amounts (on the order of 10%), the effect of aluminum is not appreciable.
Phosphorus	This element has no effect in amounts usually tolerated in steel.
Sulfur	Small amounts, such as are present in steels, have no effect. With higher percentages of sulfur, the rate of cutting is reduced and sulfur dioxide fumes are noticeable.
Vanadium	In the amounts usually found in steels, this alloy may improve rather than interfere with cutting.

Table 14.5
Approximate Depths of Heat-Affected Zones in Oxygen Cut Steels*

Thickness		Depth			
		Low Carbon Steels		High Carbon Steels	
in.	mm	in.	mm	in.	mm
Under 1/2	Under 13	Under 1/32	Under 0.8	1/32	0.8
1/2	13	1/32	0.8	1/32 to 1/16	0.8 to 1.6
6	152	1/8	3.2	1/8 to 1/4	3.2 to 6.4

* The depth of the fully hardened zone is considerably less than the depth of the heat-affected zone.

(3) It may prevent hardening the cut surface by reducing the cooling rate.

(4) It will decrease migration of carbon toward the cut face by lowering the temperature gradient in the metal adjacent to the cut.

The temperatures used for preheating generally range from 200 to 1300°F (90 to 700°C) depending upon the part size and the type of steel to be cut. The majority of carbon and alloy steels can be cut with the steel heated to the 400 to 600°F (200 to 315°C) temperature range. The higher the preheat temperature, the more rapid is the reaction of the oxygen with the iron. This permits higher cutting speeds.

It is essential that the preheat temperature be fairly uniform through the section in the areas to be cut. If the metal near the surfaces is at a lower temperature than the interior metal, the oxidation reaction will proceed faster in the interior. Large pockets may form in the interior and either produce unsatisfactory cut surfaces or cause slag entrapment that may interrupt the cutting action. If the material is preheated in a furnace, cutting should be started as soon as possible after the material is removed from the furnace, to take advantage of the heat in the plate.

If furnace capacity is not available for preheating the entire piece, local preheating in the vicinity of the cut will be of some benefit. For light cutting, preheating may be accomplished by passing the cutting torch preheating flames slowly over the line of the cut until the desired preheat temperature is reached. Another method which may give better results is to preheat with a multiflame heating torch mounted ahead of the cutting torch.

To reduce thermally induced internal stresses in the cut parts, they may be annealed, normalized, or stress relieved. Using a proper postheat treatment, most metallurgical changes caused by the cutting heat can be eliminated. If a furnace of the required size is not available for postheat treatment, the cut surface may be reheated to the proper temperature by the use of multiple flame heating torches.

CAST IRON

THE HIGH CARBON content of cast iron resists the ordinary OFC techniques used for cutting low carbon steels. Cast irons contain some of the carbon in the form of graphite flakes or nodules, and some in the form of iron carbide (Fe_3C). Both of these constituents hinder the oxidation of the iron. High-quality production cuts typical of steels cannot be obtained with cast iron. Most cutting is done to remove risers, gates, or defects, to repair or alter castings, or for scrapping.

Cast iron can usually be manually cut by using an oscillating motion of the cutting torch, as shown in Figure 14.24. The degree of motion depends on the section thickness and carbon content. Torch oscillation helps the oxygen jet to blow the slag and molten metal out of the kerf. The kerf is normally wide and rough.

A larger cutting tip and higher gas flow than those used for steel are required for cutting the same thickness of cast iron. A hot carburizing flame is used, with the streamer extending to the far side of the cast iron section. The excess fuel gas helps to maintain preheat in the kerf as it burns.

Cast iron is also sometimes cut by using the special techniques for cutting oxidation resistant steels. These are waster plate cutting, metal powder cutting (POC), and chemical flux cutting (FOC), which are described later in this chapter. Cast iron is readily cut using the air carbon arc cutting (CAC-A) and plasma arc cutting (PAC) processes, and these are frequently preferred over the OFC processes.

OXIDATION RESISTANT STEELS

THE ABSENCE OF alloying materials in pure iron permits the oxidation reaction to proceed rapidly. As the quantity and number of alloying elements in iron increase, the oxidation rate decreases from that of pure iron. Cutting becomes more difficult.

Oxidation of the iron in any alloy steel liberates a considerable amount of heat. The iron oxides produced have melting points near the melting point of iron. However, the oxides of many of the alloying elements in steels, such as aluminum and chromium, have melting points higher than those of iron oxides. These high- melting oxides, which are refractory in nature, may shield the material in the kerf so that fresh iron is not continuously exposed to the cutting oxygen stream. Thus, the speed of cutting de-

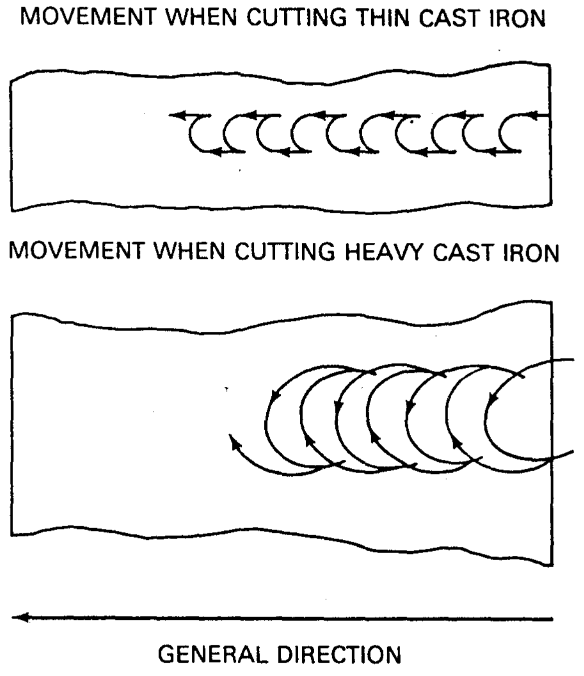


Figure 14.24—Typical Cutting Torch Manipulation for Cutting Cast Iron

creases as the amount of refractory oxide-forming elements in the iron increases.

For ferrous metals with high alloy content, such as stainless steel, the use of plasma arc cutting (PAC) and in some cases air carbon arc cutting (CAC-A) should be considered. If these options are not available or practical, then variations of OFC must be used.

There are several variations for oxygen cutting of oxidation resistant steels, which are also applicable to cast irons. The important ones are the following:

(1) Torch oscillation
(2) Waster plate
(3) Wire feed
(4) Powder cutting
(5) Flux cutting

When the above methods are used to cut oxidation resistant metals, the quality of the cut surface is somewhat impaired. Scale and slag may adhere to the cut faces. Pickup of carbon or iron, or both, usually appears on the cut surfaces of stainless steels and nickel alloy steels. This may affect the corrosion resistance and magnetic properties of the metal. If the corrosion resistance or magnetic properties of the material are important, approximately 1/8 in. (3 mm) of metal should be machined from the cut edges.

Torch Oscillation

THIS TECHNIQUE IS the one described previously for cast iron cutting. Low alloy content stainless steels up to 4 in. (100 mm) thick can sometimes be severed with a standard cutting torch and oscillation. The entire thickness of the starting edge must be preheated to a bright red color before the cut is started. This technique should be combined with some of the other cutting methods listed.

Waster Plate

ONE METHOD OF cutting oxidation resistant steels is to clamp a low carbon steel "waster" plate on the upper surface of the material to be cut. The cut is started in the low carbon steel material. The heat liberated by the oxidation of the low carbon steel provides additional heat at the cutting face to sustain the oxidation reaction. The iron oxide from the low carbon steel helps to wash away the refractory oxides from stainless steel. The thickness of the waster plate must be in proportion to the thickness of the material being cut. Several undesirable features of this method are the cost of the waster plate material, the additional setup time, the slow cutting speeds, and the rough quality of the cut.

Wire Feed

WITH THE APPROPRIATE equipment, a small diameter low carbon steel wire is fed continuously into the torch preheat flames, ahead of the cut. The end of the wire should melt rapidly into the surface of the alloy steel plate. The effect of the wire addition on the cutting action is the same as that of the waster plate. The deposition rate of the low carbon steel wire must be adequate to maintain the oxygen cutting action. It should be determined by trial cuts. The thickness of the alloy plate and the cutting speed are also factors that must be considered in the process. A motor-driven wire feeder and wire guide, mounted on the cutting torch, are needed as accessory equipment.

Metal Powder Cutting

THE METAL POWDER cutting process (POC) is a technique for supplying an OFC torch with a stream of iron-rich powdered material. The powdered material accelerates and propagates the oxidation reaction and also the melting and spalling action of hard-to-cut materials. The powder is directed into the kerf through either the cutting tip or single or multiple jets external to the tip. When the first method is used, gas-conveyed powder is introduced into the kerf by special orifices in the cutting tip. When the powder is introduced externally, the gas conveying the powder imparts sufficient velocity to the powder particles to carry them through the preheat envelope into the cutting oxygen stream. Their short time in the preheat envelope is sufficient to produce the desired reaction in the cutting zone.

Some of the powders react chemically with the refractory oxides produced in the kerf and increase their fluidity. The resultant molten slags are washed out of the reaction zone by the oxygen jet. Fresh metal surfaces are continuously exposed to the oxygen jet and powder. Iron powder and mixtures of metallic powders, such as iron and aluminum, are used.

Cutting of oxidation resistant steels by the powder method can be done at approximately the same speeds as oxygen cutting of carbon steel of equivalent thickness. The cutting oxygen flow must be slightly higher with the powder process.

Powder Cutting Equipment

DISPENSERS OF POWDER for the POC process are of two general types. One type of dispenser is a vibratory device in which the quantity of powder dispensed from the hopper is governed by a vibrator. Desired amounts of powder can be obtained by adjusting the amplitude of vibration. The vibratory-type dispenser is generally used where uniform and accurate powder flow is required.

The other type of dispenser is a pneumatic device. In the bottom of a low pressure vessel there is an ejector or fluidizing unit. The powder-conveying gas is brought into the dispenser in a manner that fluidizes the powder. The powder flows uniformly into an ejector unit where it is picked up by a gas stream that serves as the transporting medium to the torch.

In addition to the fuel and oxygen hoses, another hose is used to convey the powder to the torch. A special, manual powder cutting torch mixes the oxygen and fuel gas and then discharges this mixture through a multiplicity of orifices in the cutting tip. The powder valve is an integral part of the torch. The cutting oxygen lever on the torch also opens the powder valve in proper sequence. The powder carried by the conveying gas is brought through a separate tube into a chamber forward of the preheat gas chamber in the torch head. The powder then enters a separate group of passages in a two-piece cutting tip. From there, it discharges at the mouth of the tip in a conical pattern. The powder emerges with sufficient velocity to pass through the burning preheat gas and surrounds the central cutting oxygen stream.

Flux Cutting

THIS PROCESS IS primarily intended for cutting stainless steels. The flux is designed to react with oxides of alloying elements, such as chromium and nickel, to produce compounds with melting points near those of iron oxides. A special apparatus is required to introduce the flux into the kerf. With a flux addition, stainless steels can be cut at a uniform linear speed without torch oscillation. Cutting speeds approaching those for equivalent thicknesses of carbon steel can be attained. The tip sizes will be larger, and the cutting oxygen flow will be somewhat greater than for the carbon steels.

Flux Cutting Equipment

TO USE THE flux process, a flux feed unit is required. The cutting oxygen passes through the feed unit, and so transports the flux to the torch. The flux is held in a dispenser designed to operate at normal cutting oxygen pressures. The flux is transported through a hose from a dispenser to a conventional three-hose cutting torch. A mixture of oxygen and flux flows from the cutting oxygen orifice of the torch tip. Special operating procedures are used to prevent buildup of flux in the cutting oxygen hose and the cutting torch.

OXYGEN LANCE CUTTING

DEFINITION AND DESCRIPTION

OXYGEN LANCE CUTTING (LOC) is an oxygen cutting process that uses oxygen supplied through a consumable steel pipe or lance. The preheat required to start the cutting is obtained by other means.

The earliest version of LOC used a plain black iron pipe as a lance, with oxygen flowing through it. An oxyfuel gas cutting or welding torch is used to heat the cutting end of the lance to a cherry red, and then the oxygen flow is started. The iron pipe burns in a self-sustaining, exothermic reaction, and the heating torch is removed. When the burning end of the lance is brought close to the workpiece, the work is melted by the heat of the flame.

The oxygen lancing operation is shown schematically in Figure 14.25.

An improved version of the lance involves a number of low carbon steel wires packed into the steel tube. This increases the cutting life and capability of the lance. Commercially available tubes are typically 10 1/2 ft (3.2 m) long and 0.625 in. (16 mm) in diameter.

LOC can be used to pierce virtually all materials. It has been used successfully on aluminum, cast iron, steel, and reinforced concrete.

Oxygen lancing of a 40 in. (1 m) diameter cast iron roll used in a paper mill is shown in Figure 14.26. Cutting oxygen was supplied at 80 to 120 psi (550 to 870 kPa). Holes pierced in the roll are shown in Figure 14.27. The variable

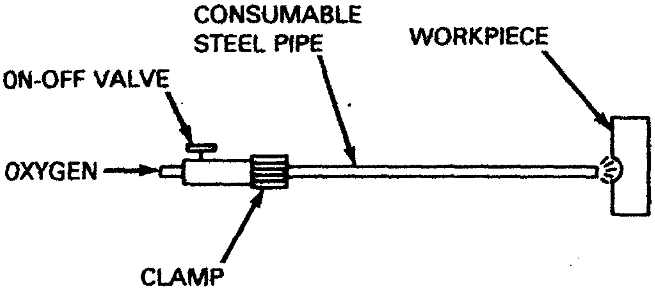


Figure 14.25–Schematic View of Oxygen Lance Cutting

angle bracket shown in Figure 14.27 was found to be helpful in guiding the lance.

A 2-1/2 in. diameter hole can be made in 24 in. of reinforced concrete at a rate of about 4 in./min. (100 mm/min.). This operation would use about 60 cu. ft (1.7 m^3) of oxygen.

The process has been used to open furnace tap holes and to remove solidified material from vessels, ladles, and molds. It can be used to cut refractory brick, mortar, and slag.

Figure 14.26–Severing a 40 in. (1 m) Diameter Cast Iron Roll by Multiple Hole Piercing Using an Oxygen Lance

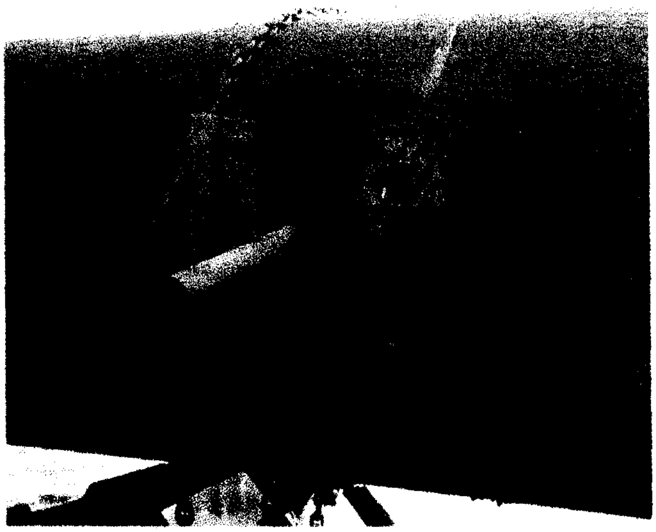


Figure 14.27–Holes Pierced in a Cast Iron Roll Using an Oxygen Lance

The LOC process can be used underwater. The lance must be lighted before it is placed underwater, but then piercing proceeds essentially as in air. The violent bubbling action produced restricts visibility.

ARC-STARTED OXYGEN LANCING

A VARIATION OF the oxygen lancing process uses an arc to start the iron-oxygen reaction. This equipment uses tubes typically 18 in. (45 cm) long and either 0.25 or 0.375 in. (6.4 or 9.5 mm) in diameter. A 12-volt battery can be used as a power source, with the cutting tube connected to one battery terminal and a copper striker plate connected to the other. To start the burning operation, the operator starts the oxygen flow and draws the steel tube across the copper plate at a 45° angle. Sparking at the copper plate will ignite the tube. The burning rod can then be used for cutting, piercing, or beveling steel. It can also be used to remove pins, rivets, and bolts.

SAFE PRACTICES

SAFE PRACTICES FOR the installation and operation of oxyfuel gas systems for welding and cutting are given in American National Standard Z49.1, latest edition. These practices and those recommended by the equipment manufacturer should always be followed by the person operating the equipment.

Fumes are a potential health hazard. When the process is used in an enclosed or semi-enclosed area, exhaust ventilation should be provided and the operator should be equipped with a respirator. Noise from the operation may exceed safe levels in some circumstances. When necessary, ear protection should be provided for the operator. Fire is a potential hazard and combustible materials should be cleared away from the cutting area for a distance of at least 35 ft (11 m).

Appropriate protective clothing and equipment for any cutting operation will vary with the nature and location of the work to be performed. Some or all of the following may be required:

(1) Tinted goggles or face shields with filter lens; the recommended filter lenses for various cutting operations are
  (a) Light cutting, up to 1 in. (25 mm) — shade 3 or 4
  (b) Medium cutting, 1 to 6 in. (25 to 150 mm) — shade 4 or 5
  (c) Heavy cutting, over 6 in. (150 mm) — shade 5 or 6
(2) Flame resistant gloves
(3) Safety glasses
(4) Flame resistant jackets, coats, hoods, aprons, etc.
  (a) Woolen clothing preferably, not cotton or synthetic materials
  (b) Sleeves, collars, and pockets kept buttoned
  (c) Cuffs eliminated
(5) Hard hats
(6) Leggings and spats
(7) Safety shoes
(8) Flame extinguishing protective equipment
(9) Supplemental breathing equipment
(10) Other safety equipment

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CHAPTER 15

ARC CUTTING AND GOUGING

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CHAPTER 15

ARC CUTTING AND GOUGING

INTRODUCTION

ARC CUTTING (AC) covers a group of thermal cutting processes that sever or remove metal by melting it with the heat of an arc between an electrode and the workpiece.

Thermal gouging is a thermal cutting process variation that removes metal by melting or burning the entire removed portion, to form a bevel or groove.

This definition covers a number of processes that are or have been used for cutting or gouging metals. This includes:

Plasma Arc Cutting	PAC
Air Carbon Arc Cutting	CAC-A
Shielded Metal Arc Cutting	SMAC
Gas Metal Arc Cutting	GMAC
Gas Tungsten Arc Cutting	GTAC
Oxygen Arc Cutting	AOC
Carbon Arc Cutting	CAC

Each of these processes offers the user certain advantages and disadvantages. When selecting a process, consideration must be given to costs relating to the volume of cutting, equipment requirements, and operator skill requirements. Plasma arc and air carbon arc cutting are addressed separately in this chapter due to their broad usage. The others are discussed in the final section of the chapter.

PLASMA ARC CUTTING

DESCRIPTION

THE PLASMA ARC cutting (PAC) process severs metal by using a constricted arc to melt a localized area of a workpiece, removing the molten material with a high-velocity jet of ionized gas issuing from the constricting orifice. The ionized gas is a plasma, hence the name of the process. Plasma arcs operate typically at temperatures of 18 000°-25 000°F (10 000°-14 000°C).

PAC was invented in the mid 1950's and became commercially successful shortly after its introduction to industry. The ability of the process to sever any electrically conductive material made it especially attractive for cutting nonferrous metals that could not be cut by the oxyfuel cutting (OFC) process. It was initially used for cutting stainless steel and aluminum. As the cutting process was developed, it was found that it had advantages over other cutting processes for cutting carbon steel as well as nonferrous metals. These advantages are summarized below.

When compared to mechanical cutting processes, the amount of force required to hold the workpiece in place and move the torch (or vice versa) is much lower with the "non-contact" plasma arc cutting process. Compared to OFC, the plasma cutting process operates at a much higher energy level, resulting in faster cutting speeds. In addition to its higher speed, PAC has the advantage of instant start-up without requiring preheat. Instantaneous starting is particularly advantageous for applications involving interrupted cutting, such as severing mesh.

There are notable limitations to PAC. When compared to most mechanical cutting means, PAC introduces hazards such as fire, electric shock, intense light, fumes and gases, and noise levels that may not be present with mechanical processes. It is also difficult to control PAC as precisely as some mechanical processes for close tolerance work. When compared to OFC, the PAC equipment tends to be more expensive, requires a fairly large amount of electric power, and introduces electrical shock hazards.

An arc plasma is a gas which has been heated by an arc to at least a partially ionized condition, enabling it to conduct an electric current. A plasma exists in any electric arc, but the term *plasma arc* is associated with torches which utilize a constricted arc. The principle feature which distinguishes plasma arc torches from other arc torches is that, for a given current and gas flow rate, the arc voltage is higher in the constricted arc torch.

The arc is constricted by passing it through an orifice downstream of the electrode. The basic terminology and the arrangement of the parts of a plasma cutting torch are shown in Figure 15.1. As plasma gas passes through the arc, it is heated rapidly to a high temperature, expands, and is accelerated as it passes through the constricting orifice toward the workpiece. The intensity and velocity of the plasma is determined by several variables including the type of gas, its pressure, the flow pattern, the electric current, the size and shape of the orifice, and the distance to the workpiece.

PAC circuitry is shown in Figure 15.2. The process operates on direct current, straight polarity. The orifice directs the super-heated plasma stream from the electrode toward the workpiece. When the arc melts the workpiece, the high-velocity jet blows away the molten metal to form the kerf or cut. The cutting arc attaches to or "transfers" to the workpiece, and is referred to as a *transferred arc.*

The different gases used for plasma arc cutting include nitrogen, argon, air, oxygen, and mixtures of nitrogen/hydrogen and argon/hydrogen.

PAC torches are available in various current ranges, generally categorized as low power [those operating at 30 amperes (A) or less], medium power level [30-100 (A)], and high power [from 100-1000 (A)]. Different power levels are appropriate for different applications, with the higher power levels being used for cutting thicker metal at higher speeds.

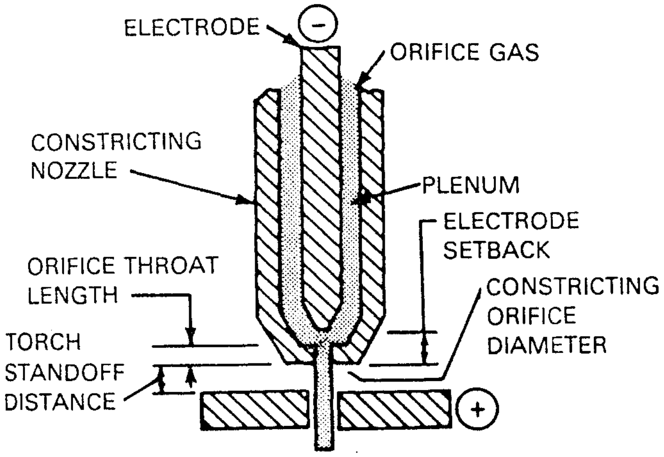


Figure 15.1–Plasma Arc Torch Terminology

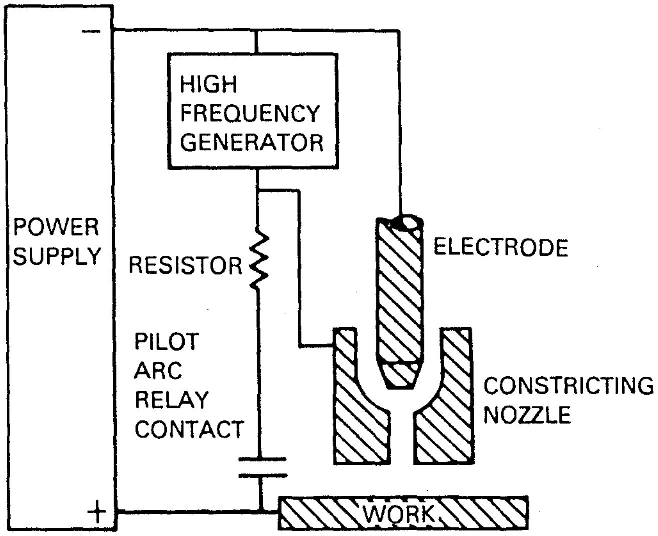


Figure 15.2–Basic Plasma Arc Cutting Circuitry

One of two starting methods is used to initiate the cutting arc: pilot arc starting or electrode (or tip) retract starting.

A pilot arc is an arc between the electrode and the torch tip. This arc is sometimes referred to as a *nontransferred arc* because it does not transfer or attach to the workpiece, as compared to the transferred arc which does. A pilot arc provides an electrically conductive path between the electrode in the torch and the workpiece so that the main cutting arc can be initiated.

The most common pilot arc starting technique is to strike a high-frequency spark between the electrode and the torch tip. A pilot arc is established across the resulting ionized path. When the torch is close enough to the workpiece so the plume or flame of the pilot arc touches the workpiece, an electrically conductive path from the electrode to the workpiece is established. The cutting arc will follow this path to the workpiece.

Retract starting torches have a moveable tip or electrode so that the tip and electrode can be momentarily shorted together and then separated or "retracted" to establish the cutting arc.

EQUIPMENT

Torches

THE PLASMA CUTTING process is used with either a handheld torch or a mechanically-mounted torch. There are several types and sizes of each, depending on the thickness of metal to be cut. Some torches can be dragged along in direct contact with the workpiece, while others require that a standoff be maintained between the tip of the torch and workpiece.

Mechanized torches can be mounted either on a tractor or on a computer-controlled cutting machine or robot. Usually a standoff is maintained between the torch tip and workpiece for best cut quality. The standoff distance must be maintained within fairly close tolerances to achieve uniform results. Some mechanized torches are equipped with an automatic standoff controlling device to maintain a fixed distance between the torch and workpiece. In other cases mechanical followers are used to accomplish this.

PAC torches operate at extremely high temperatures, and various parts of the torch must be considered to be consumable. The tip and electrode are the most vulnerable to wear during cutting, and cutting performance usually deteriorates as they wear. The timely replacement of consumable parts is required to achieve good quality cuts.

Modern plasma torches have self-aligning and self-adjusting consumable parts. As long as they are assembled in accordance with the manufacturer's instructions, the torch should require no further adjustment for proper operation.

Other torch parts such as shield cups, insulators, seals, etc. may also require periodic inspection and replacement if they are worn or damaged. Again, the manufacturer's instructions should be followed.

Power Supplies

PAC REQUIRES A constant-current or drooping volt-ampere characteristic, relatively high-voltage direct-current power supply. To achieve satisfactory arc starting performance, the open circuit voltage of the power supply is generally about twice the operating voltage of the torch. Operating voltages will range from 50 or 60 volts (V) to over 200 volts (V), so PAC power supplies will have open circuit voltages ranging from about 150 to over 400 volts.

There are several types of PAC power supplies, the simplest being the fixed output type which consists of a transformer and rectifier. The transformer of such a machine is wound with a "drooping" characteristic, so that the output voltage drops as the cutting current increases.

In some cases, several outputs are available from a single power supply through a switching arrangement. This switching arrangement can select between taps provided on the transformer or reactor of the power supply.

Variable output power supplies are also available. The most widely used units utilize a saturable reactor and current feedback circuit so that the output can be stabilized at the desired current level.

Other types of controls are available on plasma cutting power supplies, including electronic phase control and various types of "switch mode" power supplies. The switch mode power supplies utilize high-speed, high-current semiconductors to control the output. They can either regulate the output of a standard DC power supply, the so-called "chopper" power supply, or they can be incorporated in an inverter-type power supply. As new types of semiconductors become commercially available, it can be expected that improved versions of this type of power supply will appear. Switch mode supplies have the advantage of higher efficiency and smaller size, and are attractive for applications where portability and efficiency are important considerations.

Cutting Controls

PAC CONTROLS ARE relatively simple. Most manual torches are controlled by a trigger switch. This switch is pressed to start the cutting arc and released to stop the cut.

For mechanized cutting, starting and stopping the cutting arc can be manual by pushbutton or automatic by the motion controls of the system. Cutting controls can also sequence the entire operation, including varying the gas flow and power level if necessary.

Several interlocks are normally used with PAC systems. If the plasma torch is run without an adequate supply of gas, the torch may be damaged by internal arcing. For this reason, a gas-pressure switch is usually included in the circuit to ensure that adequate gas pressure is present before the torch can operate. This interlock will also shut down the torch in the event of a gas supply failure during cutting.

High-current torches are liquid cooled, and in this case an additional interlock is included in the coolant system. The interlock prevents operation of the torch without coolant flow and will shut the power supply off to prevent damage if coolant flow is interrupted during operation.

Motion Equipment

A VARIETY OF motion equipment is available for use with plasma cutting torches. This can range from straight-line tractors to numerically-controlled or direct computer-controlled machines with parts nesting capabilities, etc. Plasma cutting equipment can also be adapted to robotic actuators for cutting other than flat plates.

Environmental Controls

THE PLASMA CUTTING process is inherently a noisy and fume generating process. Several different devices and techniques are available to control and contain the hazards. One commonly used approach to reduce noise and fume emissions is to cut over a water table and surround the arc with a water shroud. This method requires a cutting table filled with water up to the work-supporting surface, a water shroud attachment to go around the torch, and a recirculating pump to draw water from the cutting table and pump it through the shroud. In this case, a relatively high (15 to 20 gpm [55 to 75 L/min]) water flow is used.

Another method, underwater plasma cutting, is also in common use. With this method, the working end of the torch and the plate to be cut are submerged under approximately 3 in. (75 mm) of water. While the torch is underwater but not cutting, a constant flow of compressed air is maintained through the torch to keep water out.

The primary requirements in water-table design are adequate strength for supporting the work, sufficient scrap capacity to hold the dross or slag resulting from cutting, procedure for removing the slag, and ability to maintain the water level in contact with the work. When the table is used for underwater cutting, it is necessary to provide a means of rapidly raising and lowering the water level. This can be accomplished by pumping the water in and out of a holding tank, or by displacing it with air in an enclosure under the surface of the water.

A cutting table for mechanized or hand plasma cutting is usually equipped with a down-draft exhaust system. This is vented to the outdoors in some cases, although fume removal or filtering devices may be required to meet air pollution regulations.

APPLICATIONS

THE FIRST COMMERCIAL application of plasma arc cutting was the mechanized cutting of manway holes on aluminum railroad tank cars. The process has since been used on a wide variety of aluminum applications. Table 15.1 shows typical conditions for mechanized cutting of aluminum plate.

Typical conditions for mechanized cutting of stainless steel plate are shown in Table 15.2.

Manual plasma arc cutting is widely used in automobile body repair for cutting high-strength low alloy steel. Instant starting and high travel speeds reduce heat input to the HSLA steel and help maintain its strength.

The chief application of mechanized plasma arc cutting to carbon steel is for thicknesses up to 1/2 in. (13 mm). The higher cost of plasma arc equipment compared to OFC equipment can be justified by its higher cutting speeds. Conditions for mechanized plasma arc cutting of carbon steel plate are given in Table 15.3.

The plasma process has been used for stack cutting of carbon steel, stainless steel, and aluminum. The plates to be stack cut should preferably be clamped together, but PAC can tolerate wider gaps between plates than OFC.

Table 15.1
Typical Conditions for Plasma Arc Cutting of Aluminum Alloys

Thickness		Speed		Orifice Diam*		Current	
in.	mm	in./min	mm/s	in.	mm	(dcsp), A	Power kW
1/4	6	300	127	1/8	3.2	300	60
1/2	13	200	86	1/8	3.2	250	50
1	25	90	38	5/32	4.0	400	80
2	51	20	9	5/32	4.0	400	80
3	76	15	6	3/16	4.8	450	90
4	102	12	5	3/16	4.8	450	90
6	152	8	3	1/4	6.4	750	170

* Plasma gas flow rates vary with orifice diameter and gas used from about 100 ft^3/h (47 L/min.) for a 1/8 in. (3.2 mm) orifice to about 250 ft^3/h (120 L/min.) for a 1/4 in. (6.4 mm) orifice. The gases used are nitrogen and argon with hydrogen additions from 0 to 35%. The equipment manufacturer should be consulted for each application.

Table 15.2
Typical Conditions for Plasma Arc Cutting of Stainless Steels

Thickness		Speed		Orifice Diam*		Current	
in.	mm	in./min	mm/s	in.	mm	(dcsp), A	Power kW
1/4	6	200	86	1/8	3.2	300	60
1/2	13	100	42	1/8	3.2	300	60
1	25	50	21	5/32	4.0	400	80
2	51	20	9	3/16	4.8	500	100
3	76	16	7	3/16	4.8	500	100
4	102	8	3	3/16	4.8	500	100

* Plasma gas flow rates vary with orifice diameter and gas used from about 100 ft^3/h (47 L/min.) for a 1/8 in. (3.2 mm) orifice to about 200 ft^3/h (94 L/min.) for a 3/16 in. (4.8 mm) orifice. The gases used are nitrogen and argon with hydrogen additions from 0 to 35%. The equipment manufacturer should be consulted for each application.

Table 15.3
Typical Conditions for Plasma Arc Cutting of Carbon Steel

Thickness		Speed		Orifice Diam*		Current	
in.	mm	in./min	mm/s	in.	mm	(dcsp), A	Power kW
1/4	6	200	86	1/8	3.2	275	55
1/2	13	100	42	1/8	3.2	275	55
1	25	50	21	5/32	4.0	425	85
2	51	25	11	3/16	4.8	550	110

* Plasma gas flow rates vary with orifice diameter and gas used from about 200 ft^3/h (94 L/min.) for a 1/8 in. (3.2 mm) orifice to about 300 ft^3/h (104 L/min.) for a 3/16 in. (4.8 mm) orifice. The gases used are usually compressed air, nitrogen with up to 10% hydrogen additions, or nitrogen with oxygen added downstream from the electrode (dual flow). The equipment manufacturer should be consulted for each application.

Plate and pipe edge beveling is done by using techniques similar to those for OFC. One to three PAC torches are used depending on the joint preparation required.

CUT QUALITY

FACTORS TO CONSIDER in evaluating the quality of a cut include surface smoothness, kerf width, kerf angle, dross adherence, and sharpness of the top edge. These factors are affected by the type of material being cut, the equipment being used, and the cutting conditions.

Plasma cuts in plates up to approximately 3 in. (75 mm) thick may have a surface smoothness very similar to that produced by oxyfuel gas cutting. Surface oxidation is almost nonexistent with mechanized equipment that uses water injection or water shielding. On thicker plates, low travel speeds produce a rougher surface and discoloration. On very thick stainless steel, 5 to 7 in. (125 to 180 mm) in thickness, the plasma arc process has little advantage over oxyfuel gas powder cutting.

Kerf widths of plasma arc cuts are 1-1/2 to 2 times the width of oxyfuel gas cuts in plates up to 2 in (50 mm) thick. For example, a typical kerf width in 1 in. (25 mm) stainless steel is approximately 3/16 in. (5 mm). Kerf width increases with plate thickness. A plasma cut in 7 in. (180 mm) stainless steel made at approximately 4 in./min. (3mm/s) has a kerf width of 1-1/8 in. (28 mm).

The plasma jet tends to remove more metal from the upper part of the kerf than from the lower part. This results in beveled cuts wider at the top than at the bottom. A typical included angle of a cut in 1 in. (25 mm) steel is four to six degrees. This bevel occurs on one side of the cut when orifice gas swirl is used. The bevel angle on both sides of the cut tends to increase with cutting speed.

Dross is the material that melts during cutting and adheres to the bottom edge of the cut face. With present mechanized equipment, dross-free cuts can be produced on aluminum and stainless steel up to approximately 3 in. (75 mm) thickness and on carbon steel up to approximately 1-1/2 in. (40 mm) thickness. With carbon steel, selection of speed and current are more critical. Dross is usually present on thick materials.

Top edge rounding will result when excessive power is used to cut a given plate thickness or when the torch standoff distance is too large. It may also occur in high-speed cutting of materials less than 1/4 in. (6 mm) thick.

METALLURGICAL EFFECTS

DURING PAC, THE material at the cut surface is heated to its melting temperature and ejected by the force of the plasma jet. This produces a heat-affected zone along the cut surface, as with fusion welding operations. The heat not only alters the structure of the metal in this zone but also introduces internal tensile stresses from the rapid expansion, upsetting, and contraction of the metal at the cut surface.

The depth to which the arc heat will penetrate the workpiece is inversely proportional to cutting speed. The heat-affected zone on the cut face of a 1 in. (25 mm) thick stainless steel plate severed at 50 in./min. (21 mm/s) is 0.003 to 0.005 in. (0.08 to 0.13 mm) deep. This measurement was determined from microscopic examination of the grain structure at the cut edge of a plate.

Because of the high cutting speed on stainless steel and the quenching effect of the base plate, the cut face passes through the critical 1200°F (650°C) temperature very rapidly. Thus, there is virtually no chance for chromium carbide to precipitate along the grain boundaries, so corrosion resistance is maintained. Measurements of the magnetic properties of Type 304 stainless steel made on base metal and on plasma arc cut samples indicate that magnetic permeability is unaffected by arc cutting.

Metallographic examination of cuts in aluminum plates indicates that the heat-affected zones in aluminum are deeper than those in stainless steel plate of the same thickness. This results from the higher thermal conductivity of aluminum. Microhardness surveys indicate that the heat effect penetrates about 3/16 in. (5 mm) into a 1 in. (25 mm) thick plate. Age hardenable aluminum alloys of the 2000 and 7000 series are crack-sensitive at the cut surface. Cracking appears to result when a grain boundary eutectic film melts and separates under stress. Machining to remove the cracks may be necessary on edges that will not be welded.

Hardening will occur in the heat-affected zone of a plasma arc cut in high carbon steel if the cooling rate is very high. The degree of hardening can be reduced by preheating the workpiece to reduce the cooling rate at the cut face.

Various metallurgical effects may occur when long, narrow, or tapered parts, or outside corners are cut. The heat generated during a preceding cut may reach and adversely affect the quality of a following cut.

PLASMA ARC GOUGING

Process Description

PLASMA ARC GOUGING is an adaptation of the plasma cutting process. For gouging, arc constriction is reduced, resulting in a lower arc stream velocity. The temperature of the arc and the velocity of the gas stream are used to melt and expel metal in a similar manner to other gouging processes. A major difference compared to other gouging processes is that the gouge is bright and clean, particularly on nonferrous material such as aluminum and stainless steel. Virtually no post-cleaning is required when the plasma gouged surface is to be welded. A plasma arc gouging operation on stainless steel plate is shown in Figure 15.3.

Equipment

THE BASIC EQUIPMENT for plasma gouging is the same as for plasma cutting. Most plasma cutting equipment can be used for plasma gouging providing that the volt-ampere output curve of the power source is steep enough and the voltage high enough to sustain the long arc used for plasma gouging.

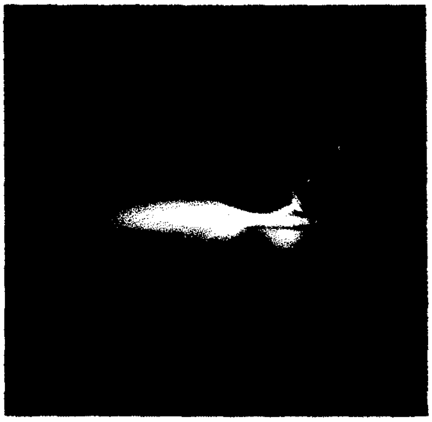


Figure 15.3—Plasma Arc Gouging of Stainless Steel Plate

The torch utilizes a gouging tip which is designed to give a softer, wider arc and proper stream velocity. The torch used is the same as a plasma cutting torch and may be either single- or dual-gas flow and air or water cooled.

Gases

THE RECOMMENDED PLASMA gas for all gouging is argon plus 35-40 percent hydrogen. The gas can be supplied from cylinders or prepared using a gas-mixing device. Helium may be substituted for the argon-hydrogen mixture, but the resulting gouge will be shallower. The secondary or cooling gas, when used, is argon, nitrogen, or air. Selection is based on brightness of gouge desired, fume generation, and cost.

Air is sometimes used for the plasma gas on air operating systems but is generally limited to carbon steel gouging. Most manual air cutting systems are limited to 100 A output and this restricts the size and speed of plasma gouging.

Operating Procedure

THE TECHNIQUE FOR plasma gouging is essentially the same as for other gouging methods. The torch is angled approximately 30 degrees from the horizontal. Gouge depth is determined by speed of travel. It is important not to attempt removal of too much metal in a single pass.

Applications

PLASMA GOUGING CAN be used on all metals. It is particularly effective on aluminum or stainless steel, where the gouges produced are clean and devoid of any carbon contamination.

SAFETY

THE POTENTIAL HAZARDS of plasma arc cutting and gouging are similar to those of most arc welding and cutting processes. The obvious hazards such as fires, burns, etc. that are related to the heat of the arc are discussed at the end of this section. Emphasis here is placed on the less obvious hazard categories of electrical shock, fume and gas generation, noise, and radiation.

The equipment should not be operated until the manufacturer's instructions have been read and understood. In addition, other potential physical hazards such as those due to the high-pressure gas and water systems must be considered.

Some cutting gas mixtures contain hydrogen. Inadvertent release of such gases can result in explosion and fire hazards. Do not operate equipment when gas leaks are suspected. The manufacturer should be contacted if there is a question about the equipment operation with certain gases.

Electrical

VOLTAGES USED IN plasma cutting equipment range from 150 to 400 V direct current. Electric shock can be fatal. The equipment must be properly grounded and connected as recommended by the manufacturer.

Emergency first aid should be available. Prompt, trained emergency response may reduce the extent of injury due to accidental electrical shock. Only trained personnel should be permitted to operate or maintain the equipment. In addition to the manufacturer's instructions, the following may be of assistance:

(1) ANSI C-2, the National Electrical Safety Code
(2) ANSI Z49.1, Safety in Welding and Cutting
(3) 29CFR1910, OSHA General Industry Standards and NFPA Standard 51B, Fire Prevention in the Use of Cutting and Welding Processes

Some additional safety items are listed below:

(1) Keep all electrical circuits dry. Moisture may provide an unexpected path for current flow. Equipment cabinets that contain water and gas lines as well as electrical circuits should be checked periodically for leaks.

(2) All electrical connections should be kept mechanically tight. Poor electrical connections can generate heat and start fires.

(3) High-voltage cable should be used. Make sure cables and wires are kept in good repair. Consult the manufacturer's instructions for proper cable and wire sizes.

(4) Do not touch live circuits. Keep equipment access doors closed.

(5) The risk of electrical shock is probably the greatest when replacing used torch parts. Operators must make sure that the primary power to the power supplies and the power to the control circuitry is disconnected when replacing torch parts.

(6) Operators and maintenance personnel should be aware that plasma arc cutting equipment, due to the higher voltages, presents a greater hazard than conventional welding equipment.

Fumes And Gases

PAC PRODUCES FUMES and gases which can harm your health. The composition and rate of generation of fumes and gases depend on many factors including arc current, cutting speed, material being cut, and gases used. The fume and gas by-products will usually consist of the oxides of the metal being cut, ozone, and oxides of nitrogen.

These fumes must be removed from the work area or eliminated at the source by using an exhaust system. Codes may require that the exhaust be filtered before being vented to the atmosphere.

Several alternative fume removal systems are available for mechanized cutting. One system consists of two parts, a cutting table which maintains a bed of water that contacts the bottom surface of the workpiece, and an annular nozzle which generates a water shroud around the arc.

Another system also uses a water bed, but instead of having the level of the water contact only the bottom surface of the workpiece, the water totally submerges the workpiece. This system is referred to as *underwater cutting* and does not require the use of a water-shroud nozzle. It does require that the level of the water be periodically lowered for loading and unloading the plate, positioning of the torch and plate, etc. Since the operator cannot see the plate during cutting with this system, it is intended for use with numerically controlled systems.

There is a possibility of hydrogen detonation beneath the workpiece when cutting aluminum or magnesium plate on a water table. The actual cause of such detonations is not fully understood, but they are believed to be due to hydrogen released by the interaction of molten aluminum or magnesium and water. The hydrogen can accumulate in pockets under the workpiece and ignite when the cutting arc is near the pocket. Before cutting aluminum or magnesium on a water table, the equipment manufacturer should be contacted for recommended practices.

Noise

THE AMOUNT OF noise generated by a PAC torch operated in the open depends primarily on the cutting current. A torch operating at 400 A typically generates approximately 100 dBA measured at about six feet. At 750 A the noise level is about 110 dBA. Much of the noise is in the frequency range of 5000—20 000 HZ. Such noise levels can damage your hearing. Hearing protection should be worn when the noise level exceeds specified limits. These values may vary locally and are specified by OSHA for most industrial environments.

The water-shroud technique described earlier is commonly used to reduce noise in mechanized cutting applications. The water effectively acts as a sound absorbing enclosure around the torch nozzle. The water directly below the plate keeps noise from coming through the kerf opening. Noise reduction is typically about 20 dBA. This reduction will usually be sufficient to bring the operation within OSHA limits.

The water-shroud technique should not be confused with water injection or water shielding, since neither of those process variations use sufficient water to significantly reduce noise.

Underwater PAC provides greater noise reduction than the water shroud because the nozzle end of the torch and the arc are totally submerged.

Radiation

THE PLASMA ARC emits intense visible and invisible (ultraviolet and infrared) radiation. In addition to potential harm to the eyes and skin, this radiation may produce ozone, oxides of nitrogen, or other toxic fumes in the surrounding atmosphere.

It is necessary to wear eye and skin protection when exposure to radiation is unavoidable. The recommended eye protection is shown in Table 15.4. The likelihood of radiation exposure may be reduced by the use of mechanical barriers such as walls and welding curtains. The water shroud will also act as a light-absorbing shield, especially when dye is added to the water in the table. When the use of dye is contemplated, contact the equipment manufacturer for information on the type and concentration to use. It is advisable to provide operator eye protection, even when using these dyes, because of the possibility of unexpected interruption of water flow through the water shroud.

Table 15.4
Recommended Eye Protection for Plasma Arc Cutting (Source: ANSI/AWS C5.2-83, Recommended Practices for Plasma Arc Cutting)

Cutting Current Amperes	Lens Shade Number
Up to 300	9
300–400	12
400–800	14

Underwater plasma cutting reduces the amount of radiation because of the greater depth of the water. Additional dye is not generally required.

AIR CARBON ARC CUTTING

DESCRIPTION

AIR CARBON ARC cutting (CAC-A) is a carbon arc cutting process variation that removes molten metal with a jet of air. In the air carbon arc cutting process, the intense heat of the arc between a carbon-graphite electrode and the workpiece melts a portion of the workpiece. Simultaneously, a jet of air of sufficient volume and velocity is passed through the arc to blow away the molten material. The exposed solid metal is then melted by the heat of arc, and the sequence continues. The process is used for severing and gouging.

Air carbon arc cutting does not depend on oxidation to maintain the cut, so it is capable of cutting metals that OFC will not cut. The process is used successfully on carbon steel, stainless steel, many copper alloys, and cast irons. The melting rate is a function of current. The metal removal rate is dependent upon the melting rate and the efficiency of the air jet in removing the molten metal. The air must be capable of blowing the molten metal out and clear of the arc region before it can resolidify. The process is shown schematically in Figure 15.4.

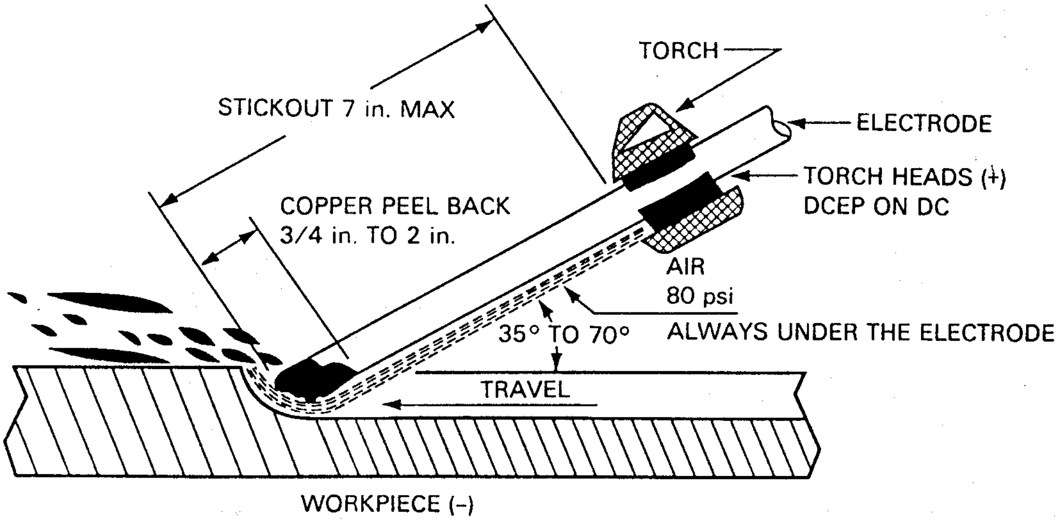


Figure 15.4–Typical Operating Procedures for Air Carbon Arc Gouging

Air carbon arc cutting was developed in the 1940's as an extension of carbon arc cutting (CAC). CAC must be done in the vertical or overhead position to permit gravity to remove the melted metal. The air CAC version enables the operator to remove metal in all positions.

First attempts at achieving an air-blast version of CAC involved two operators. The first held a CAC torch to melt the metal and the second directed a nozzle with an air jet at the molten pool. A single torch combining the air blast with the carbon electrode holder evolved shortly as the forerunner to today's improved CAC-A torches. The first commercial CAC-A torch was introduced in 1948.

EQUIPMENT AND CONSUMABLES

THE PROCESS REQUIRES an electrode holder, cutting electrodes, a power source, and an air supply. For mechanized cutting, a control and carriage are also required. Figure 15.5 shows a typical arrangement for CAC-A equipment.

Cutting Torches

MANUAL ELECTRODE HOLDERS for CAC-A are similar to conventional heavy-duty shielded metal arc welding holders, as shown in Figure 15.6. The electrode is held in a rotatable head which contains one or more air orifices, so that, regardless of the angle at which the electrode is set with respect to the cutting torch, the air jet remains in alignment with the electrode. A valve is provided for turning the air on and off. A cross section diagram of a manual CAC-A torch is shown in Figure 15.7.

Torches available range from light-duty farm and hobby shop sizes to extra heavy-duty foundry torches. Following is a guide for torch usage:

Light Duty. These are recommended for small shops, farms, and maintenance operations with limited air supply. Maximum current is about 450 amps dc.

General Purpose. These torches are for general purpose applications in shipyards, fabrication shops, and general maintenance. Limited to a maximum of 1000 amps.

Heavy Duty. These torches are for general foundry work, padwashing, and cutoff. High amperage work in shipyards and fabrication shops. Limited to 1600 amps with air-cooled cables and 2000 amps with water-cooled cables.

Mechanized. Mechanized electrode holders are used for edge preparation and high production applications. They are used with 5/16 through 3/4 in. (8 through 19 mm) jointed carbons. Typical automatic CAC-A equipment is shown in Figure 15.8.

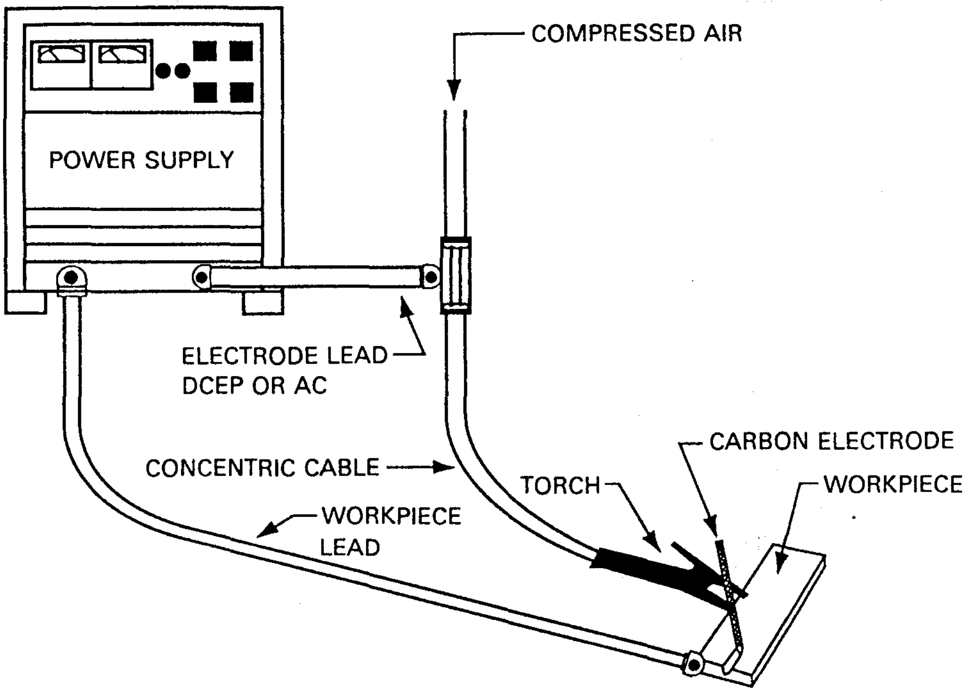
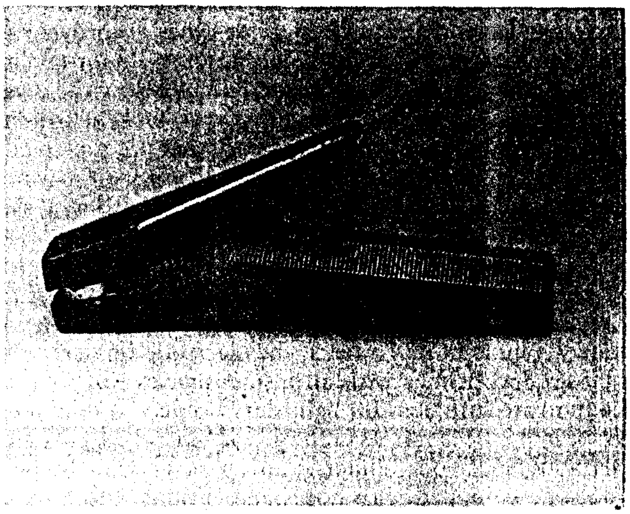
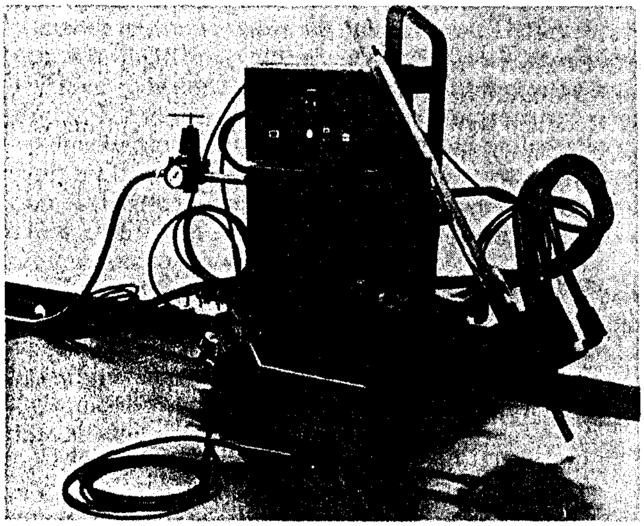


Figure 15.5–Typical Air Carbon Arc Gouging Equipment



15.6–Typical 400 Ampere Manual Air Carbon Arc Gouging Electrode Holder



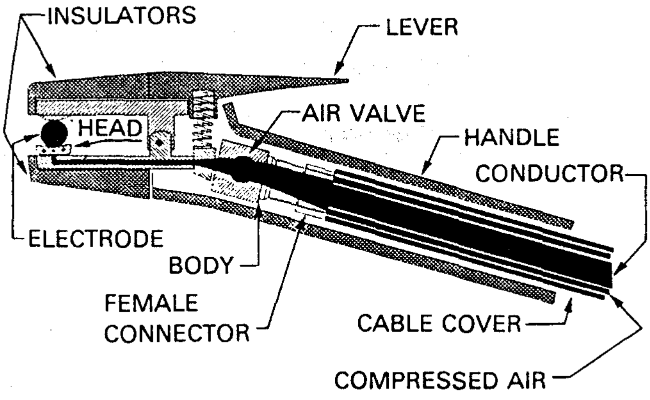
15.8–Typical Automatic CAC-A Equipment

Controls. There are three types of controls for mechanized CAC-A. All systems are capable of making grooves of consistent depth to a tolerance of ± 0.025 in. (0.6 mm). These units are used where high-quality, high-production gouges are desired. They are as follows:

(1) An amperage-controlled type which maintains the arc current by amperage signals through solid-state controls. This type of system controls the electrode feed speed, which maintains the preset amperage and can be operated with constant-voltage power sources only.

(2) A voltage-controlled type which maintains arc length by voltage signals through solid-state electronic controls. This type controls the arc length determined by the preset voltage, and can be used with constant-current power supplies only.

(3) A dual system which can be adjusted for either amperage control or voltage control by means of a selector switch located in the control.



15.7–Schematic Cross Section of an Air Carbon Arc Gouging Torch

Electrodes

THREE TYPES OF electrodes are used for CAC-A: dc copper coated, dc plain, and ac copper coated. Round electrodes are the shape most frequently used. Flat and half-round electrodes are available to produce rectangular grooves.

DC Copper Coated Electrodes. This type is most widely used because of its comparatively long electrode life, stable arc characteristics, and groove uniformity. These electrodes are made from a special mixture of carbon and graphite with a suitable binder. The mixture is extruded and baked to produce dense, homogeneous graphite electrodes of low electrical resistance. The electrodes are then coated with a controlled thickness of copper. These electrodes are available in diameters ranging from 1/8 to 3/4 in. (3.2 to 19.1mm).

Jointed electrodes are available for operation without stub loss. They are furnished with a female socket and a matching male tenon, and are available in diameters ranging from 5/16 to 1 in. (8 to 25.4 mm).

DC Plain Electrodes. Of limited use, these electrodes have no copper coating. During cutting they are consumed more rapidly than the coated electrodes. Plain electrodes are available in sizes ranging from 1/8 to 1 in. (3.2 to

25.4 mm) diameter, but their principal use is in diameters less than 3/8 in. (9.5 mm).

AC Coated Electrodes. These electrodes are made from a mixture of carbon and graphite with rare-earth materials added to provide arc stabilization for cutting with an alternating current. These electrodes, coated with a controlled thickness of copper, are available in diameters ranging from 3/16 to 1/2 in. (4.8 to 12.7 mm).

Power Sources

MOST STANDARD WELDING power sources can be used for the air carbon arc cutting process. The open circuit voltage should be sufficiently higher than the required arc voltage to allow for the voltage drop in the circuit. The arc voltages used in air carbon arc gouging and cutting range from 35 to 55 V. An open circuit voltage of at least 60 V is adequate. The actual arc voltage in air carbon arc gouging and cutting is governed to a large extent by the size of the electrode and the application. Recommended power sources are given in Table 15.5.

The power supply manufacturer should be consulted concerning its use for CAC-A because some types of power supplies that are satisfactory for use with welding cannot be used for CAC-A.

Electrical leads in the cutting circuit should be standard welding cables recommended for arc welding. Cable size is determined by the maximum cutting current that will be used.

Air Supply

COMPRESSED AIR WITH pressure ranging from 80 to 100 psi (560 to 700 kPa) is normally required for air carbon arc gouging. Light-duty electrode holders allow for gouging with as little as 40 psi (280 kPa) at 3 ft^3/min (8.5 liter/min). Compressed nitrogen or inert gas may be used where compressed air is not available. Oxygen should not be used in a CAC-A electrode holder.

The air stream must be of sufficient volume and velocity to properly remove the melted slag from the kerf. The orifices in air carbon arc torches are designed to provide an adequate air stream for gouging. However, poor-quality gouging may result if the air pressure falls below the minimum specified by the torch manufacturer, or if the volume of air is restricted by hoses or fittings that are too small.

While gouges or cuts made with insufficient air may not always look particularly bad, they may be loaded with slag and carbon deposits. For this reason, it is important that the air pressure be at or above the minimum specified for the type of torch being used. The inside diameter of all hoses and fittings must be large enough to allow the intended volume of air to reach the electrode holder.

Hoses and fittings with an inside diameter of 1/4 in. (6.4 mm) are sufficient for light-duty holders. A minimum I.D. of 3/8 in. (9.5 mm) is required for general purpose and heavy-duty electrode holders. Automatic gouging holders should be equipped with hoses and fittings with a minimum inside diameter of 1/2 in. (12.7 mm).

APPLICATIONS

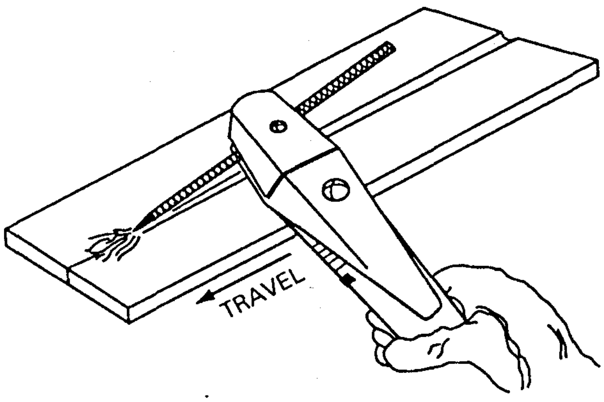
THE AIR CARBON arc cutting process can be used to sever and gouge carbon, low alloy, and stainless steels; cast iron; and alloys of aluminum, magnesium, copper, and nickel. Gouging may be used to prepare plate and pipe edges for welding. Two edges may be butted together and a U-groove gouged along the joint, as shown in Figure 15.9. The root of a weld may be gouged out to sound metal before completing the weld on the second side. Similarly, defective weld metal may be gouged out for repair. Another application is the removal of old surfacing material before a part is resurfaced.

OPERATING PROCEDURES

AIR CARBON ARC cutting electrodes are designed to operate with ac or dc, or both, depending on the material being cut. Table 15.6 gives the recommended electrodes and types of current for cutting several common alloys.

Table 15.5
Power Sources for Air Carbon Arc Cutting and Gouging

Type of Current	Type of Power Source	Remarks
dc	Constant current motorgenerator, rectifier, or resistor grid unit	Recommended for all electrode sizes.
dc	Constant potential motorgenerator or rectifier	Recommended for 6.4mm (1/4 in.) and larger diameter electrodes only. May cause carbon deposit with small electrodes. Not suitable for automatic torches with voltage control.
ac	Constant current transformer	Recommended for ac electrodes only.
ac or dc	Constant current	DC supplied from three phase transformer-rectifier supplies is satisfactory, but dc from single phase sources gives unsatisfactory arc characristics. AC output from ac/dc units is satisfactory provided ac electrodes are used.



15.9–Manual Air Carbon Arc Gouging Operation in the Flat Position

Current ranges for commonly used CAC-A electrodes are shown in Table 15.7. The actual current used for a given electrode size will depend on the operating conditions such as the material being cut, type of cut, cutting speed, cutting position, and required cut quality. Recommendations of the manufacturer should be followed for the operation and maintenance of the equipment and consumables.

Gouging

THE ELECTRODE SHOULD be gripped, as shown in Figure 15.4, so that a maximum of 7 in. (178 mm) extends from the cutting torch. For nonferrous materials, this extension should be reduced to 3 in. (76.5 mm).

The air jet should be turned on before striking the arc, and the cutting torch should be held as shown in Figure 15.9. The electrode slopes back from the direction of travel with the air jet behind the electrode. Under proper operating conditions, the air jet will sweep beneath the electrode end and remove all molten metal. The arc may be struck by lightly touching the electrode to the workpiece. The electrode should not be drawn back once the arc is struck. The gouging technique is different from that of arc welding because metal is removed instead of deposited. A short arc should be maintained by progressing in the direction of the cut fast enough to keep up with metal removal. The steadiness of progression controls the smoothness of the resulting cut surface.

When using jointed carbon electrodes, it is important to strike the arc with the open or blunt end of the electrode. The reason for this becomes apparent when the electrode has been almost completely consumed and is approaching the jointed section. If the arc had been struck on the tapered end of the electrode, the jointed section would consist of a tapered end surrounded by a loose red-hot sleeve of carbon. This hot sleeve tends to be ejected violently from the gouging arc and, similar to weld spatter, can cause burns or set fire to combustibles.

When the arc is struck with the open end of the electrode, and the electrode is consumed to the jointed section, the sleeve is part of the incoming electrode and is restrained from violent ejection.

When gouging a workpiece in the vertical position, gouging should be done downhill, to let gravity assist in removing the molten metal. Gouging in the horizontal position may be done either to the right or to the left, but always in the forehand direction.

In gouging to the left, the cutting torch should be held as shown in Figure 15.9. In gouging to the right, the cutting torch will be reversed to locate the air jet behind the electrode. When gouging overhead, the electrode and torch should be held at an angle that will prevent molten metal from falling on the operator.

Table 15.6
Electrode and Current Recommendations for Air Carbon Arc Cutting of Several Alloys

Alloy	Electrode Type	Current Type	Remarks
Carbon, low alloy, and stainless steels	dc	dcrp	
	ac	ac	Only 50% as efficient as dcrp
Cast irons	ac	dcsp	At middle of electrode current range
	ac	ac	
	dc	dcrp	At maximum current only
Copper alloys:			
copper 60% or less	dc	dcrp	At maximum current
copper over 60%	ac	ac	
Nickel alloys	ac	ac	
	ac	dcsp	
Magnesium alloys	dc	dcrp	Before welding, surface must be cleaned.
Aluminum alloys	dc	dcrp	Electrode extension should not exceed 4 in. (100 mm). Before welding, surface must be cleaned.

Table 15.7
Suggested Current Ranges for the Commonly Used CAC-A Electrode Types and Sizes

Electrode Diameter		DC Electrode with DCEP, A		AC Electrode with ac, A		AC Electrode with DCEN, A	
in.	mm	min	max	min	max	min	max
5/32	4.0	90	150	--	--	--	--
3/16	4.8	150	200	150	200	150	180
1/4	6.4	200	400	200	300	200	250
5/16	7.9	250	450	--	--	--	--
3/8	9.5	350	600	300	500	300	400
1/2	12.7	600	1000	400	600	400	500
5/8	15.9	800	1200	--	--	--	--
3/4	19.1	1200	1600	--	--	--	--
1	25.4	1800	2200	--	--	--	--

The depth of the groove produced is controlled by the travel speed. Slow travel speeds will produce a deep groove, while fast speeds will produce a shallow groove. Grooves up to 1 in. (25 mm) deep may be made. However, the deeper the groove, the more experience required on the part of the operator.

The width of the groove is determined by the size of the electrode used and is usually about 1/8 in. (3.2 mm) wider than the electrode diameter. A wider groove may be made by oscillating the electrode with a circular or weaving motion.

When gouging, a push angle of 35 degrees from the surface of the workpiece is used for most applications. A steady rest is recommended in gouging to ensure a smoothly gouged surface. This is particularly advantageous for use in the overhead position. Proper travel speed depends on the size of the electrode, type of base metal, cutting amperage, and air pressure. An indication of proper speed and good gouge quality is a smooth hissing sound in the arc.

Severing

IN GENERAL, THE technique for severing is the same as for gouging, except that the electrode is held at a steeper angle—between 70 and 80 degrees to the surface of the workpiece.

For cutting thick nonferrous metals, the electrode should be held perpendicular to the workpiece surface, with the air jet in front of the electrode in the direction of travel. With the electrode in this position, the metal may then be severed by moving the arc up and down through the metal with a sawing motion.

Washing

IN USING THE air carbon arc cutting process for removing metal from large areas, such as the removal of surfacing metal or riser pads on castings, the proper position of the electrode is shown in Figure 15.10. The electrode should be oscillated from side-to-side while pushing forward at the depth desired. In pad washing operations, an angle of 15 to 70 degrees to the workpiece surface is used. The 15 degree angle is used for light finishing passes, while the steeper angles allow deeper rough cutting to be done with greater ease.

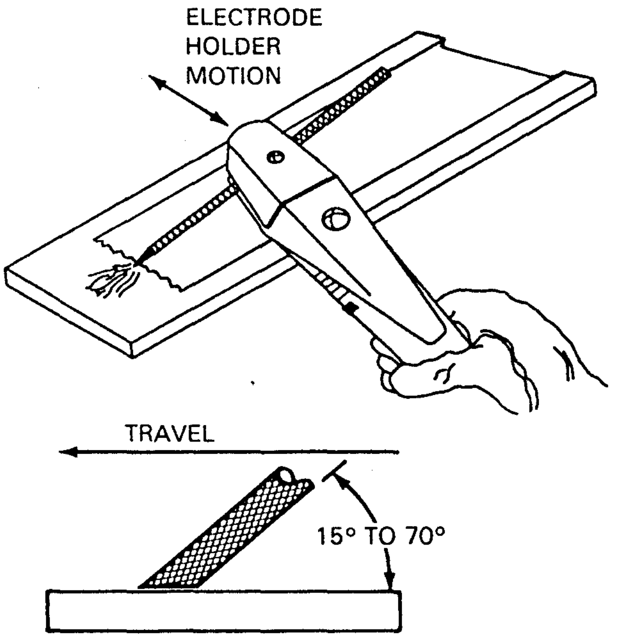
Cutting torches with fixed angle heads that hold the electrode at the correct angle are particularly well-suited for this application. With other types of torches, care should be taken to keep the air behind the electrode. The steadiness of the cutter's hand determines the smoothness of the surface produced.

METALLURGICAL EFFECTS

TO AVOID DIFFICULTIES with carburized metal, users of the air carbon arc cutting process should be aware of the metallurgical events that occur during gouging and cutting. When the carbon electrode is positive (reverse polarity), the current flow carries ionized carbon atoms from the electrode to the base metal. The free carbon particles are rapidly absorbed by the melted base metal. Since this absorption cannot be avoided, it is important that all carburized molten metal be removed from the kerf, preferably by the air jet.

When the air carbon arc cutting process is used under improper conditions, the carburized molten metal left on the surface can usually be recognized by its dull, gray-black color. This is in contrast to the bright blue color of the properly made groove. Inadequate air flow may leave small pools of carburized metal in the bottom of the groove. Irregular electrode travel, particularly in a manual operation, will produce ripples in the groove wall that tend to trap the carburized metal. Finally, an improper electrode angle may cause small beads of carburized metal to remain along the edge of the groove.

The effect of carburized metal that remains in the kerf or groove through a subsequent welding operation depends on



15.10–Pad Washing Techique with Air Carbon Arc Electrode Holder. Electrode to Work Angle is 15° to 70° with the Steeper Angle Being Used on Cast Iron

many factors including the amount of carburized metal present, the welding process to be employed, the kind of base metal, and the weld quality required. Although it may seem that filler metal deposited during welding would dissolve small pools or beads of carburized metal, experience with steel base metals shows that traces of metal containing approximately 1 percent carbon may remain along the weld bond line. Carbon pickup in the weld metal becomes significant with demands for increasing weld strength and toughness. Increased carbon content can decrease weld toughness, especially in quenched and tempered steels.

There is no evidence that the copper from copper-coated electrodes is transferred to the cut surface in the base metal.

Carburized metal on the cut surface may be removed by grinding, but it is much more efficient to conduct air carbon arc gouging and cutting properly within prescribed conditions, which will completely avoid the retention of undesirable metal.

Studies have been conducted on stainless steel to determine whether air carbon arc gouging, carried out in the prescribed manner, would adversely affect corrosion resistance. Corrosion rates typical for Type 304L stainless steel were obtained, and the studies showed no significant difference in the corrosion rates of welds prepared by CAC-A and those prepared by grinding. Had any appreciable carbon absorption occurred, the corrosion rates for welds prepared by CAC-A would have been significantly higher. However, surfaces prepared using CAC-A may be more susceptible to stress corrosion cracking depending on the service environment. If a question exists, the surfaces should be mechanically dressed following CAC-A.

Compared to oxyfuel gas cutting, CAC-A is a lower heat input process. For that reason, a workpiece gouged or cut by CAC-A will have less distortion than one prepared by OFC.

SAFE PRACTICES

THE GENERAL SUBJECTS of safety and safe practices in welding and thermal cutting processes, such as air carbon arc, are covered in ANSI Z49.1, *Safety in Welding and Cutting*, and NFPA 51B, *Fire Prevention in Use of Welding and Cutting Processes*. Air carbon arc cutters and their supervisors should be familiar with the practices discussed in these documents.

Furthermore, there are other potential hazard areas in arc cutting and gouging. Fumes, gases, noise, and radiant energy warrant additional consideration. Those areas associated with air carbon arc cutting and and gouging are discussed in this section.

Gases

THE MAJOR TOXIC gases which may be produced during arc cutting are ozone, nitrogen dioxide, and carbon monoxide. Phosgene gas could be present as a result of thermal or ultraviolet decomposition of chlorinated hydrocarbon cleaning agents or suspension agents used in some aerosol anti-spatter agents or paints. Degreasing or other operations involving chlorinated hydrocarbons should be located so that vapors from these operations are not exposed to radiation from the arc.

Ozone

THE ULTRAVIOLET LIGHT emitted from the arc acts on the oxygen in the surrounding atmosphere to produce ozone. The amount of ozone produced will depend upon the intensity of the ultraviolet energy, the humidity, the amount of screening afforded by the fume, and other factors. The ozone concentration will generally be increased with an increase in current and when aluminum is gouged. The concentration can be controlled by natural ventilation, local exhaust ventilation or by respiratory protective equipment described in ANSI Z49.1.

Nitrogen Dioxide

TESTS HAVE SHOWN that high concentrations of nitrogen dioxide are found only close to the arc. Natural ventilation reduces these concentrations quickly to safe levels in the cutter's breathing zone, so long as the cutter keeps his or her head out of the cutting fumes.

Metal Fumes

THE METAL FUMES generated by the CAC-A process can be controlled by natural ventilation, local exhaust ventilation, or by respiratory protective equipment described in ANSI Z49.1. The method of ventilation required to keep the level of toxic substances in the cutters breathing zone within acceptable concentrations is directly dependent upon a number of factors, among which are the metal being cut, the size of the work area and the degree of confinement or obstruction to normal air movement where the cutting is taking place. Each operation should be evaluated on an individual basis in order to determine what will be required.

Acceptable levels of toxic substances associated with cutting and designated as time-weighted average threshold limit values (TLVs) and ceiling values have been established by the American Conference of Governmental Hygienists and by the Occupational Safety and Health Administration. Compliance with these levels can be tested by sampling the atmosphere under the cutter's helmet or in the immediate vicinity of the cutter's breathing zone. Sampling should be in accordance with ANSI/AWS F1.1 *Method for Sampling Airborne Particulates Generated by Welding and Allied Processes.*

Fire Prevention

CAC-A REQUIRES SPECIAL fire prevention precautions because of the metal removal process. All combustibles within 35 ft (11 m) of the work area should be removed. Protection such as metal screens should be placed in the line of hot metal ejected by the compressed air stream if ample room for dissipation is not available.

Noise

NOISE FROM CAC-A gouging may exceed safe levels. When necessary, ear protection should be provided for the operator.

Radiant Energy

ANY PERSON WITHIN the immediate vicinity of the cutting arc should have adequate eye and skin protection from radiation produced by the cutting arc. The filter shade recommended for CAC-A is shade twelve. Leather or wool clothing that is dark in color is recommended to reduce reflection which could cause ultraviolet burns to the neck and face inside the helmet.

OTHER ARC CUTTING PROCESSES

THIS CONCLUDING SECTION of the chapter provides a brief explanation of five remaining processes. In general, these are not widely used because of economic considerations. However, the reader should be aware of them because they can be used when other processes are not available. Consult the supplementary reading list for more information.

SHIELDED METAL ARC CUTTING

Principles of Operation

SHIELDED METAL ARC cutting (SMAC) is an arc cutting process that uses a covered electrode. A constant-current power source operating on direct current straight polarity (dcen) is preferred. The principal function of the electrode covering in cutting is to serve as electrical insulation, permitting insertion of the electrode into the gap of the cut without short-circuiting the sides of the electrode, and to act as an arc stabilizer, thereby concentrating and intensifying the arc action. Effectiveness of this procedure in cutting heavy thicknesses is a function of manipulation of the electrode. E6010, E6012, and E6020 electrode types are usually employed, but cutting can be achieved using virtually any SMAW electrode. Electrodes with coverings specially made for cutting are also available.

Equipment

ALTHOUGH A DC constant welding machine is preferred for SMAC, an ac constant-current power source may also be used. For shielded metal arc cutting in air, heavy-duty electrode holders should be used with 3/16 in. diameter and larger electrodes. For SMAC under water, specially constructed, fully insulated electrode holders are mandatory. A straight polarity power source must be used to protect the holder and the metal parts of the diver's outfit from electrolytic corrosion.

Applications

SMAC HAS BEEN used for cutting risers and gates in nonferrous foundries and to cut nonferrous scrap for remelting. The workpiece should be positioned so that gravity assists in removing the molten metal. Generally, the process does not provide satisfactory edge preparation for welding without considerable cleanup by chipping or grinding.

OXYGEN ARC CUTTING

Principles of Operation

OXYGEN ARC CUTTING (AOC) is an oxygen cutting process that uses an arc between the workpiece and a consumable tubular electrode through which oxygen is directed to the workpiece. Mild steel is cut by using the arc to raise the temperature of the material to its kindling point in the presence of oxygen. The combustion reaction that occurs is self-sustaining, liberating sufficient heat to maintain the kindling temperature on all sides of the cut. The necessary preheat at the start of cutting is provided by the electric arc. A schematic illustration of the process is shown in Figure 15.11.

For oxidation-resistant metals, the cutting mechanism is more of a melting action. In these instances, the covering on the electrode provides a flux that helps the molten metal flow from the cut.

Metallurgical Effects

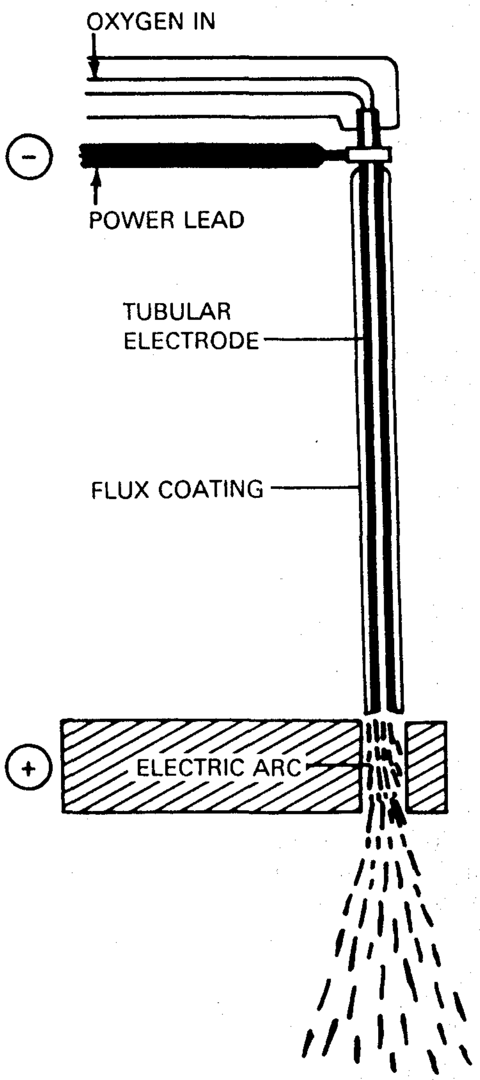
THE OXYGEN ARC method of cutting produces metallurgical effects in the heat-affected zone comparable to those that occur in shielded metal arc welding. The power input approaches that of shielded metal arc welding, but the heat penetration is generally not as deep in AOC because of the faster speed of travel. This produces a somewhat more pronounced quench effect. Metals that do not require a postheat treatment after welding may be severed by this process without detrimental effect. Grades of austenitic stainless steels that are sensitive to corrosion attack when subjected to shielded metal arc welding will be sensitized along the cut when severed by this process.

Oxygen arc cuts in cast iron and medium carbon, low alloy steels are apt to develop cracks on the face of the cut. The extent and frequency of cracking depend on the composition and hardenability of the steel.

Equipment

OXYGEN ARC CUTTING may be performed using either constant current ac or dc power sources of sufficient capacity. Direct current electrode negative is preferred for rapid cutting. The electrode holder used for oxygen-arc cutting is of special design; it must convey not only electric current to the electrode but also oxygen to the cut. This is accomplished by bringing oxygen to the electrode holder and passing it through the bore of the electrode into the arc.

For cutting in air, a fully insulated electrode holder is desirable. When used for underwater cutting, a fully insulated holder equipped with a suitable flash-back arrester is required.



15.11–Schematic of Oxygen–Arc Electrode in Operation

Tubular steel electrodes are available in 3/16 and 5/16 in. (5 to 8 mm) diameter sizes, 18 in. (46 cm) long, with bore diameter approximately 1/16 in. (1.6 mm). The extruded covering is comparable to a mild steel electrode of AWS classification E6013. Underwater electrodes are steel tubes with a waterproof coating.

Cutting Techniques

IN THE OXYGEN arc method of cutting, piercing, and gouging, the coating is kept in contact with the base metal at all times. The coating insulates the core from the work and automatically maintains the proper length of arc.

The start of cutting and piercing operations is the same. The tip of the electrode is tapped on the work at the desired location as though striking an arc for welding, and the arc is maintained for a moment while the oxygen valve is opened. Piercing action begins immediately and the electrode is pushed through the plate as the hole is formed. The coating insulates the electrode core from shorting against the sides of the hole.

In cutting, the electrode is dragged along the plate surface at the speed of travel dictated by the progress of the cut. The inclination of the electrode and the speed of motion are adjusted to give the most efficient and highest quality cut.

Template-guided cutting is common. The electrode is pressed against the template; it is insulated from it by the coating. For straight-line cuts, any straight edge may be clamped along the line to be cut. The cut is accomplished by holding the electrode against the guide and the plate at the same time. Circular openings in tanks have been cut by using the circumference of a suitably sized pipe as the guiding template.

When cutting in air (up to 3 in. of mild steel or 1/2 in. of certain nonferrous alloys), the technique is to drag the electrode along the intended line of cut while applying slight pressure. In underwater cutting, regardless of the thickness of the metal being cut, positive pressure must be maintained against the metal being cut.

Gouging is performed by striking the arc, releasing the oxygen stream, and inclining the rod until it is almost parallel to the plate surface and pointed away from the operator along the line of the prospective gouge. The arc and oxygen melt the plate surface, and the molten metal is blown away by the force of the oxygen jet.

Applications

OXYGEN ARC CUTTING electrodes were developed primarily for use in underwater cutting and were later applied to cutting in air. In either application, oxygen arc electrodes can cut ferrous and nonferrous metals in any position.

Oxygen arc cutting has been used effectively by foundries and scrap yards for cutting mild and low alloy steels, stainless steel, cast iron, and nonferrous metals in any position. The usefulness of the process varies with the thickness and composition of the material being cut.

The edges of metal cut by the oxygen arc torch are somewhat uneven and usually require a light surface preparation to make them suitable for welding.

GAS TUNGSTEN ARC CUTTING

Principles of Operation

GAS TUNGSTEN ARC cutting can be used to sever nonferrous metals and stainless steel in thicknesses up to 1/2 in. using standard gas tungsten arc welding equipment. Metals cut include aluminum, magnesium, copper, silicon-bronze, nickel, copper-nickel, and various types of stainless steels. This cutting process can be used either manually or mechanized. The same electric circuit is used for cutting as for welding. Higher current is required to cut a given thickness of plate than to weld it. An increased gas flow is also required to melt through and sever the plate.

In practice, a 5/32 in. (4 mm) diameter 2 percent thoriated tungsten electrode is extended approximately 1/4 in. (6.4 mm) beyond the end of a 3/8 in. (9.5 mm) diameter metallic or ceramic gas cup. A mixture of approximately 65 percent argon and 35 percent hydrogen is delivered to the torch at a flow rate of 60 cfh. Nitrogen can also be used, but the quality of the cut is not as good as that obtained with an argon-hydrogen mixture. Best cutting results are obtained using dcsp, but alternating current with superimposed high frequency has produced satisfactory cuts on material up to 1/4 in. (6.4 mm) thick.

Arc starting can be accomplished with either a high-frequency spark or by scratching the electrode on the workpiece. An electrode-to-work distance of 1/16 to 1/8 in. (1.6 to 3.2 mm) is used, but this is not a critical factor. As the torch is moved over the plate, a small section of the plate is melted by the heat of the arc and the molten metal is blown away by the gas stream to form the kerf. At the end of the cut, the torch is raised from the workpiece to break the arc.

One face of the cut is usually dross-free, with dross adhering to the side of the workpiece away from the work-lead. The cut quality on the dross-free side is usually acceptable while the other requires considerable cleanup.

Equipment

STANDARD GAS TUNGSTEN arc welding torches can be used for cutting. As shown in Table 15.8, cutting currents up to 600 A are used. Welding torches can be used for cutting at currents up to 175 percent of their nominal ratings because there is little reflected heat from the cutting operation. For example, a 300 A torch can be used for cutting with 500 A for short periods.

A constant-current dc power supply, either rectifier or motor generator, with a minimum open circuit voltage of 70 V is recommended for cutting. Cuts made with ac power have a plate thickness limitation of 1/4 in. (6.4 mm). The major difficulty encountered when using ac power is the loss of tungsten from the electrode at the high currents required.

GAS METAL ARC CUTTING

Principles of Operation

GAS METAL ARC cutting (GMAC) is an arc cutting process that uses a continuous consumable electrode and a shielding gas. GMAC was developed soon after the commercial introduction of the gas metal arc welding process. GMAC first occurred accidentally during a welding operation, when it was found that if the electrode feed rate was set too high, it would penetrate through the plate. When the torch was moved, a cut was made.

The chief drawbacks to use of GMAC are the high consumption of welding electrode and high cutting currents (up to 2000 amps) required.

Applications

GMAC HAS BEEN used to cut shapes in stainless steel and aluminum. Using normal welding equipment and a 3/32 in. (2.4 mm) diameter carbon steel electrode, stainless steel up to 1-1/2 in. thick and aluminum up to 3 in. thick can be cut.

CARBON ARC CUTTING

CARBON ARC CUTTING is the oldest arc cutting process and is rarely used today. The process utilized an arc between a carbon (graphite) electrode and the base metal to melt the surface of the workpiece. Since the process depends on gravity to remove the molten metal, it can only be used in the vertical and overhead positions.

One variation used the arc force to assist in pushing metal out of the kerf by using higher amperages. The cuts produced required extensive cleanup of dross and slag. Prior to welding, the cut edges required grinding to remove the melted area remaining on the metal, which was high in carbon picked up from the carbon electrode.

Table 15.8
Conditions for Gas Tungsten Arc Cutting

Material	Thickness in.	Travel Speed, ipm	Current dcsp amps	Type of Gas
Stainless Steel	1/8	20	350	80% A + 20% H(2)
Stainless Steel	1/4	20	500	65% A + 35% H(2)
Stainless Steel	1/2	15	600	65% A + 35% H(2)
Aluminum	1/8	30	200	80% A + 20% H(2)
Aluminum	1/4	20	300	65% A + 35% H(2)
Aluminum	1/2	20	450	65% A + 35% H(2)

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CHAPTER 16

LASER BEAM AND WATER JET CUTTING

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CHAPTER 16

LASER BEAM AND WATER JET CUTTING

LASER BEAM CUTTING

INTRODUCTION

LASER BEAM CUTTING is a thermal cutting process that severs material by locally melting or vaporizing with the heat from a laser beam. The process is used with or without assist gas to aid the removal of molten and vaporized material.

Drilling with a laser is a pulsed operation involving higher power densities and shorter dwell times than laser cutting. Holes are produced by single or multiple pulses. Laser drilling is a cost-effective alternative to mechanical drilling, electro-chemical machining, and electrical-discharge machining for making holes of relatively shallow depths.

A laser is a heat source with some unique characteristics. See Chapter 22 for a description of the equipment used to produce a laser beam. Relatively modest amounts of laser energy can be focused to very small spot sizes, resulting in high power densities. In cutting and drilling, these power densities are in the range of 6.5×10^6 to 6.5×10^8 W/in.^{2} (10^4 to 10^6 W/mm^2). Such high concentrations of energy cause melting and vaporization of the workpiece material, and material removal is enhanced by a jet of gas. Depending on the material, a jet of reactive gas such as oxygen can be applied coaxially with the beam, improving process speed and cut edge quality. The physical mechanisms involved in the material removal process are quite complex, involving material properties and several process variables.

Among laser material processing applications, cutting is the most common process, enjoying excellent growth rate worldwide. The first laser material processing application was drilling diamonds for wire drawing dies. Today, laser cutting and the related processes of drilling, trimming, and scribing account for more than 50 percent of the international industrial laser installations.

A high-power CO_2 laser can cut up to 1 in. (25 mm) thick carbon steel. However, good quality cuts on steel are typically made on metal thinner than 0.375 in. (9.5 mm), because of the limited depth of focus of the laser beam. CO_2 lasers in the range of 400 to 1500 W dominate the cutting area. Neodymium-doped, yttrium aluminum garnet (Nd:YAG) lasers are also used.

Laser cutting has the advantages of high speeds, narrow kerf widths, high-quality edges, low-heat input, and minimal workpiece distortion. It is an easily automated process that can cut most materials. The cut geometry can be changed without the major rework required with mechanical tools; there is no tool wear involved, and finishing operations are not usually required. Within its thickness range, it is an alternative to punching or blanking, and to oxyfuel gas and plasma arc cutting. Laser cutting is especially advantageous for prototyping studies and for short production runs. Compared to most conventional processes, noise, vibration, and fume levels involved in laser cutting are quite low.

Laser cutting results are highly reproducible, and laser systems have achieved operating uptimes greater than 95 percent. Relative movement between the beam and the workpiece can be easily programmed using CNC workstations currently available. High precision and good edge quality are quite common even in three-dimensional laser cutting. Lasers also have the flexibility for power and time sharing so that cost effectiveness of full-time beam operation can be maximized.

LASER DRILLING

HOLE DIAMETERS PRODUCED by laser beam drilling typically range from about 0.0001 to 0.060 in. (0.0025 to 1.5 mm). Depths achieved are usually less than 1 in. (25 mm) because of beam focusing limitations. Examples of laser drilling on jet engine blades and a rotor component are shown in Figure 16.1.

The process produces clean holes with very small recast layers. When large holes are required, a trepanning technique is used where the beam cuts a circle with the required diameter.

Laser drilling shares most of the advantages found in laser cutting. It is especially advantageous when the required hole diameters are less than 0.020 in. (0.5 mm) and when holes are to be made in areas inaccessible to conventional tools. Beam-entry angles can be very close to zero, a situation where mechanical tools are susceptible to breakage. The high-intensity pulsed outputs from solid-state lasers with shorter wavelengths such as Nd:YAG, Nd:glass, and ruby, are more suitable for drilling. The industrial laser drilling area is dominated by Nd:YAG lasers. The elements of a Nd:YAG laser are shown schematically in Figure 16.2. CO_2 lasers are usually used for drilling nonmetals like ceramics, composites, plastics, and rubber.

The two most discouraging aspects of laser material processing have been its high equipment cost and the intimidation workers feel about a "high technology" process, requiring high operator skills and good knowledge of laser-material interaction. More laser and system manufacturers are entering the field worldwide, and more reliable products with lower prices and new features are being produced. The industrial laser market is presently enjoying a 20 percent annual growth rate, and the prices of laser cutting systems are expected to drop by a small percentage every year for the next several years.

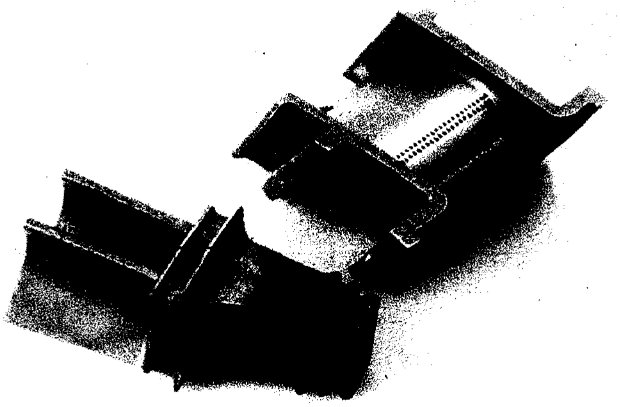

Figure 16.1–Jet Engine Blades and a Rotor Component Showing Laser Drilled Holes

New software packages and easy-to-learn programming are making laser cutting more welcome in low operator-skill areas. Fully integrated laser-robot systems and easy interfacing with personal computers are offering better control of laser systems and operating variables. CO_2 lasers with reduced size and weight, multi-kilowatt pulsable CO_2 lasers with better beam quality, single mode YAG lasers, and YAG laser outputs up to 1.5 KW are some of the improvements being made. Improved system designs are leading to higher accuracy and repeatability of the process.

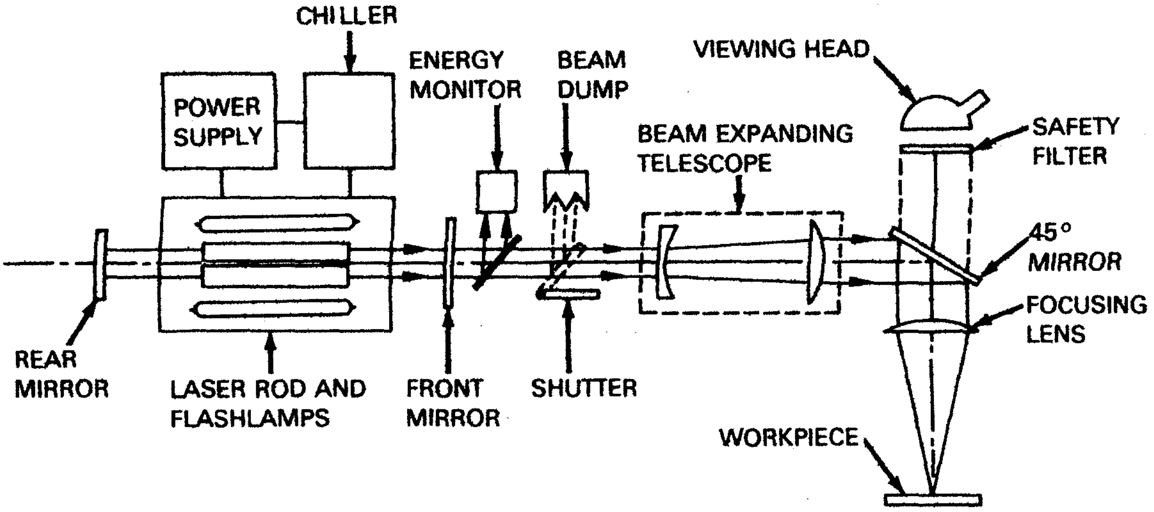

Figure 16.2–Schematic Representation of the Elements of A Nd: YAG Laser

PROCESS PRINCIPLES AND CHARACTERISTICS

LASER BEAM CUTTING (LBC) and laser beam drilling (LBD) are two completely different processes for removing material. These processes have been widely investigated both experimentally and theoretically to understand the mechanisms which take place in the material removal process.

Both processes can use either pulsed or continuous lasers as the primary energy source. Many factors, as listed in Table 16.1, are involved in laser cutting and drilling. The engineering disciplines involved include lasers themselves, optics, fluid dynamics, and materials.

Simplistic Model

Cutting. The laser beam cutting process can be described quite simply. It requires simultaneous action of a focused laser beam with a power density greater than 6.5 x 10^6 W/in.^{2} (10^4 W/mm^2), and an assist gas jet, which together produce a kerf in the workpiece. The laser beam acts as a line heat source which produces a keyhole after the initial transient conditions have come to steady-state. The assist gas jet ejects the molten material within the keyhole through the root of the kerf. In certain cases, an active gas can be used to improve the cutting efficiency by an exothermic chemical reaction. Commonly used assist gases are listed in Table 16.2.

The advantages of laser cutting over other processes include: (1) narrow kerf width, (2) narrow heat-affected zone, (3) high cutting speeds, (4) good cut quality, (5) adaptability to automation, and (6) no mechanical contact between the cutting device and the workpiece.

Drilling. The process of laser drilling requires merely a pulsed laser with beam focused to power densities of

Table 16.1
Factors Influencing Laser Drilling and Cutting Processes

I. Laser Type

- Solid State
  - YAG (pulsed & cw)
- Gas
  - Carbon dioxide (pulsed & cw)
  - Excimer (pulsed)

II. Optical

- Raw Beam
  - Power
  - Divergence
  - Wavelength
  - Mode structure
  - Polarization
  - Size
- Focusing Optics
  - Lens or reflecting
  - Quality
  - Focal length
  - Optical material
  - Aperture
- Focused Beam
  - Focal length
  - Beam diameter
  - Optical mode
  - Wavelength
  - Power density
  - Depth of focus

III. Material

- Surface
  - Condition
  - Reflectivity
  - Absorptance
- Bulk
  - Thickness
  - Density
  - Heat of fusion
  - Heat of vaporization
  - Diffusivity

IV. Gas Assist Jets

- Inert Gas
  - Pressure
  - Orifice size
  - Orifice contour
  - Momentum
  - Depth of cut
  - Stand off distance
  - Type
  - Additive (water)
- Exothermic Gas
  - Pressure
  - Orifice size
  - Orifice contour
  - Momentum
  - Depth of cut
  - Mass flow
  - Type
  - Additive (water)

Table 16.2
Assist Gases Used for Laser Beam Cutting of Various Materials

Assist Gas	Material	Comments
Air	Aluminum	Good result up to 0.060 in. (1.5 mm)
	Plastic	
	Wood	
	Composites	
	Alumina	All gases react similarly; air is the least expensive
	Glass	
	Quartz	
Oxygen	Carbon Steel	Good finish, high speed; oxide layer on surface
	Stainless Steel	Heavy oxide on surface
	Copper	Good surface up to 1/8 in. (3 mm)
Nitrogen	Stainless Steel	
	Aluminum	Clean, oxide-free edges to 1/8" (3 mm)
	Nickel Alloys	
Argon	Titanium	Inert assist gas required to produce good cutting of various materials

greater than 6.5 x 10^7 W/in.^{2} (10^5 W/mm^2). When the focused beam strikes a surface, material is melted and volatilized, and the molten and vaporized material is violently ejected, forming a hole. Depths normally achieved are approximately six times the diameter of the hole. Thus, multiple pulses may be required to completely penetrate the thickness of the material. Materials up to 1 in. (25 mm) thick have been drilled in the pulsed mode to date.

The advantages of laser drilling include (1) short drilling times, (2) adaptability to automation, (3) ability to penetrate difficult-to-drill materials, and (4) no mechanical contact.

Laser Types

LASER BEAM CUTTING and drilling require a precisely focused, coherent laser beam. Two primary laser sources, the pulsed YAG laser operating at a wavelength of 1.06 microns, and the CO2 laser operating either pulsed or continuously at a wavelength of 10.6 microns, are predominately used for these applications. Table 16.3 describes the basic cutting mechanisms and the laser used in each case. For the pulsed YAG laser, its interaction with material results in evaporation and removal at very high power densities. The continuous and pulsed CO2 laser removes most material by first melting it, which then must be blown from the kerf with an inert gas assist. If the inert gas is replaced by a reactive gas such as oxygen, the process becomes exothermic and additional energy is supplied by oxidation of the material.

More recently, the excimer laser operating at a wavelength of 248 nanometers has been added as a laser source for drilling. The process of material removal using this laser is thought to be by photo ablation when used on polymers having bond energies below the excimer photon energies.

In either of the processes (cutting or drilling, Figure 16.1), it is necessary to achieve power densities from 6.5 x 10^6 to 6.5 x 10^8 W/in.^{2} (10^4 to 10^6 W/mm^2). This is accomplished by focusing the beam with either lenses or reflective optics, depending upon the laser type and wavelength. In either case, the beam spot size is defined the same way and is given by the relationship,

$$d_s = 2.44\ K\ F/D \tag{16.1}$$

where
d_s = focused spot diameter μ in. (μ mm)
K = a constant dependent upon optical beam mode (See Table 16.4)
F = focal length of lens or mirror in. (mm)
D = aperture diameter of beam on focusing mirror in. (mm)
λ = laser optical wavelength μ in. (μ mm)

Table 16.4 gives the values of K, which are dependent upon the optical beam mode structure and its divergence, for three of the most common continuous laser beams.

In the case of drilling, short focal-length lenses are used to focus the high-peak power optical beams from the pulsed lasers to spot sizes on the order of 0.024 in. (0.6 mm) diameter to achieve power density levels exceeding 6.5 x 10^7 W/in.^{2} (10^5W/mm^2). Under these conditions, the material is volatilized and ejected from the workpiece, leaving a partially drilled hole. Multiple pulses are used to achieve full penetration.

In most cutting applications the laser is of the continuous type operating at power levels between 400 and 1500 W, somewhat lower than the peak powers of the pulsed lasers described for the drilling applications. As a result, the required power densities are lower and generally in the range of 6.5 x 10^6 to 6.5 x 10^7 W/in.^{2} (10^4 to

Table 16.3
Basic Cutting Mechanisms

A. Solid-State Laser—YAG

Evaporation

—Material removal by volatilization at >6.5 x 10^7 W/in.^{2} (>10^5 W/mm^2)
—Pulsed only.

B. Gas Laser—CO_2

Fusion

—Most material removed in liquid state by means of inert gas assist with beam intensities of 6.5 x 10^6 W/in.^{2}(10^4 W/mm^2).

Exothermic

—Most material removed in liquid state at beam intensities of 6.5 x 10^6 W/in.^{2} (10^4 W/mm^2).
—Additional energy supplied by oxygen gas assist.

C. Excimer Laser

Photo Ablation

—Material removed by photo ablation when used on polymers having bond energies below the eximer photon energy level.

10^5 W/mm^2). This requires spot sizes on the order of 0.04 in. (1 mm) at the CO_2 laser wavelength in order to achieve the required power densities.

Laser-Material Interactions

A FUNDAMENTAL AND important feature of LBC and LBD is the interaction of the laser beam with the material surface. Figure 16.3 shows the relationship between the optical beam, the focusing system, the assist gas jet, and the workpiece to be cut. The optical lens or mirror focuses the input laser beam to a spot size given by equation 16.1. The location (generally aimed within the thickness of the workpiece) of the focal plane relative to the workpiece surface depends upon several factors, all governed by the relationships listed above. In practice, the exact location is determined experimentally, to suit the application.

Because most metals are highly reflective at the laser wavelengths under consideration, the coupling of the beam and workpiece is very inefficient and absorption is low. However, the absorption coefficient is a function of the temperature of the material, which changes during the transient phase of the process. This relationship is shown in Figure 16.4.

Table 16.4
Effect of Beam Mode on Focusability

Type of Laser Beam	K
1. Uniform Wavefront	1.0
2. Gaussian Beam	0.86
3. Unstable Resonator*	
a. M=2**	4.0
b. M=4	3.5

* Magnifications 'M' most used

** M, Magnification ratio of an annular beam, $= \frac{\text{Beam OD}}{\text{Beam ID}}$

The initial weak absorption at the surface of the workpiece begins to increase the workpiece temperature directly under the optical beam, and that decreases the reflectivity quite rapidly. Temperature and absorption

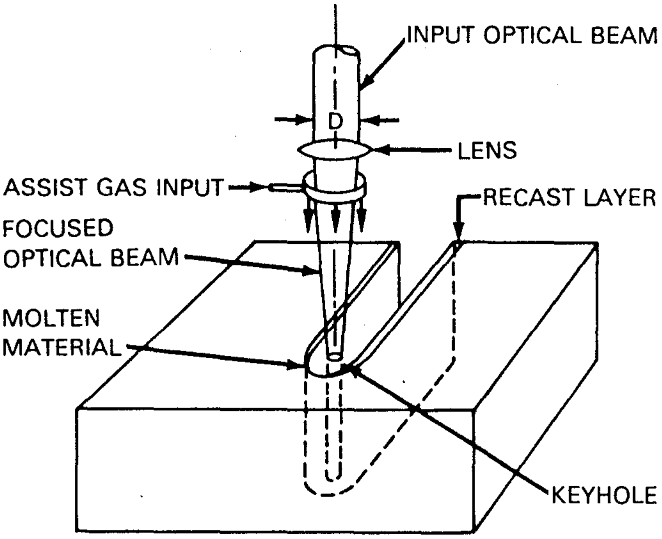

Figure 16.3–Schematic View of Laser Cutting Operation

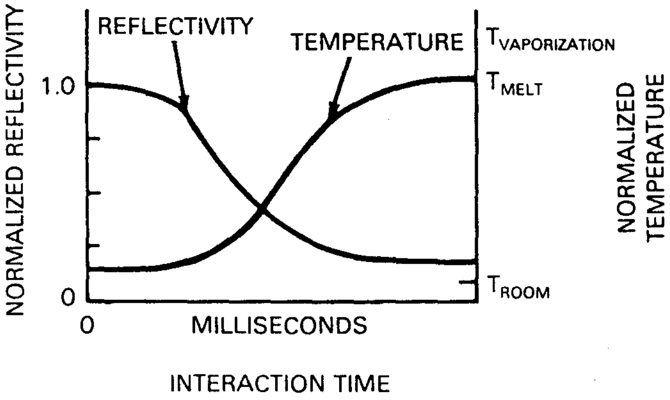

Figure 16.4–Reflectivity and Temperature Transient Time for Typical Metals

increase until melting and vaporization temperatures are reached. That permits a keyhole or radiation trap to form. The laser beam then acts as an energetic line heat source within the material and forms a molten pool. When the pool is exposed to a high-pressure gas jet, molten metal is ejected through the root of the workpiece to produce a cut.

For the keyhole cutting process to be initiated, it is essential that the power density be high enough to overcome the reflection barrier. The depth of the cut is then controlled by the melting and vaporization relationships depicted in Figure 16.5. At power density levels below 3.25 x 10^6 W/in.^{2} (5 x 10^3 W/mm^2), only surface melting is achieved. To develop a keyhole, power densities in the range of 6.5 x 10^6 to 6.5 x 10^7 W/in.^{2} (10^4 to 10^5W/mm^2) are required. Within the keyhole range, both melting and vaporization occur. Complete vaporization required for drilling is achieved above this range.

Gas Jet Assist

THE LIQUID COLUMN formed by the laser during welding is supported against gravity by both surface tension and capillary action. An assist gas jet, as shown in Figure 16.3, is used to remove the molten metal before resolidification can occur. This action prevents the formation of a weld. The momentum of the gas from the jet ejects a large percentage of the molten material from the root of the kerf. A very thin recast layer is left along the sidewall of the kerf. A beam delivery system for laser cutting with gas assist is shown in Figure 16.6.

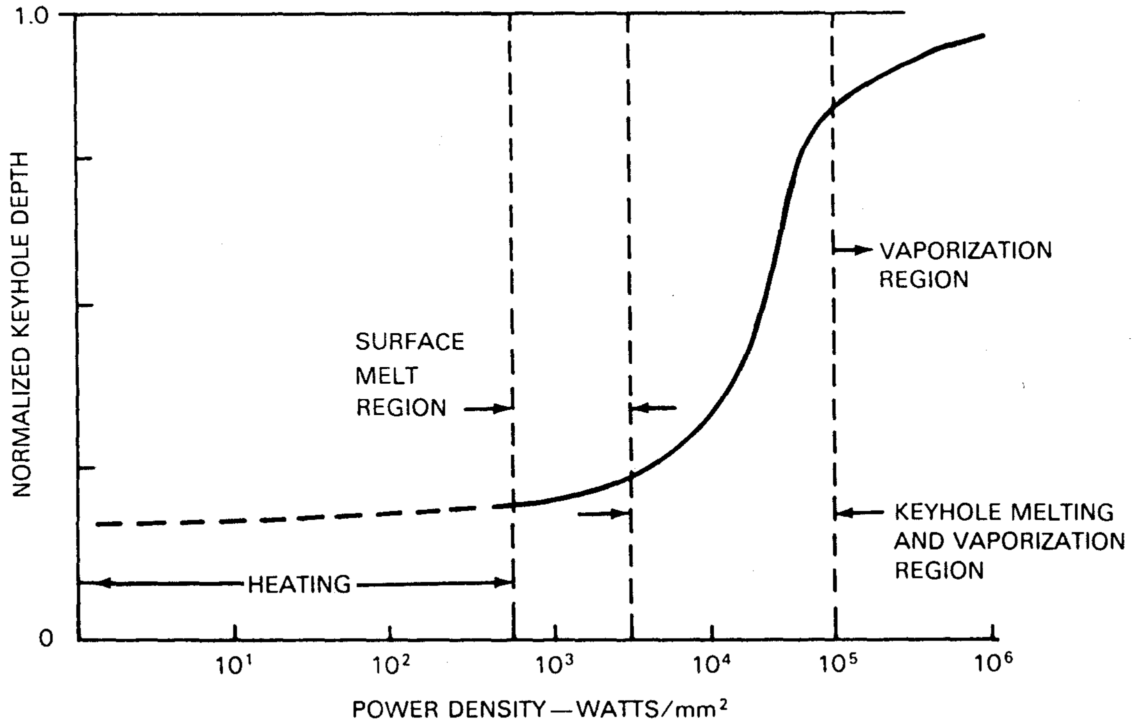

Figure 16.5–Power Density Requirements for Laser Keyhole Cutting and Drilling

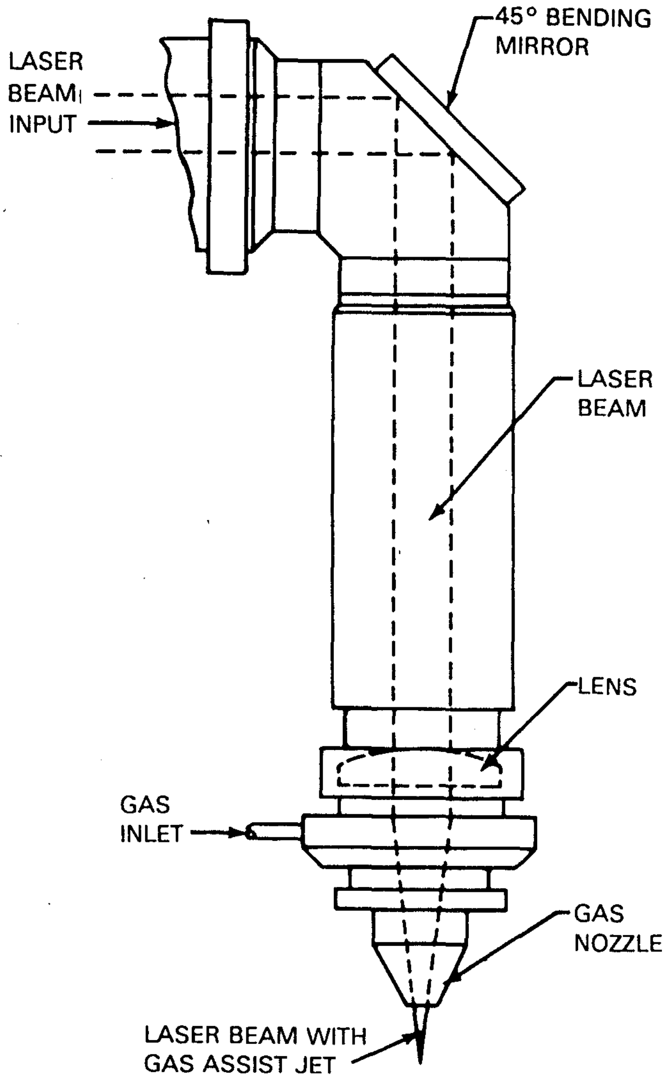

Figure 16.6–Beam Delivery System for Laser Cutting With Gas Assist

A factor which limits thick-section cutting at the power levels available is the narrow kerf width. Narrow kerfs are desirable from an applications standpoint; however, they are a detriment to the gas-assist approach because of the small jet nozzle diameters required to deliver gas into a small kerf. The coherent length of an overexpanded free jet is typically on the order of a few jet orifice diameters. This leads to an overexpansion of the gas jet within the keyhole cavity and limits the effective length of the jet. This limits the depth and surface smoothness of the cut. As a result, edges toward the bottom of a laser cut in thick material are generally rougher than those produced by other cutting methods.

THEORY AND PHYSICAL MECHANISMS

IN RECENT YEARS, the theory and physical mechanisms of laser cutting have been studied in detail. These studies should be continued so that the technical limits of the process can be evaluated and extended into regions not presently possible. It has been the purpose of these studies not only to increase the cutting and drilling depths, but to improve the quality of the cut surfaces as well. This section is a brief overview of the mechanisms; greater detail is provided in the referenced articles.

The primary factors which influence the laser-cutting process (see Table 16.1) are the power level, mode, polarization, and such optical variables as the focal length, aperture diameter, depth of focus, and location of the focal plane relative to the workpiece.

The energy balance of the laser-cutting process is shown in Figure 16.7. The energy sources are the laser and the reactive gas. The primary losses are the heat of conduction, reflection from the erosion front, heat of vaporization, convection, radiation, and the energy contained in material ejected at the root of the cut.

The most critical process taking place is the absorption of the incident radiation on the erosion front. Without absorption of the incoming beam, cutting would not be possible. It is also very important that this process be efficient. Absorption efficiency is dependent upon several factors, including the cut width, the instantaneous slope of the erosion front, polarization of the input optical beam, and the optical beam intensity distribution in the longitudinal and radial directions.

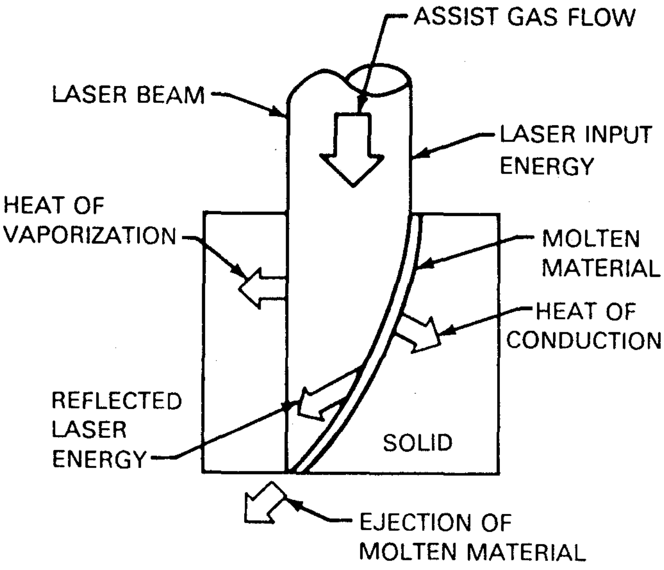

Figure 16.7–Schematic View of Laser Cutting Showing Energy Balance

The erosion front, merely sketched in Figure 16.7, is the interface between the incoming beam with its gas assist, and the molten layer of material. This front is the equilibrium surface along which the ejected material moves out of the root of the base metal due to the momentum of the assist gas. Its shape almost always has a lagging angle relative to the vertical, depending upon the forward speed of the incoming beam across the workpiece. The angle of the incident optical beam relative to the molten layer along the erosion front determines the efficiency of absorption. This depends on the polarization of the optical beam. The beam can be either linearly polarized, in which case the quality of the cut depends on the cutting direction, or circularly polarized, in which case the cut is good in two dimensions, assuring uniformly contoured cuts in a plane.

Cutting with a circularly polarized beam is generally less efficient than with a linearly polarized beam. As an example, up to 80 percent of a linearly polarized beam is absorbed at an incident angle of 85 degrees. With a circularly polarized beam at its optimum ample, the peak absorptance drops to about 40 percent. As the angle of incidence varies above or below the optimum angles, the absorption begins to fall. Thus, the energy absorption by the erosion front is dependant upon the shape of the erosion front, the spatial intensity of the input beam, and its polarization.

EQUIPMENT

CO_2 LASERS

THE CARBON DIOXIDE (CO_2) laser is the standard beam source for contour cutting applications. This is because it is the most powerful and reliable type of laser in general use.

The CO_2 laser is a gas-discharge device: it operates by sending an electric current through a gas. In industrial lasers, high efficiency is obtained by using a mixture of helium, nitrogen, and carbon dioxide. Electrical energy is coupled to the gases by establishing a glow discharge in the nitrogen. The nitrogen transmits this energy to the CO_2 molecules by collisions which put a large percentage of them in an elevated state. Laser emission at 10.6 microns in the infrared zone is produced when these molecules drop to an intermediate state. Collisions with the helium bring the CO_2 back to energy ground level, where the process can begin again. The gas is typically passed through a heat exchanger where it is cooled before being recycled.

Temporal Characteristics

CO_2 LASERS CAN operate by continuous wave (CW) or in a variety of pulsed modes. The pulse frequency may be as high as 10 kHz. The most common types of pulsing are termed *gated* and *enhanced*. In the gated mode, the laser operates at a peak power level that is within its normal CW range. The output is modulated to generate a reduced duty cycle. Gated pulses can be any length that is compatible with the chosen repetition rate. Lasers that can produce enhanced pulses have peak powers that are several times their CW rating. Enhanced pulses are usually about 100 microseconds long regardless of the repetition rate.

Spatial Characteristics

THE LOW-DENSITY AND high-thermal diffusivity of a gaseous laser medium reduce its tendency to distort the light that goes through it. This allows even high-power CO_2 lasers to have good optical quality. Beams from many lasers with outputs of up to 1500 watts are close approximations of the fundamental Gaussian mode TEM_{00}. Such beams may be focused to the limit set by the diffraction of light. A spot size of .004 in. (0.1 mm) is easily achieved by normal focusing lenses for CO_2 lasers.

Another property of TEM_{00} beams is *low divergence*, a term describing the angle at which the laser beam spreads out as it propagates. Typical values are in the range of 1 milliradian, which allows great flexibility in machine design since the laser can be distant from the focusing lens.

Slow-Flow Lasers

THE EARLIEST INDUSTRIAL CO_2 lasers consisted of glass tubes with mirrors on both ends. The laser gas flowed through the tube while electricity was applied near each mirror. These devices very simple and reliable, but are limited to about 50 watts per meter of discharge length, because there is no way to cool the gas. Such slow-flow lasers become unwieldy if more than 400 watts is required. They are in use today because they can produce stable high-quality outputs, and because the large volume of active medium allows for massive pulse enhancement.

Transverse-Flow Lasers

THE TRANSVERSE-FLOW LASER was developed to produce high power in a small package. It does this by circulating the laser gas through the discharge region at high speed and then cooling it with a heat exchanger so that it can be reused. Transverse-flow lasers tend to have asymmetrical modes because of the gain characteristics of the discharge currents. Despite these limitations, transverse-flow machines have been highly successful as cutting lasers.

The newest laser design in use today is the fast axial-flow type. This is a modification of the slow-flow laser, using a Rootes pump to circulate the gas. Fast axial lasers are small, powerful, and inexpensive to build. While they have appeared in many laser systems, most models have severe problems with instability of the output beam. This results in roughness on the surface of laser-cut parts.

YAG LASERS

THE YAG (MORE correctly, neodymium-doped, yttrium aluminum garnet) is the standard drilling laser in industry. Some contour cutting is also appropriate for its characteristics.

Principle of Operation

A YAG LASER contains a crystalline rod surrounded by xenon or krypton lamps. The crystal is an yttrium aluminum garnet (YAG) which has been doped with neodymium. Light from the lamps "pump" the neodymium atoms to an excited state, where they emit light at a wavelength of 1.06μm. Water flowing around the rod cools the atoms to the ground state.

Temporal Characteristics

INDUSTRIAL YAG LASERS generally operate in the pulsed mode for cutting or drilling. The repetition rate is generally below 200 Hz. Control of the power going into the lamps allows tailoring of the shape and duration of the laser pulse. The solid laser medium has a high concentration of light-emitting atoms, so the peak power can be very large. High-energy pulses of short duration remove the material being cut or drilled.

Spatial

LASER RODS GENERATE heat in the center and are cooled on the outside. Whenever substantial power is produced, a temperature gradient develops across the rod's diameter. That gradient induces changes in the rod's refractive index, which degrades the optical performance of the laser. High power YAG lasers have multimode outputs with high divergence, which limits the ability of the system to focus the beam to a small spot and requires the laser head to be near the work area.

OTHER TYPES

Glass

GLASS LASERS ARE very similar to YAG lasers. The laser rod is made of neodymium-doped glass rather than garnet. When glass rather than YAG is used as a matrix, a higher concentration of neodymium atoms can be incorporated in the laser rod. This allows glass lasers to produce stronger pulses than YAG lasers, which makes them more appropriate for deep drilling. The disadvantage of glass is that its poor thermal conductivity limits the pulse repetition rate to about 1 pps, making it useless for contour cutting.

Ruby

RUBY WAS THE first material in which laser emission was observed. The ruby laser is a flashlamp-pumped, solid-state device like the YAG and glass lasers, but emits visible light. Although largely replaced by other types, it is still suitable for drilling, with characteristics similar to Nd-glass lasers.

Excimer Lasers

EXIMER LASERS ARE pulsed high-pressure gas lasers which emit at wavelengths in the ultraviolet band. The term *excimer* is a contraction of the words "excited dimer". A dimer is basically a molecule that exists only in the excited state, such as krypton fluoride (KrF). Such molecules are formed when the appropriate gas mixture (typically a noble gas and a halogen) is excited in a pulsed electrical discharge. Lasing occurs when the excited molecule relaxes to the lower state.

SYSTEMS

IN ORDER TO cut, a laser must be integrated with a mechanism to deliver the beam and with means to handle the workpiece. Today, laser contour cutters are controlled by some sort of computer. The most common type of control is one which reads numerical data and transforms it into axis commands. Such devices are called *computer numerical controls*, or CNC's. The cutting head, consisting of a focusing lens and provision for assist gas, must be kept at a certain distance from the part to be cut. These components are enclosed, to provide safety for personnel, in a package termed a *laser cutting system.*

There is considerable variety in the design of these systems. Standard machines are available for work such as contour cutting of sheet metal or drilling of turbine blades, while special units can be obtained for tasks such as slitting of sheet materials on production lines.

For optimum cut quality, the optics should be held motionless, since any vibration or misalignment in the beam delivery system results in poor cut quality or inaccuracy. Fixed optics, however, require that the workpiece move, which becomes more complicated with large sheets. The minimum floor area for a fixed beam system is four times the maximum sheet size, which again is a problem with large workpieces. Automatic sheet feeding and part removal are difficult, as is accurate contouring with widely varying loads.

Under these conditions, moving the optics simplifies the laser system. With a "moving beam" system, sheets move only when they are being loaded onto or removed from the cutting table. The drive system always handles the same load, allowing servo response to be optimized. There are, however, several problems with moving the optical system:

(1) Beam divergence—Laser beams do not propagate unchanged through space. Beam diameters and other properties vary as a function of distance from their source. Since, with a moving beam system, the focusing lens intercepts the laser beam at different locations, the focal-point location and spot size will vary. The net result is that cutting conditions will vary at different locations on the table.

(2) Alignment—With fixed optics, it is only necessary to get the laser beam through the delivery system without it being clipped by any apertures. For a moving beam to function properly, the beam must be allowed to travel across the entire workpiece without a change in alignment.

(3) Rigidity—A fixed cutting head can be made rigid by using a massive support structure, and there is little penalty for doing this. When the head is moving, however, vibration and deflection are more difficult to suppress. This results in surface roughness or deviations from the programmed path, especially when the machine is making sharp corners.

(4) Beam path cleanliness—All high-power laser systems are sensitive to dirt on their optical elements. Dust particles that settle on lenses and mirrors are heated by the beam, causing damage to the components. As a result, all industrial laser systems must seal the beam path against the contaminants that exist in shop environments. This is, again, simple to do for a fixed beam but more complex when the elements are moving. In many moving beam systems, the laser optics share enclosures with gears, motors, and other sources of contaminants, shortening the life of the optics.

The ultimate extension of a moving beam system is the 6-axis gantry robot. Engineering difficulties involved in making a gantry are similar to those for a moving beam, only more severe. The ability of gantries to cut complex contours, however, makes the effort worthwhile.

A cantilevered robot with a moving beam delivery system is shown in Figure 16.8.

FOCUSING HEADS

THERE ARE FEW fixed-beam systems in use because of production limitations. Most systems move the lens to focus it, this motion ranging from a few thousandths of an inch to many feet. The relation between the surface of the workpiece and the focal point of the lens is one of the most important variables in laser cutting, so control of it is essential to maintaining process consistency. Depth of focus for CO_2 systems is on the order of .010 in. (0.25 mm). In many cases, variation in part thickness is greater than this. It is important, then, for the system to provide some way to hold focus when cutting uneven materials.

Machines that cut flat sheets often have heads that ride on the surface of the work with ball bearings. This approach works well but can mar the work finish on some parts, and it is unsuitable for contoured material. A more sophisticated approach is to attach a drive motor to the focusing mechanism and control it with a sensor. Capacitive probes work well in all orientations and do not protrude from the cutting head but are restricted to conductive workpieces. Contact probes, consisting of a fork or cup around the cutting nozzle, work on any material but function only in the vertical direction.

CONSUMABLES

THE PRIMARY COSTS associated with operating laser systems are those for electricity, optics, flashlamps (solid-state only), and gases. Gases are used for two purposes: for generating CO_2 light and to assist in cutting.

Operating Cost for a Co_2 Laser Cutting System

TYPICAL CONSUMABLE COSTS for a CO_2 laser system operating at 1500 watts are shown in Table 16.5. Gas costs are based on averages from different parts of the country. Depending on the material being cut, hourly operating costs range from \$9.89 to \$25.04 per hour.

Operating Cost for a Yag Laser Drilling System

THE PRIMARY COST in most YAG processes is flashlamp replacement. Lamp life is in the range of 1 to 10 million pulses, depending on the power used. A cost analysis made for a YAG laser drilling at 20 pps is shown in Table 16.6.

Table 16.5
Typical Laser Beam Cutting Costs for a CO_2 System Operating at 1500 Watts

Consumable	Hourly Cost
Electricity	2.10
Internal laser optics*	2.06
Laser gas	1.03
Focusing lens*	1.10
Assist gas:	
O_2 for 10 ga. carbon steel	3.60
N_2 for .060 in. stainless steel	3.60
Ar for .060 in. titanium	18.75

* Cost based on manufacturer's estimate of operating life for these parts.

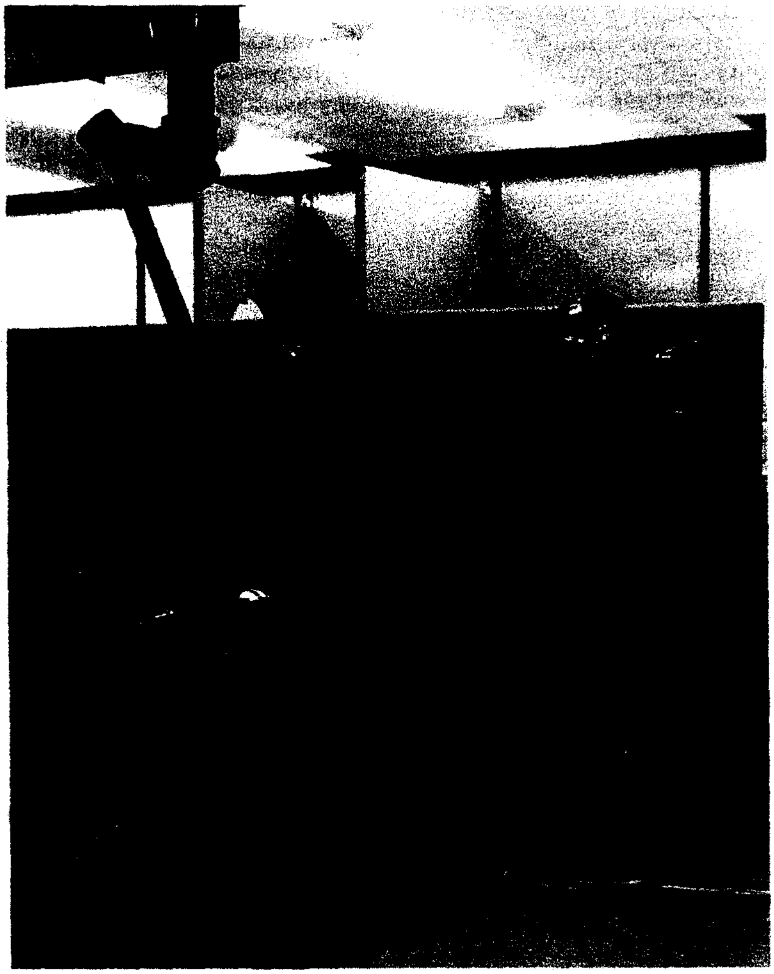

Figure 16.8–Laser Contour Cutter Using a Robot and a Beam Delivery System

Table 16.6
Typical Operating Costs for a YAG Laser Drilling System

Consumable		Hourly Cost
Electricity		.75
Laser optics*		1.00
Flashlamps*		2.00
Assist gas		4.00
	Total	7.75

* Cost based on manufacturer's estimate of operating life for these parts.

MATERIALS

LASER CUTTING IS a thermal process: materials are cut because the laser beam heats them until they melt, decompose, or vaporize. It is therefore useful to examine the thermal properties of materials to determine their response to laser radiation. Equally important are a substance's optical properties, since energy is transferred in the form of light. In many cases, reactive or inert gases are used to assist cutting, so the chemical behavior of the material is important.

Compared to other classes of materials, metals have high thermal diffusivities and optical reflectivities. They also melt without decomposing and have very high boiling points. Laser metal cutting, then, requires high power densities to put energy into the material faster than it is conducted away, along with an assist gas to remove the liquid metal from the kerf. Within this broad characterization, there are significant variations among metals in their suitability for laser cutting. Typical laser cutting conditions for various materials are shown in Table 16.7.

CARBON STEEL

CARBON STEEL IS one of the easiest metals to cut with a laser. An examination of the energy balance during cutting, when oxygen is used as the assist gas, shows that most of the heat comes from the exothermic reaction of iron and oxygen, with the laser beam serving as a pilot or preheat energy source. The metal heated by the laser burns in the oxygen stream, leaving the surrounding material unaffected. The cut edge can be extremely smooth, with finishes better than 32 micro-inches achievable in 0.06 in. (1.5 mm) thick sheet.

ALLOY STEEL

THE TERM *alloy steel* covers a wide range of metals. Low alloy steels, such as AISI 4140 and 8620, cut much like carbon steel. The generally lower impurity levels found in low alloy steels result in improved cut quality compared to commercial cold rolled carbon steel. Increasing quantities of alloying elements change the steel's behavior. Tool steels with high tungsten additions cut slowly and with some slag adherence. Chromium additions reduce the steel's reactivity with oxygen and produce adherent scale on the cut edge.

STAINLESS STEEL

STAINLESS STEELS ARE a subset of alloy steels with two primary classifications: austenitic (300 series) and ferritic/martensitic (400 series). Stainless steels have relatively low thermal conductivity, which should make them easy to cut with a thermal process. However, the alloying elements that give stainless steels their corrosion resistant properties make them resistant to oxidation. This makes such materials react quite differently to laser energy than carbon steels.

The 400 series stainless steels, which have chromium as their primary alloying element, cut cleanly with oxygen assist but have a tenacious chrome oxide layer on the cut edge.

The austenitic materials, which have nickel and chromium additions, tend to have tenacious slag on the bottom of the kerf edges in addition to the oxide layer. This slag and the oxide are serious problems in production, since

Table 16.7
Typical Laser Cutting Variables

Material	Thickness Inches	Travel Speed IPM	Power Watts	Assist Gas
Carbon steel	.060	150	400	O_2
	.125	120	800	O_2
	.250	80	1200	O_2
	.375	50	1500	O_2
Stainless steel	.060	150	1500	N_2
	.125	40	1500	N_2
	.250	40	650	O_2
	.375	30	800	O_2
Titanium Ti6Al4V	.060	150	1500	argon
Kevlar-epoxy	.125	250	400	air
	.250	250	1500	air
G10 glass-polyester	.060	600	1000	air
Boron-Aluminum	.040	300	1500	air
Silicon Carbide	.030	25	150	argon

they require additional operations to produce a finished part. Slag can be removed by a grinder. The oxide must be removed prior to welding.

Use of an inert assist gas has proved successful in making cuts in stainless steel without oxide or slag adherence. The edges produced in this manner can be welded with no additional operations.

ALUMINUM

SEVERING ALUMINUM WAS a problem in the early days of laser cutting. Because of aluminum's very high diffusivity and reflectivity, it required large amounts of laser power to melt it. If the focus was incorrect, the aluminum reflected the beam back into the laser, often destroying the laser. As lasers with one kilowatt or more of power became available, along with accurate focusing methods, cutting problems diminished, but cut quality remained poor. Laser-cut aluminum had heavy slag on the bottom edges of the kerf sides. The cost involved in removing this slag usually made laser cutting uncompetitive compared to other methods. The recent development of inert gas cutting has made it possible to produce high-quality aluminum cuts with a CO_2 laser.

COPPER

COPPER, WITH DIFFUSIVITY and reflectance both higher than aluminum, is very difficult to cut with low-power lasers. However, copper is easily cut with kilowatt-class CO_2 lasers, as long as they have good TEM modes and the system keeps the beam focused on the work. YAG lasers, with their high-pulse power and shorter wavelength, cut copper with no problems.

COPPER ALLOYS

CUTTING RESULTS ON copper alloys such as brass are similar to those obtained on aluminum.

NICKEL BASE ALLOYS

MOST NICKEL-BASE ALLOYS are intended for some form of severe service, like high temperatures or corrosive environments. While these metals are easily laser cut, it is usually necessary to examine the part for such metallurgical defects as microcracking and grain growth to ensure that the part will perform properly. Recent tests with inert gas laser cutting show higher quality than with oxygen-assist cutting.

TITANIUM

TITANIUM AND ITS alloys react with oxygen and nitrogen to form brittle compounds at the cut edge, generally an unacceptable condition. Therefore, it is necessary to use argon as the assist gas for titanium cutting. Argon ionizes easily under laser cutting conditions, which can lead to plasma formation above the workpiece. When this happens, the laser output must be revised to obtain consistent results.

NONMETALS

ONE OF THE laser's attributes is that it can cut an extremely wide range of materials without regard to their hardness or electrical conductivity. It is convenient to divide materials into the categories of metals and nonmetals, and to subdivide the nonmetals into organic and inorganic categories.

Inorganic Materials

NONMETALLIC, INORGANIC MATERIALS, as a class, have low vapor pressures and poor thermal conductivities. These characteristics, combined with their generally high absorption of 10.6 μm wavelength light, should make them good candidates for laser cutting. Unfortunately, many of the common varieties have very high melting points and poor thermal shock resistance. This tends to make them harder to process than metals.

Alumina. Alumina (Al_2O_3) is often cut or scribed by lasers. Cutting is performed using high-power pulses to vaporize the material, since recast melted material is a problem. The high melting point of alumina, coupled with the low average power of lasers operating in the enhanced pulse mode, results in low cutting speeds.

The process of scribing is the standard method of preparing alumina substrates for hybrid microcircuits. Scribing is performed by drilling rows of holes partially though the material. These perforations make it possible to snap the ceramic apart along the lines. For typical 0.025 in. (0.64 mm) thick alumina substrates, holes are drilled 0.008 in. (0.2 mm) deep and 0.007 in. (0.18 mm) apart. For such conditions a laser pulsing at 1000 Hz can scribe at 7 in./s (175 mm/s).

Quartz. Quartz can be processed much like metal because it has a high thermal shock resistance. Continuous CO_2 radiation is used, since quartz is quite transparent to the 1.06 μm light emitted by YAG lasers. Strains caused by thermal stresses must often be relieved by annealing the parts after cutting.

Glass. The laser cutting of glass is limited by the poor thermal shock resistance of most compositions. This causes complex glass parts to crack apart after cutting. Glass also tends to form recast material on the cut edge, because it does not have a well-defined melting point.

Organic Materials

ORGANIC MATERIALS ARE generally decomposed by laser light. The energy required to do this is usually much lower than that required to melt inorganic substances, so cutting can often be done at high speeds or with lower power lasers. The large volume of decomposition products causes some problems: gases in the kerf have trouble escaping, limiting process speeds and degrading edge quality. In addition, many organic materials evolve toxic compounds during laser cutting. These effluents must be handled in a manner to eliminate hazards to operators and to the environment.

Cloth. Since cloth is so thin, it presents few problems for laser cutting. Most of the difficulties are related to the construction of systems capable of moving fast enough to fully utilize laser cutting capability.

Plastics. A wide variety of polymers are cut with lasers. The beam causes melting, vaporization, and decomposition of the material. Thermoplastics such as polypropylene and polystyrene are cut by shearing of molten material, while thermosets such as as phenolics or epoxies are cut by decomposition. Materials which decompose in the beam leave a carbon residue on the cut edge. This must often be removed by some operation such as bead blasting before the parts may be used. Decomposition products of laser cut polymers have been found to be quite hazardous, and precautions must be taken to protect operating personnel.

Composites

COMPOSITES ARE MATERIAL consisting of two or more distinct constituents. Usually, one component is fibrous, while the other forms a surrounding matrix. By selecting appropriate matrices and reinforcing elements, the material can be engineered to have properties optimized for a specific use. From the standpoint of laser cutting, the main differences between composites are whether the matrix, the fibers, or both are organic.

Organic. If organic fibers are set in an organic matrix, the laser has little difficulty cutting. Kevlar (aramid) fibers in an epoxy matrix, a common high-performance composite, is readily laser-cut in thicknesses up to 1/4 in. Thicker sections exhibit considerable charring of the cut edge.

Organic-Inorganic Materials. The presence of inorganic materials changes the response of composites to laser heating. To cut fiberglass-epoxy, the laser must melt the glass. This takes much more energy than decomposing the epoxy, and so controls the processing rate. Graphite-epoxy is extremely difficult to cut because graphite must be heated to 6500 F to vaporize it. Since graphite has fairly good thermal conductivity, the epoxy near the cutting zone is exposed to high temperatures which decompose it for a significant distance from the cut edge. Laser cutting of graphite-epoxy is thus limited to relatively thin [1/16 in (1.6 mm) or less] sections.

Inorganic Materials. Some of the highest-performance materials available today are metal-matrix composites. The addition of refractory fibers to a superalloy matrix produces tremendous strength at high temperatures, combined with high toughness. Unfortunately, these characteristics also make it difficult to machine such materials. Lasers have successfully cut several types of metal-matrix composites, and should see increasing use for this application. One effect that must be controlled is the melting back of the matrix from the cut edge, leaving exposed fibers. The use of high-energy pulses, as produced by YAG lasers, minimizes that problem.

LASER CUTTING VARIABLES

A GREAT NUMBER of variables affect the results of laser cutting. They can be divided into material-related, laser-related, and process-related variables.

MATERIAL-RELATED VARIABLES

THE PRIMARY VARIABLES that make materials behave differently have been discussed above. Any specific material, however, can behave differently depending on its condition.

Thickness

THICKNESS IS THE most important variable affecting how a given material can be cut with a laser. In general, cutting speed is inversely proportional to thickness.

Surface Finish

FOR HIGHLY REFLECTIVE materials, such as pure aluminum or copper, the surface finish can affect the initial coupling of laser energy. Sheets with extremely shiny surfaces may not cut consistently.

Carbon steel often has rust and scale on it. These oxides interfere with the oxygen-assisted cutting process and cause poor edge quality. One of the factors that makes hot-rolled plate less amenable to laser cutting than cold-rolled is the generally poorer surface of hot-rolled material.

Highly finished sheets of stainless steel and aluminum for decorative applications often have coatings of paper or plastic to protect the surface from scratches during manufacturing. While these layers do not have much direct effect on the cutting process, they can cause problems when the assist gas gets under them and lifts them. This action can foul mechanical parts such as focusing heads.

LASER-RELATED VARIABLES

MANY CUTTING VARIABLES are related to the laser itself. The suitability of a laser for cutting is a function of all of these variables.

Power Limitations

MOST LASERS ARE characterized by their maximum continuous power output. While this is a useful quantity, it does not describe the machine completely. Lasers that operate only in the continuous mode are fairly well defined by a power specification. Others can be pulsed to high peak powers but produce low average powers. YAG lasers, which typically operate in the pulsed mode, will deliver their rated average powers only under specific pulse conditions.

Some materials, such as thick steel, require high continuous power, while others such as alumina must be cut with short, high-energy pulses. As power is increased, cutting speed for a specific material also increases.

The ability to vary laser power using CNC control is important when cutting intricate shapes, because the motion system often cannot maintain constant speed for all features of a part.

Mode

THE IDEAL LASER output for cutting is the fundamental Gaussian mode TEM_{00}. This can be focused on the smallest spot and has the greatest depth of focus (the least change in power density with distance) of all possible modes. CO_2 lasers with power not over 2000 watts can be made to produce beams which closely approximate the Gaussian profile.

The method of evaluating the beam is important: lasers which appear to have a good beam as indicated by the traditional acrylic-mode burn can, in fact, be unstable on a millisecond time scale. Recent work has demonstrated that these short-time variations in the mode are common and have significant effects on cut quality.

Beam stability and focusing ability are especially important in the contour cutting of thin [0.125 in. (3.2 mm) or less] carbon steel sheet. A stable, low-order beam is required to produce surface finishes of 32 μin. or better. Since this is a significant market, considerable attention has been devoted towards achieving such results. When the material thickness exceeds the depth of focus of the laser system, the focusing quality of the beam has less effect on the edge quality.

Duty Cycle

THE HIGHEST SPEED (and often the highest quality) is achieved using a beam that is on all the time. Many situations exist, however, that make it necessary to pulse the beam.

When cutting intricate steel parts with a CO_2 laser, a motion system may not be able to maintain the linear speeds that are appropriate for good cut quality. Reducing the continuous wave (CW) power with travel speed is useful, but is ineffective at speeds below about 20 inches per minute because of bulk heating of the workpiece. The solution to this difficulty is to maintain CW power and pulse the beam to reduce the percent of time that it is on. A typical schedule is to have the beam on 25 percent of the time with a repetition rate of 500 Hz. The actual repetition rate is dependent on the ability of the laser to generate clean pulses. There should be no laser emission during the off part of the cycle, because that heats the material and reduces the benefit of pulsing. The pulses themselves should be uniform in duration and power.

Certain electronically pulsable lasers have high "simmer" levels. Simmer current is applied to ensure uniform response to the pulse current, and can result in significant CW output. Cutting of thin materials with this type of beam gives poor results. Mechanical choppers (used with nonpulsable lasers) actually have an advantage here, since they produce highly uniform pulses and reduce output to absolutely nothing between them. The main disadvantages of mechanical pulsing are limited repetition rate and slow response to commands to change the cycle.

Another type of pulse which is used in cutting is termed *enhanced pulsing* or *superpulsing.* This involves circuitry designed to trigger a pulse whose duration and power are preset. The pulse is usually repeated at a frequency of 10 to 200 Hz for YAG lasers and 100-5000 Hz for CO_2. YAG lasers generally operate this way, and many CO_2 lasers can be set up to do it. Slow-flow CO_2 lasers can produce several times their CW outputs when operated in enhanced pulse mode. Fast-flow lasers, because of their small volume of active medium, cannot deliver the same degree of enhancement and lose effectiveness at high repetition rates.

Operations such as ceramic scribing and cutting of refractory materials are usually done with enhanced pulsing. Short, high-intensity pulses vaporize substances before they have time to conduct heat away. This reduces the volume of molten material, minimizing recast. The same technique produces good results in metal-matrix composites.

Beam Propagation

THE FOCUS DISTANCE and spot size that result when a lens focuses a laser beam are well defined functions of the distance between the lens and the laser. Because of high divergence (the beam spreads out rapidly as it leaves the laser head), YAG lasers are usually set within 4 ft (1.2 m) of the focusing lens and maintained at that distance. The small size of a YAG laser head allows it to be set on a moving axis, so that there are no significant in-process variations in the focus.

CO_2 laser heads are large and best kept stationary, and their low divergence allows the beam to propagate 30 ft (10 m) or more. A potential problem arises when the process variables are set correctly for a specific laser-to-lens distance, and then the distance changes, as with a moving-beam system. Large changes in distance will change the focal point, with possible loss of process quality.

PROCESS-RELATED VARIABLES

ONCE A LASER system is built, many of the above variables are fixed. There are, however, a large number of variables that must be controlled to get reliable cutting.

Focusing Lens

THE FOCUSING LENS controls the spot size and depth of focus. For a CO_2 laser with a raw beam diameter of 0.8 in. (20 mm), a 5 in. (125 mm) focal length produces a spot 0.01 in. (0.25 mm) in diameter and has a depth of focus of 0.020 in. (0.5 mm). This works well for metals from 0.010 to 0.38 in. (0.25 to 10 mm) thick, and so it is the most popular focal length for such laser systems.

For thin material, a focal length of 2.5 in. (64 mm) gives better results because its spot size is half that of the 5 in. (125 mm) lens. The smaller spot allows higher travel speeds, produces a smoother surface, and leaves a narrower kerf. The depth of focus, however, is only a quarter that of the 5 in. (125 mm) lens and limits the utility of the 2.5 in. (64 mm) lens to materials 1/8 in. (3.2 mm) thick or less.

For thick metal or organic materials, a 7.5 or 10 in. (190 or 250 mm) lens is sometimes used. The long depth of focus provided by such lenses results in straighter kerfs than those made by shorter lenses.

Assist Gas Variables

ALMOST ALL LASER cutting is gas-assisted. Gas-related variables have a significant effect on cutting results. Oxygen reacts with most metals and many nonmetals. Carbon steel is usually cut with oxygen to get the best surface and process rates. Acrylic plastic may be cut with oxygen to achieve very high cutting speeds.

Air is used for cutting aluminum and alumina. Since it is the cheapest assist gas available, it is commonly used for nonmetals, where the gas composition does not make much difference.

Nitrogen gives good results with aluminum, stainless steel, and nickel base alloys. It is reactive with respect to titanium, and should not be used on that metal. Argon, which is inert, must be used to get clean edges on titanium.

Assist Gas Pressure. Material is removed from the cut by gas pressure. This pressure varies from near zero for acrylic to 120 psi (830 kPa) for inert gas cuts. Generally speaking, as the pressure increases, the effectiveness of the gas-sweeping action improves.

For certain applications, however, the assist gas pressure cannot exceed specific limits. For example, in oxygen-assisted cutting of carbon steel, excess pressure causes uncontrolled burning of the material. Thick plate is usually cut at pressures of 10 to 20 psi (70 to 140 kPa) measured in the cutting head.

In thick organic materials, high assist gas pressure results in incandescent decomposition products in the kerf. These radiate energy and widen the kerf in the middle of the cut face.

Assist Gas Nozzle. The gas pressure in the laser head is transmitted to the workpiece through a nozzle which is coaxial with the laser beam. For laminar flow, a nozzle must have a high-aspect (length to diameter) ratio. Such a design isn't compatible with beam focusing optics, so compromises must be made.

Cutting nozzle diameters vary from 0.030 to 0.125 in. (0.75 to 3.2 mm). The smaller sizes are used with thin materials. Cutting 1/4 in. (6.4 mm) steel with a nozzle smaller than 0.06 in (1.5 mm) diameter gives poor results because the pressure profile of a small nozzle doesn't extend far enough from the beam centerline to clean up the bottom of the kerf. A nozzle too large for a given material uses excessive amounts of assist gas.

Nozzle damage has serious effects on cut quality. Asymmetry in the opening causes changes in performance as the direction of cutting varies. It is not possible to get good results in metal cutting with a dented or burned nozzle.

Nozzle Standoff. The distance between the nozzle and work controls the pressure in the kerf. The relationship is not linear because most laser cutting is done at supersonic flow velocities, and the resulting shock waves produce complex pressure patterns. The pressure at the workpiece can, in fact, decrease as the nozzle is brought closer to it. Typical standoff distances are of the order of the nozzle diameter. It is often more critical to control the nozzle standoff than it is to maintain beam focus.

Travel Speed. One of the reasons that laser cutting is used is that the process rates are high. In contour cutting, process rate is the same as travel speed. For a given material, thickness, and laser power, there is a range of speeds that gives satisfactory results. Above the maximum speed, the cut doesn't go through or has excessive slag. Below the minimum, the heat from the cutting process destroys the edge of the work.

For most materials, cutting speed at constant laser power is more or less inversely proportional to thickness. There is a characteristic maximum thickness, above which no cutting will occur at any travel speed, and there are dynamic effects which reduce process efficiency at very high speeds.

It is often impossible to maintain the linear speed that gives the best results. For example, 16 gage or 0.060 in. (1.5 mm) cold-rolled steel should be cut at about 150 in./min (64 mm/sec) with 500 watts of CW power from a CO_2 laser. Typical laser-cut parts, however, are too intricate for most motion systems to trace out at this speed. Corners, for example, require that one axis decelerate to zero and the other accelerate to the cutting speed. If motion accelerates at 0.1 g (3.2 ft/sec^2), the table must travel 0.080 in. (2.0 mm) before it reaches 150 in./min (64 mm/sec). The reduced speed in the corner can cause burning of the part.

Laser systems incorporate several ways of dealing with this. One way is to vary CW power as a function of speed. This is very effective when the right relationship is used and the laser responds quickly to power commands. Another method is to change to pulsed operation and cut at low speed. While simpler to implement than power control, pulsing has the obvious disadvantage of increasing processing time.

Controlling the duty cycle as a function of speed has the potential of maximizing speed and quality: at full speed, the laser runs CW. As speed drops in corners or small radii, the laser is pulsed at a high repetition rate. The percent of time that the beam is on is varied to suit the instantaneous speed. The range of travel speeds accomodated by a variable duty cycle is much greater than the range that varying CW power can handle. With a suitable schedule of duty cycle vs. speed, optimum quality can be achieved on any geometry.

Characteristics of Cuts

LASERS ARE USED for cutting because of the high quality of the cuts produced. The attributes of laser cutting are narrow kerf width, smooth surface finish, clean edges, and good dimensional accuracy.

Kerf Width. Kerf widths produced by CO_2 lasers range from .004 to .040 in. (0.1 to 1.0 mm). The usual goal is to generate the narrowest kerf possible, since that minimizes the amount of material that is removed. This has two advantages: The heat input is reduced and accuracy is increased. Short focal length lenses, which have small focused spot sizes, are used to produce narrow kerfs. As material thickness increases, the kerf width tends to widen. Narrow kerfs in thick material make it difficult for the cut material to be ejected. Carbon steel has a tendency to start burning back from the cut line, further widening the kerf.

Roughness. One gage of cut quality is the degree of surface roughness. The ability to produce finished parts can depend on maintaining acceptable smoothness. It is possible to cut 20 gauge or 0.036 in. (0.92 mm) carbon steel sheet with an average roughness (R_a) less than 32 μin. This type of finish is adequate for most purposes. Laser stability, motion-system smoothness, and beam-delivery rigidity must all be optimized to achieve such results. As steel gets thicker, the roughness of the edge increases. The best finish achievable on 3/8 in. (9.5 mm) plate is on the order of 250 μin. R_a. Inert gas cutting, used on many metals to obtain weld-ready edges, uses high pressure to cut. The turbulence created by this pressure increases surface roughness to about 63 μin. on 0.063 in. (1.6 mm) thick material.

Other materials have different characteristics. Acrylic plastic, which vaporizes during cutting, can have an 8 μin. finish on a 1 in. (25 mm) section if the assist gas flow is low enough to avoid turbulence. Plastics such as polycarbonate, which decompose in the beam, are much rougher. It is hard to produce finishes better than 250 μin. on polycarbonate.

Dross. Gas-assisted laser cutting of metal works by pushing molten material out of the narrow channel created by a focused laser beam. Under some circumstances a portion of this material adheres to the bottom of the cut edge. This slag or dross is always undesirable and often unacceptable. With carbon steel, dross appears when the focus is incorrect, the gas pressure is too low, or the travel speed too high. Cuts in stainless steel and aluminum are very likely to have slag adherence; extremely high-assist gas pressures are often needed to eliminate it, even in thin sections. Anti-spatter coatings such as graphite can be used to reduce the adhesion of recast material to the bottom of a laser-cut sheet.

Dimensional Accuracy

THE ACCURACY ATTAINED by laser cut parts is a function of the following:

(1) Table accuracy
(2) Ability of the CNC to contour to the programmed path
(3) Stability of the laser beam

(4) Distortion induced in the workpiece by the cutting process

Machines which produce close-tolerance parts must limit their travel speeds to keep motion errors to a minimum. Once a table and its control are able to follow a programmed path accurately, a beam delivery system must be constructed that will inhibit vibration and deflection during cutting. In addition, changes in focal position or focused spot size will change the effective cutting size, which will alter the dimensions of the part. The workpiece itself is the last source of dimensional error. If the workpiece moves because of thermal expansion during cutting, the parts cut out of it will not match the tool path. As laser cutters approach accuracies of 0.0001 in. (0.0025 mm), thermal effects will be more apparent. The only way to deal with them at present is to distort the part program in the opposite direction.

Setting up for CO2 Cutting

AS INDICATED ABOVE, several areas must be considered before consistent quality cutting can be done.

Alignment. The beam coming from the laser goes through several optical elements before it hits the work. Correct alignment of the beam-delivery system is essential for proper operation.

It is relatively easy to align a fixed beam system. As long as the beam does not clip (hit something opaque like the side of a mirror housing) and goes through the middle of the focusing lens and gas nozzle, the system is aligned. The stationary elements of a fixed beam delivery also tend to stay aligned because they aren't subject to shaking or vibration.

A moving-beam system is aligned if there is no change in the beam location when the axes are run through their range of motion. This is usually checked for each axis at both extremes of its travel, and mirrors are adjusted until the beam stays in place. Moving-beam systems have a tendency to become misaligned because they have many mirrors, long beam paths, and moving parts.

Gantry-type systems are aligned much like moving beams. Rotational axes add some difficulty because they require that the beam be parallel to the axis within 0.2 milliradian to maintain nozzle alignment when the axis rotates.

Beam Focus. Laser-cutting quality depends on the focusing of the beam. The relation of the focal point to the surface of the work is one of the most important variables in the process.

Finding the Focal Point. Since there is significant variation between different lenses of the same nominal focal length, it is necessary to test each one under power. There are several tests for focal point. One method is to make a flat position weld along a sloping plate and measure from the nozzle to the narrowest part of the weld bead. Another is to make a series of cuts in thin metal while changing focus and find the thinnest kerf. Whatever method is used, it is important to be consistent so that process data have continuity.

Setting the Focus Point Position. Focus for most metal cutting is at or slightly below the surface of the work. With inert gas cutting, slag is minimized by locating the focus deeper into the material. The focus can be set with calipers, feeler gauges, or through CNC commands.

Maintaining Focus. It is important to keep the focus in the same place throughout the cutting process. It is easy to do this with flat sheets, but most material has some warping. The cutting system must have some form of focus control to accommodate out-of-flat sheets.

The focusing lens is part of the pressurized head and is limited in the pressure that it can stand. A standard 1.1 in. (28 mm) diameter x 0.10 in. (2.5 mm) thick zinc selenide lens will take up to 80 psi (550 kPa). Higher pressures, such as are used in inert gas cutting of metals, require thicker lenses.

At high pressures, the cost of operating the system increases, from increased gas consumption. In addition, there is more chance of leakage and seal damage.

Assist Gas. Table 16.2 shows commonly used combinations of assist gases and the materials on which they are used.

Concentricity. The focused laser beam must go through the center of the assist gas nozzle to get uniform cutting performance in all directions. All laser systems provide some means of adjusting for concentricity, and there are several ways to check it. One of the most accurate ways is to pierce a hole in thin [0.030 in. (0.75 mm)] steel while observing the material to see the direction that metal is ejected. The lens or nozzle is then adjusted to make the ejected metal form a uniform starburst around the nozzle. This will occur when the beam and nozzle are concentric to within 0.002 in. (50 μmm), which is the order of accuracy needed.

TROUBLE SHOOTING

CONSIDERING THE FACT that carbon dioxide lasers are now being used to process a wide variety of metallic and nonmetallic materials, it can often be difficult to identify causes of poor-quality cuts. A deterioration in cutting performance will usually be attributable to one of the following conditions:

Incorrect Cutting Speed

THE EFFECT OF cutting speed on cut quality for individual materials has been discussed in previous sections. Often the speed which gives the best quality is somewhat slower than the maximum speed. But slowing down beyond a certain point will also reduce the quality. Consistent results will be obtained when the optimum speed is determined empirically.

Relatively small changes in chemical composition of ferrous metals can produce significant changes in optimum cutting speed when cutting with oxygen as the assist gas.

Generally, cutting speed is directly related to laser power and the power density at the workpiece. If it becomes necessary to reduce the cutting speed from a previously determined optimum, then a fault involving loss of power or power density should be suspected. Loss of power from the laser itself will usually be indicated by a lower reading on a power meter internal to the laser. Loss of power could also occur along the path of the beam between the laser and the focusing lens, if any of the reflecting mirrors become dirty. If laser power has not changed, and the material being cut has not changed, then the need to reduce cutting speed will likely have resulted from reduced power density, caused by a larger focused spot at the work surface. The larger spot usually produces a wider cut than was previously obtained.

Other potential causes of reduced power density include a distorted laser output coupler, and organic or other absorbing vapors in the beam path. Freon, trichloroethylene, paint solvents, and polymer plasticizing agents are some such absorbing vapors. A small, positive flow of clean, dry air or nitrogen into one end of the beam path between the laser and the focussing lens is usually sufficient to keep such vapors out.

Incorrect Cutting Gas or Cutting Gas Pressure

WHEN CHANGING FROM cutting one type of material to another, it may be necessary to change the type of gas used. Attempting to cut flammable materials with pure oxygen is a potential fire hazard. Attempting to cut most metals with air or inert gas would give the appearance of cutting with insufficient power.

A deterioration of cut quality can also be noted as the pressure of assist gas varies from its optimum level. One example of this occurs as a gas cylinder empties. The effect noted would be a greater accumulation of oxide slag when cutting metal.

Incorrect Nozzle Height

IN METAL CUTTING, the nozzle should be relatively close to the surface [0.02 to 0.08 in. (0.5 to 2 mm)], to ensure maximum removal of molten slag. When cutting materials where there is no molten cutting product to be removed, the spacing is less critical. In the case of plastics that are softened by heat, such as acrylics, there can be a frosting effect on the cutting edge produced by the gas flow from the nozzle. This effect can be minimized by increasing the nozzle to workpiece distance and by using minimum gas flow.

A height-control probe can be used to maintain a constant nozzle-to-workpiece distance. Both contact and noncontact sensors are available to detect workpiece undulations. Noncontact devices, such as capacitive sensors, are best suited to metals.

Incorrect Lens Focal Length or Beam-Focus Setting

THIS SITUATION IS most likely to occur after changing a lens.

If the point of focus is considerably above or below the nozzle tip, the nozzle will intercept part of the beam and hence become very hot. There will be less power reaching the workpiece, resulting in a reduction of cutting performance. There may be reflections off the bore of the nozzle which can cause burn marks at the side of the cut; this can be particularly noticeable in thermally sensitive materials, such as paper and plastics.

If the focus is inside or just above the nozzle tip, the beam may pass safely through the nozzle orifice, but the beam will be diverging when it reaches the surface of the workpiece; this will result in a wider kerf than normal, and because of the loss of power density, a lower cutting speed may result.

Defective or Dirty Lens

IF THE LENS becomes defective or dirty, then the position of the focal point will change during cutting operations due to thermal lensing. If this happens during a cutting operation, its effect would be as described above for incorrect beam focus setting.

It should be noted that a reduction in focal length can also occur due to a thermally focussing laser output coupler.

Incorrect Alignment of the Beam in the Cutting Head

IF THE LASER beam, as it exits from the nozzle, is not concentric with the gas jet, an asymmetric cutting action can take place. If the misalignment is such that the beam clips the nozzle, overheating of the nozzle will occur.

The effect of asymmetric metal cutting is to induce a burn-out action preferentially on one side of the cut, or to produce a cut with asymmetric dross adherence on the bottom surface. When preferential burn-out occurs, it is due to the beam being offset in the nozzle towards the side where burn out occurs.

Damaged Nozzle Tip

THIS CAN OCCUR as a result of molten oxide blown on the nozzle when piercing metal or when attempting to cut metal too fast.

The effect is the same as a misalignment of the beam in the nozzle, because the gas jet profile will be permanently asymmetric through damage.

Effect of Polarization

POLARIZATION OF THE laser beam is particularly important when cutting ferrous and other reactive metals with oxygen. Laser light may be polarized in several different ways: linearly, elliptically, circularly, or randomly, depending on the design of the laser. The best results in oxygen-assisted cutting of metals are obtained by using circular polarization. Linear and elliptical polarizations will not cut the same in all directions of travel, and they tend to produce a slanted cut edge in some directions. Random polarization will produce an acceptable cut only if it remains consistently random. A laser which produces linearly polarized light can be made to cut well by inserting optical devices (known as *phase shifters* or *circular polarizers*) into the beam path which convert the linear polarization to circular polarization.

INSPECTION AND QUALITY CONTROL

INSPECTION

INSPECTION CRITERIA FOR laser cuts are largely dependent on the material to be cut. Three areas of concern when inspecting laser cut materials are physical appearance, dimensional accuracy, and thermal alterations.

Visual inspection is the first and often the only inspection method in laser cutting. A laser-cut surface is visually inspected for dross (resolidified metal attached at the bottom of the cut), which is usually unacceptable. Surface roughness is viewed qualitatively to determine if the cut is similar to previous acceptable cuts produced in the same metal. Color of the cut metal edge is also a consideration.

Some metals, such as titanium, stainless steels, and nickel based alloys are usually cut with inert gas to produce oxide free cuts with a bright silver appearance. Oxide-free cuts are advantageous when the cut component will subsequently be welded, or when the cut surface is exposed in the end product. The angle of the striations in the laser cut is viewed because of its relationship to the cut speed. If cut rates are near the maximum speed, the vertical striations deflect at the root of the cut. Slower cutting speeds will yield striations that are completely vertical.

Nonmetals such as plastics, ceramics, wood, and composites are often cut with lasers. The appearance of the cut surface for these materials varies greatly. Cuts made with proper conditions produce a fire polished edge on thermoplastics. Thermoset plastics are cut with the objective of minimizing charring or discoloration. Ceramics are visually inspected for cracks due to their low ductility and toughness.

Dimensional accuracy is another factor in cut quality. Components can be inspected with traditional measuring devices and accuracies of ± 0.001 in. (25 μmm) are commonly achieved. A controlling factor in dimensional accuracy is the surface finish of the cut.

The surface roughness on laser cut metals varies through the thickness of the cut. Typically, the top surface is smoother than the bottom surface. Therefore, the surface roughness measurements should always be taken in the same location.

Taper or parallelism is another dimensional value on which laser cuts are evaluated. The minimum value for parallelism is dependent on the material cut. Parallelism in metal cutting can be held within 5 to 25 angular minutes for sheet metal.

Thermal alterations to the substrate can have dramatic effects on the service life of the laser-cut component. Inspection for thermal alterations is usually accomplished destructively.

Metals that are cut with lasers are inspected for the size of the heat-affected zone (HAZ), the amount of resolidified metal on the cut surface (recast), and the length and number of microcracks penetrating into the recast, HAZ, and base metal.

The HAZ in laser-cut metals varies with composition and thickness. The width of the HAZ is usually between 0.001 and 0.010 in. (0.025 to 0.25 mm). The HAZ is uniform along the face of the cut. Dross on the bottom of the cut can increase the HAZ at the root of the cut.

Laser cutting of metals produces a liquid phase in the metal, which is removed with a coaxial gas jet. Some of the molten phase clings to the base metal and resolidifies on the walls of the cut surface. This resolidified metal is known as *recast* or *remelt*. The depth of the recast is usually only a few thousandths of an inch in laser cutting.

Microcracks can result from the thermal input of laser cutting. The laser cutting process can produce high thermal stresses at the cut edge which may result in the nucleation of microcracks. These small cracks can be detrimental to the service life of the laser-cut component if the material has poor toughness. Some metals will microcrack easier than others. For instance, heat treatable aluminum alloys lose ductility at elevated temperatures, a phenomenon known as hot shortness. These metals are particularly sensitive to the formation of microcracks.

Microcracks are quantified by metallographic cross-section to determine either maximum crack length, average crack length, or the total number of cracks. The location of the microcracks is also pertinent. Microcracks in the recast layer may be acceptable, but microcracks extending into the HAZ or parent metal may not be acceptable. Acceptability of the size, number, and location of microcracks is dependent on the toughness of the metal, the intended service for the laser-cut component, and industry specifications.

Thermal alterations to nonmetals could be advantageous or detrimental. A laser cut in a fibrous material in a thermoplastic will seal the edge, while mechanical cuts will leave a frayed edge. Delamination caused by laser cutting in other composites can lead to premature failure.

QUALITY

HIGH QUALITY LASER cuts can be produced when the proper procedures are followed. The high-energy density achievable with this process allows materials to be separated with minimal-heat input and minimum alteration of the cut surface.

A key factor in obtaining good quality with minimum-heat input to the material is the laser mode. The mode governs the energy distribution across the laser beam. The optimum laser mode has a gaussian distribution. This gaussian distribution in laser modes is referred to as TEM_{00}. A gaussian mode allows the laser beam to be focused to the smallest spot size for a given focal-length lens. The smallest spot size will yield minimum heat input and maximum feed rates.

The focal length of the lens also affects quality. Usually, as the material thickness increases, the focal length should also be increased for a given beam diameter. The longer focal length lens will have greater depth of field, which will maintain the proper power density to cut the material and minimize taper.

Focal position in the material is important to maintain consistant results. Often this is the only variable controlled in real time using autofocus techniques. The two most common autofocus methods are mechanical and capacitive sensor. The mechanical method operates on a spring-loaded mechanism that rides on the material being cut to maintain proper focus. This method is primarily used when cutting flat sheet. The capacitive sensor method is used on conductive materials.

The proper combination of the above variables will produce excellent quality cuts in a wide variety of materials.

LASER CUTTING SAFETY

THE AREAS OF safety concern for laser cutting may be divided into the following categories:

(1) General safety
(2) High-voltage power supplies
(3) Exposure to direct or reflected light
(4) Fumes from materials being cut

Each of these areas is discussed separately in the following sections. The section on general safety applies to the other sections since it includes definitions and terms used throughout this guide.

Laser safety guidelines should be stressed and understood by all persons who operate or work in the vicinity of lasers.

GENERAL SAFETY

THE STANDARD USED in the United States to design a laser facility is ANSI Z136.1 (latest edition), *Safe Use of Lasers*. This specification details the minimum criteria to be met for facility construction and defines the common terminology for laser safety. Although new facilities should have no difficulty in meeting these requirements, it should be remembered that modifications to existing facilities should also meet these requirements.

ANSI Z136.1 also defines the hazard classifications for lasers. Four classes are defined, of which only Class IV lasers ("high power") are typically used for cutting. However, some laser cutting systems do use a "low-power," visible-light, helium-neon laser (He-Ne) for beam-alignment purposes. Proper warning signs or signals should be posted around areas that are exposed to laser beams. Some form of light-tight enclosure must surround areas in which these beams are exposed to the atmosphere. It should be remembered that a high-power collimated or unfocused beam is more dangerous over large distances than focused beams, which diverge much more rapidly.

Some lasers may be extremely noisy, especially if used in enclosed areas. A hearing protection specialist should be consulted to recommend the proper methods to guard against excessive noise.

HIGH-VOLTAGE POWER SUPPLIES

SINCE HIGH VOLTAGES as well as large capacitive storage devices are associated with lasers, the possibility for lethal electric shock is ever present. All reported laser-related deaths have been associated with the high voltage present in the laser system.

All electrical components should comply with NEMA Standards and ANSI/NFPA 70 (latest edition). All personnel working around the high-voltage components of a laser should be trained in the proper safety techniques for electrical systems. Appropriate grounding and interlocking devices should be employed around any high-voltage components. There should be provisions for discharging capacitors before human access to areas containing electrically charged components.

EXPOSURE TO DIRECT OR REFLECTED LIGHT

BEAM EXPOSURE IS the most common safety hazard associated with laser cutting. Lasers that can cut engineering materials can also cause great damage to the human body. Laser beam exposure can cause eye damage, including burning of the cornea or the retina, or both. Lasers may also cause severe skin and tissue damage on unprotected areas of the body.

Two main references are available for eye protection around lasers: ANSI Z87.1 (latest edition) on eye and face protection, and the Laser Institute of America's *Guide for the Selection of Laser Eye Protection*, provide guidelines for proper eye protection. The main concern when choosing eye protection for lasers is blocking the wavelength of light being used for welding or cutting. At high-beam power, lasers tend to produce plasma plumes of extreme brilliance. Shaded glasses must be worn to protect against these brilliant light sources. Frequent eye examinations should also be part of the eye protection program to ensure that eye protection is adequate.

FUMES FROM MATERIALS BEING CUT

MANY MATERIALS THAT are cut with lasers emit toxic vapors, dusts, or fumes. Studies have shown that laser cutting of polymethyl metharcrylate, polyvinyl chloride, and Kelvar produces byproducts containing toxicants and carcinogenic compounds. Precautions should be taken so that proper ventilation is supplied in the area of laser operation. Before cutting any material, Material Safety Data Sheets should be consulted to determine associated health hazards and prevention techniques. Fire extinguishers should also be available in case a fire is started by the laser cutting process.

WATER JET CUTTING

INTRODUCTION

WATER JET MACHINING, also called *hydrodynamic machining*, cuts a wide variety of materials, both nonmetals and metals, using a high-velocity water jet. The jet is formed by forcing water through a 0.004 to 0.024 in. (0.1 to 0.6 mm) diameter orifice in a man-made sapphire under high pressure (30,000 to 60,000 psi [207 to 414 MPa]). Jet velocities range from 1700 to 3000 ft/s (520 to 914 m/s). At these speeds and pressures, the water erodes many materials rapidly, acting like a saw blade. The water stream, with a flow rate of 0.1 to 5 gallons/min. (0.4 to 19 L/min) is usually manipulated by a robot or gantry system, but small workpieces may be guided past a stationary water jet by hand. A typical range of nozzle to work distances is 0.010 to 1.0 in. (0.25 to 25 mm), with distances under 1/4 in. (6.4 mm) being preferred.

Metals and other hard materials are cut by adding an abrasive in powder form to the water stream. With this method, called hydroabrasive machining or abrasive-jet machining, the abrasive particles (often garnet) are accelerated by the water and accomplish most of the cutting. Higher flow rates of water are required to accelerate the abrasive particles.

Materials are cut cleanly, without ragged edges (unless the traverse speed is too high), without heat, and generally faster than on a bandsaw. A narrow (0.030 to 0.100 in. [0.8 to 2.5 mm]), smooth kerf is produced. There are no thermal, delamination, or deformation problems when properly applied. Dust is nonexistent.

HISTORY

THE ANCIENT EGYPTIANS used sand combined with water for mining and cleaning. Sandblasters in this century used a pressurized stream [500 psi (3400 kPa)] for cleaning and paint removal. In 1968, Franze patented a concept for a very high-pressure water jet cutting system. His patent for producing a coherent cutting stream involved the addition of a long-chain liquid polymer to the water stream to prevent it from breaking up as it left the exit orifice of the pressurized chamber.

Prior to its application as a cutting tool in industry, high-pressure water was used for cutting in both forestry and mining. In the 1970's, high pressure (30 000 to 55 000 psi [207 to 379 MPa]) water jet cutting technology was developed to cut nonmetals. The first commercial water jet cutting system was sold in 1971, to cut furniture shapes from laminated paper stock that bandsaws, reciprocating saws, and routers couldn't handle well. In 1983, the process was modified by the addition of abrasives such as silica and garnet particles to the stream to cut metals, composites, and other hard materials.

SCOPE

WATER JET AND abrasive water jet systems compete with such processes as bandsaws, the reciprocating knife, flame cutting, plasma, and laser cutting. They can handle materials that suffer heat damage from thermal processes or gum up mechanical cutting tools. In some cases, they can cost-effectively replace three operations: rough-cutting, milling, and deburring of contoured shapes.

The extremely wide range of materials which may be cut can be seen from Table 16.8. Water and abrasive jet machining are often thought of as sheet-material processing systems, but this need not be the case. Examples of cuts made to test the limits of the process are 7.5 in. (190 mm) thick carbon steel, 3 in. (75 mm) thick 7075 T-6 aluminum, 2.5 in. (64 mm) thick graphite/epoxy with 470 plies, and 10 in. (250 mm) thick titanium.

USES AND ADVANTAGES

THE WIDE APPLICATION range and lack of heat are the major advantages of water jet cutting. The versatility of the process is demonstrated by the simultaneous cuts through carbon steel, brass, copper, aluminum, and stainless steel shown in Figure 16.9. An abrasive jet is particularly good for cutting laminates of different materials, including sandwiches of metals and nonmetals. Since the abrasive jet can penetrate most materials, no predrilling is required to start, and cutting may be omnidirectional. Multiple shapes can be nested and cut, depending on the limits of the control system and the workpiece size. Tapering of the kerf is generally not a problem unless the cutting speed is too high, the workpieces are too thick, or worn nozzles are involved. Minimal or no deburring is required. The process is easily adapted to robotic control.-

There are no tools to wear out, other than the orifice and the nozzle; perhaps there will be some wear on the robot mechanism. Minimal lateral forces are generated, simplifying fixturing.

Tolerances depend on the equipment and the workpiece material and thickness, but can be as close as ± 0.004 in. (0.1 mm) on dimensions and ± 0.002 (50 μm) on positioning. Laser cutting achieves closer tolerances.

Finishes vary widely. Abrasive water jet finishes on aerospace components have been reported in the 63 to 250 μin. Ra range.

In simple water jet cutting, the kerf width is usually 0.005 in. (0.13 mm) or wider; in abrasive water jet cutting it is usually 0.032 in. (0.8 mm) or larger. The water jet tends to spread as it leaves the nozzle, so the kerf is wider at the bottom than at the top. Kerf tapering may be reduced by adding long chain polymers, such as polyethelyne oxide, to the water, or by reducing cutting speed.

With the exception of sophisticated systems for aerospace applications, most abrasive and water jet CNC systems are relatively easy to program.

LIMITATIONS

RELATIVELY LOW CUTTING speeds are the chief limitation of the water jet cutting system. Typical cutting speeds are shown in Table 16.9. Another limitation is that a device must be provided to collect the exhaust liquid from the cutting stream. Initial capital costs are high because of the pumps and pressure chamber required to propel and direct the water jet.

The material to be cut must be softer than the abrasive used. Very thin ductile metals tend to suffer bending stress from an abrasive jet and show exit burrs. Ceramics cut with a water jet show a decrease in as-fired strength.

Nozzles must be replaced every two to four hours (sometimes even more frequently) in abrasive water jet sys-

Table 16.8
Water Jet Cutting Speeds on Various Materials

Material	Thickness in.	Thickness mm	Travel Speed in./min.	Travel Speed mm/s
ABS Plastic	0.080	2.0	80	34
Cardboard	0.055	1.4	240	102
Corrugated cardboard	0.250	6.4	120	51
Circuit board	0.103	2.6	100	423
Leather	0.063	1.6	3800	1600
Plexiglass	0.118	3.0	35	15
Rubber	0.050	1.3	3600	1500
Rubber-backed carpet	0.375	9.5	6000	2500
Wood	0.125	3.2	40	17

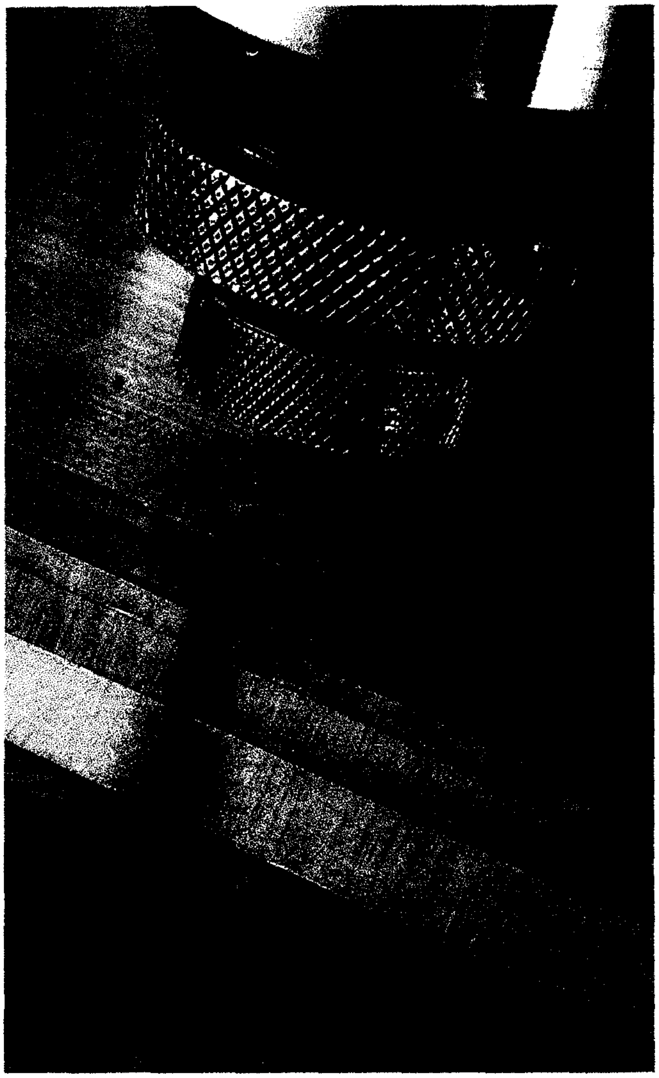

Figure 16.9–Abrasive Jet Stack Cutting of Various Metals

tems. The abrasive grit wears the carbide nozzles to an out-of-round condition, and the jet loses its symmetry, causing cut quality to deteriorate.

The water supply should optimally be deionized water filtered to 0.5 micron particle size to reduce maintenance, but other water-treatment options are possible. Many systems operate successfully with simple line filters on the incoming municipal water supply, if the water is relatively soft. Waste water and slurry from the cutting operation must be disposed of properly.

The fatigue life of abrasive water jet cut edges in critical aerospace structures can be lower than for a raw-sheared edge if the abrasive particle used is a coarse 60 grit. Decreasing the particle size to 150 grit increases fatigue life 50 percent or more, but at a corresponding decrease in cutting speed.

FUNDAMENTALS

INCOMING WATER FIRST passes through a booster pump to pressurize it to about 190 psi (1300 kPa) and to filter it. Then an intensifier pump (a hydraulically driven double acting reciprocating type pump) creates a water pressure of 30 000 to 60 000 psi (207 to 414 MPa) with a flow rate of up to 3.5 gallons/min. (13.3 L/min.). Forced through a sapphire orifice, the stream forms a water jet. The jet velocity depends on the water pressure.

For abrasive cutting, dry abrasives may be fed from a hopper into a mixing chamber. There the water accelerates the particles to supersonic velocities. The high-speed slurry is focused and then exits the nozzle in a stream 0.020 to 0.090 in. (0.5 to 2.3 mm) in diameter. Water jets can be made with jet diameters down to 0.003 in. (80 μmm) in diameter, suitable for cutting paper. Abrasive jets are generally not made smaller than 0.009 in. (0.23 mm) in diameter.

Depending on the properties of the target material, the actual cutting is a result of erosion, shearing, or failure under rapidly changing localized stress fields. The process does not produce thermal or mechanical distortions. There is a slight work hardening of metals at the cut surface. Downstream of the kerf, the water or water-abrasive stream is collected in a tank or catcher.

PROCESS VARIATIONS

CUTTING DEPTH AND surface characteristics of the cut vary with the following variables: (1) waterjet pressure and diameter; (2) the size, type, and flow rate of the abrasive material; (3) traverse speed; (4) angle of cutting; and (5) number of passes.

Increasing the pressure, increasing the jet diameter, and lowering the traverse speed all increase the thickness and density of workpieces that can be cut with a water jet. Increasing the flow rate of the water, the abrasive, or both and increasing the abrasive size will increase the cutting speed of an abrasive jet. Use of smaller abrasive particle sizes and slower cutting speeds will improve the edge quality of both cuts.

Increasing the water pressure in abrasive jet cutting increases the plate thickness cutting capability because of increased particle velocities. The optimum pressure tends to remain in the 30 000 to 45 000 psi (207 to 310 MPa) range, because higher pressures result in increased equipment maintenance costs with only slight process advantages.

Fine abrasive particles, below 150 mesh, are relatively ineffective; the most effective general purpose size for cutting metals is 60 or 80 mesh. For very hard ceramics, boron

Table 16.9
Cutting Speeds on Various Materials With Abrasive Water Jet

Material	Thickness		Travel Speed	
	in.	mm	in./min.	mm/s
Aluminum	0.125	3.2	40	17
Aluminum	0.50	12.7	18	8
Aluminum	0.75	19.0	5	2
Brass	0.125	3.2	20	8.5
Brass	0.425	10.8	5	2
Bronze	1.0	25.4	1	0.5
Copper	0.063	1.6	35	15
Copper	0.625	15.9	8	3
Lead	2.0	50.8	8	3
Carbon steel	0.75	19.1	8	3
Cast iron	1.5	38.1	1	0.5
Stainless steel	0.1	2.5	25	25
Stainless steel (304)	1.0	25.4	4	2
Stainless steel(304)	4.0	101.6	1	0.5
Armor plate	0.75	19.1	10	4
Inconel	0.625	15.9	8	3
Inconel 718	1.25	31.8	1	0.5
Titanium	0.025	0.6	60	25
Titanium	0.500	12.7	12	5
Tool steel	0.250	6.4	10	4
Ceramic (99.6% aluminum)	0.025	0.6	6	2.5
Fiberglass	0.100	2.5	200	85
Fiberglass	0.250	6.4	100	42
Glass	0.250	6.4	100	42
Glass	0.75	19.1	40	17
Graphite/epoxy	0.250	6.4	80	34
Graphite/epoxy	1.0	25.4	15	6
Kevlar	0.375	9.5	40	17
Kevlar	1.0	25.4	3	1.3
Lexan	0.5	12.7	12	5
Metal-matrix composite	0.125	3.2	30	13
Pheonolic	0.5	12.7	10	4
Plexiglass	0.175	4.4	50	21
Rubber belting	0.300	7.6	200	85

carbide abrasive is sometimes used.

High-abrasive flow rates result in high cutting costs: a nominal 2 lb/min flow rate at $0.12/lb will result in an hourly cost of $14.40, not including cleaning and disposal costs. This represents a large portion of the total hourly cost. These high flow rates also result in rapid wear of the mixing nozzles.

While many operations are completed in a single pass, the optimum cutting of thick metals may require multiple passes at an optimum traverse rate. This will increase the standoff distance at each pass, requiring a lowered traverse rate.

EQUIPMENT

THE KEY PIECES of equipment for a water jet or an abrasive water jet system are (1) the special high-pressure pump or intensifier used to provide the stream of water, (2) the plumbing and tank or catcher unit to handle the water, (3) the gantry, robotic, or other delivery system to traverse and guide the water jet, and (4) the nozzle assembly unit, which forms the jet. In the case of abrasive water jets, there is an abrasive delivery system including a hopper, a metering valve, and a mixing unit, which mixes the abrasive par-

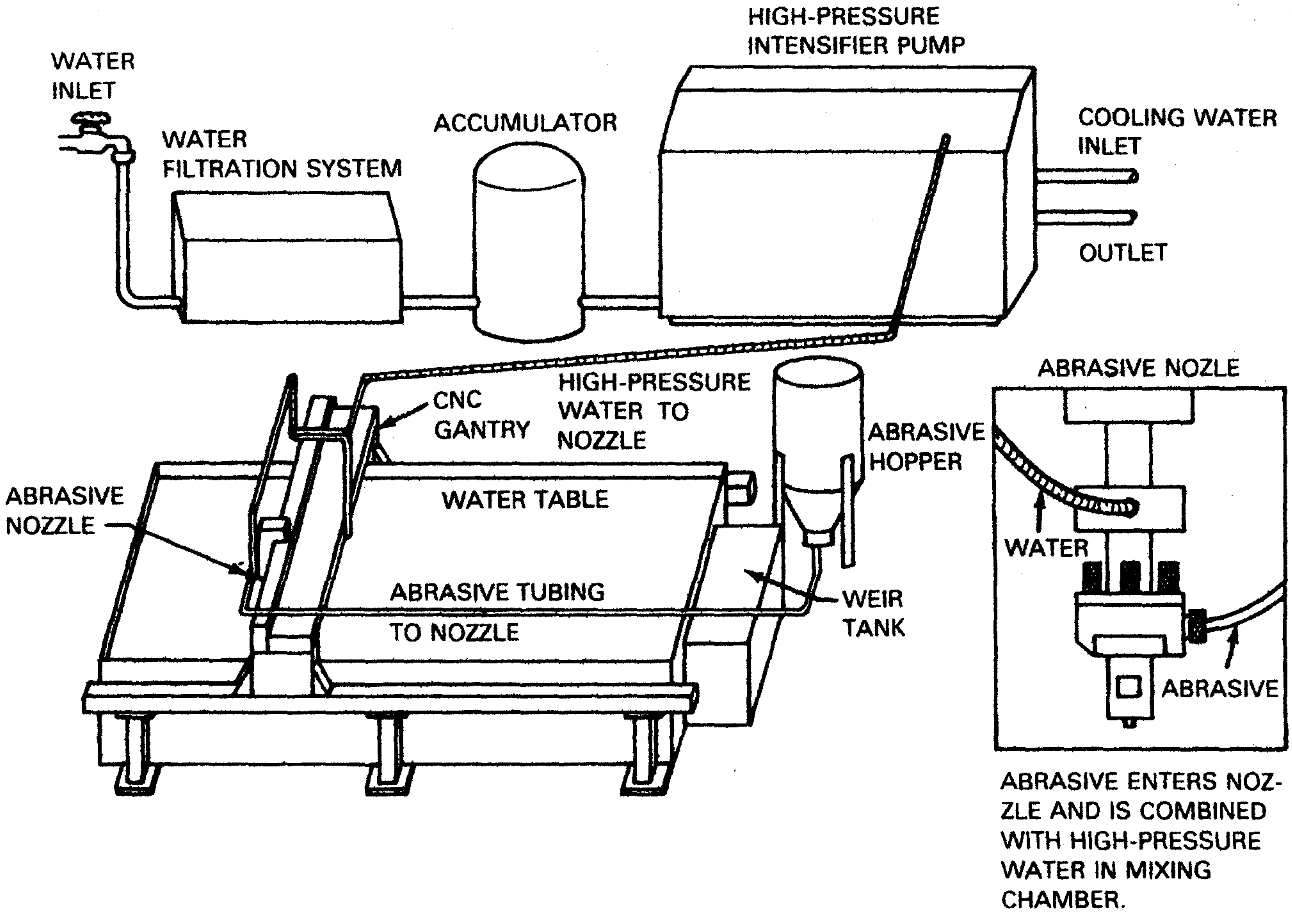

Figure 16.10–Typical Abrasive Water Jet Cutting System

ticles into the water stream. See Figure 16.10.

Equipment is available in a range from individual components to finished machine tools. More complex systems, such as 5-axis robotic systems, tend to be custom-built. There are several instances of flame cutting machines converted to water jet cutting.

Consumables

THE MAIN WEAR item on the equipment is the sapphire orifice and, on abrasive systems, the carbide abrasive nozzle. On pure water jet systems, a man-made sapphire may last up to 200 hrs. In abrasive systems, the carbide abrasive nozzles last only two to four hours. Other consumables are water, abrasive, and electricity. Abrasive particles are used at the rate of 0.25 lb. to 3.0 lbs. (0.1 to 1.4 kg) per minute.

Accessory Equipment

AUXILIARY EQUIPMENT FOR loading and unloading workpieces, such as cranes, gantry robots, or pedestal mounted robots, may used. This work handling equipment is generally distinct from the system, robotic or other, which drives the water jet cutting head.

For contour cutting in five axes it may be necessary to have a special catcher device to stop the water jet and dissipate its energy.

Hard water may require a water-treatment system.

Periodic cleaning of the water table to remove abrasive grit and metal particles generated during cutting is a necessary operation.

APPLICATIONS

THERE ARE NOW hundreds of factory applications in place in dozens of countries, including over 100 water-jet-equipped robots. Industries which use the technology include automotive, aerospace and defense, building supplies, circuit boards, fabrication shops, foundries, food, glass, job shops, mining, oil and gas well equipment, packaging, paper, rubber, shipyards, and steel service centers. A steel, circular saw-blade cut using hydroabrasive machining is shown in Figure 16.11.

Aerospace applications include the abrasive jet cutting of advanced composite structures; titanium, nickel, and cobalt super-alloys; and stack cutting of metals and fiberglass. Abrasive water jet is particularly useful for cutting composites because of the absence of both delamination and heat damage.

Automotive companies and their suppliers use water jets and abrasive jets for trimming carpeting, composite panels and bumpers, door panel linings, and glass.

Foundries use abrasive jets to remove exterior burned-in sand from iron castings and mono-shell ceramic coatings from investment castings. Degating and definning are also common applications.

ECONOMICS

THE TOTAL HOURLY cost of operating a $200 000 (capital equipment cost) abrasive water jet system has been estimated at $27 per hour. This includes maintenance, electricity, abrasive additive, and nozzle wear. Labor cost would be extra.

SAFETY CONSIDERATIONS

SINCE THE WATER jet or abrasive jet would easily cut flesh or bone, operator protection is required. Noise generated during cutting is typically in the range of 80-95 decibels, but may reach 120 dB. Safety enclosures provided to protect the operator from the cutting operation are designed to deaden sound, but the operator should use ear protection.

Maintenance personnel need to be trained to handle the high-pressure equipment and water lines. Each cutting installation should be designed to provide shielding to prevent a discharge of high-pressure water if the high pressure should rupture any of the tubing. Pressure sensors are used to shut down the system in case of tubing failure.

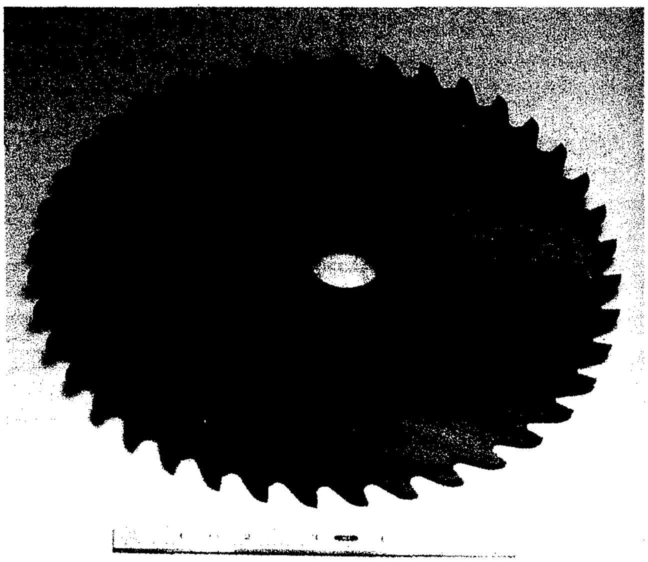

Figure 16.11–Steel Saw-Blade Cut Using Hydroabrasive Machining

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CHAPTER 17

SPOT, SEAM, AND PROJECTION WELDING

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CHAPTER 17

SPOT, SEAM, AND PROJECTION WELDING

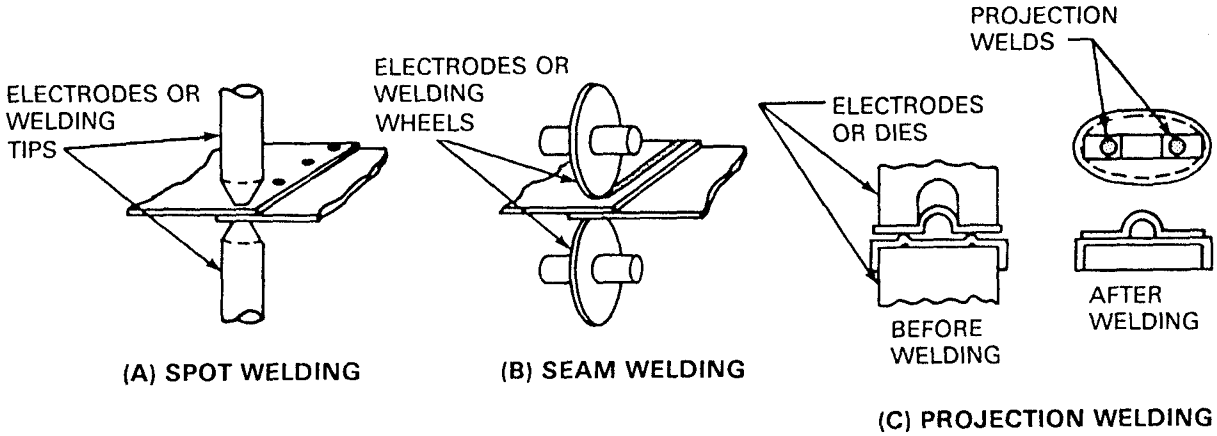
FUNDAMENTALS OF THE PROCESSES

DEFINITION AND GENERAL DESCRIPTION

SPOT, SEAM, AND projection welding are three resistance welding processes in which coalescence of metals is produced at the faying surfaces by the heat generated by the resistance of the work to the passage of electric current. Force is always applied before, during, and after the application of current to confine the weld contact area at the faying surfaces and, in some applications, to forge the weld metal during postheating. Figure 17.1 illustrates the three processes.

In spot welding, a nugget of weld metal is produced at the electrode site, but two or more nuggets may be made simultaneously using multiple sets of electrodes. Projection welding is similar except that nugget location is determined by a projection or embossment on one faying surface, or by the intersection of parts in the case of wires or rods (cross-wire welding). Two or more projection welds can be made simultaneously with one set of electrodes.

Seam welding is a variation of spot welding in which a series of overlapping nuggets is produced to obtain a continuous, leak tight seam. One or both electrodes are generally wheels that rotate as the work passes between them. A



(A) SPOT WELDING

(B) SEAM WELDING

(C) PROJECTION WELDING

Figure 17.1–Simplified Diagrams Depicting the Basic Process of

seam weld can be produced with spot welding equipment but the operation will be much slower.

A series of separate spot welds may be made with a seam welding machine and wheel electrodes by suitably adjusting the travel speed and the time between welds. Movement of the work may or may not be stopped during the spot weld cycle. This procedure is known as *roll spot welding.*

PRINCIPLES OF OPERATION

SPOT, SEAM, AND projection welding operations involve a coordinated application of electric current and mechanical pressure of the proper magnitudes and durations. The welding current must pass from the electrodes through the work. Its continuity is assured by forces applied to the electrodes, or by projections which are shaped to provide the necessary current density and pressure. The sequence of operation must first develop sufficient heat to raise a confined volume of metal to the molten state. This metal is then allowed to cool while under pressure until it has adequate strength to hold the parts together. The current density and pressure must be such that a nugget is formed, but not so high that molten metal is expelled from the weld zone. The duration of weld current must be sufficiently short to prevent excessive heating of the electrode faces. Such heating may bond the electrodes to the work and greatly reduce their life.

The heat required for these resistance welding processes is produced by the resistance of the workpieces to an electric current passing through the material. Because of the short electric current path in the work and limited weld time, relatively high welding currents are required to develop the necessary welding heat.

Heat Generation

IN AN ELECTRICAL conductor, the amount of heat generated depends upon three factors: (1) the amperage, (2) the resistance of the conductor (including interface resistance), and (3) the duration of current. These three factors affect the heat generated as expressed in the formula

$$Q = I^2Rt \tag{17.1}$$

where:
Q = heat generated, joules
I = current, amperes
R = resistance of the work, ohms
t = duration of current, seconds

The heat generated is proportional to the square of the welding current and directly proportional to the resistance and the time. Part of the heat generated is used to make the weld and part is lost to the surrounding metal.

The welding current required to produce a given weld is approximately inversely proportional to the square root of the time. Thus, if the time is extremely short, the current required will be very high. A combination of high current and insufficiently short time may produce an undesirable distribution of heat in the weld zone, resulting in severe surface melting and rapid electrode deterioration.

The secondary circuit of a resistance welding machine and the work being welded constitute a series of resistances. The total resistance of the current path affects the current magnitude. The current will be the same in all parts of the circuit regardless of the instantaneous resistance at any location in the circuit, but the heat generated at any location in the circuit will be directly proportional to the resistance at that point.

An important characteristic of resistance welding is the rapidity with which welding heat can be produced. The temperature distribution in the work and electrodes, in the case of spot, seam, and projection welding, is illustrated in Figure 17.2. There are, in effect, at least seven resistances connected in series in a weld that account for the temperature distribution. For a two thickness joint, these are the following:

(1) 1 and 7, the electrical resistance of the electrode material.

(2) 2 and 6, the contact resistance between the electrode and the base metal. The magnitude of this resistance depends upon the surface condition of the base metal and the electrode, the size and contour of the electrode face, and the electrode force. (Resistance is roughly inversely proportional to the contacting force.) This is a point of high heat generation, but the surface of the base metal does not reach its fusion temperature during the current passage, due to the high thermal conductivity of the electrodes(1 and 7) and the fact that they are usually water cooled.

(3) 3 and 5, the total resistance of the base metal itself, which is directly proportional to its resistivity and thickness, and inversely proportional to the cross-sectional area of the current path.

(4) 4, the base metal interface resistance at the location where the weld is to be formed. This is the point of highest resistance and, therefore, the point of greatest heat generation. Since heat is also generated at points 2 and 6, the heat generated at interface 4 is not readily lost to the electrodes.

Heat is generated at all of these locations, not at the base metal interface alone. The flow of heat to or from the base metal interface is governed by the temperature gradient established by the resistance heating of the various components in the circuit. This in turn assists or retards the creation of the proper localized welding heat.

Heat will be generated in each of the seven locations in Figure 17.2 in proportion to the resistance of each. Welding heat, however, is required only at the base metal interface, and the heat generated at all other locations should be minimized. Since the greatest resistance is located at 4, heat is

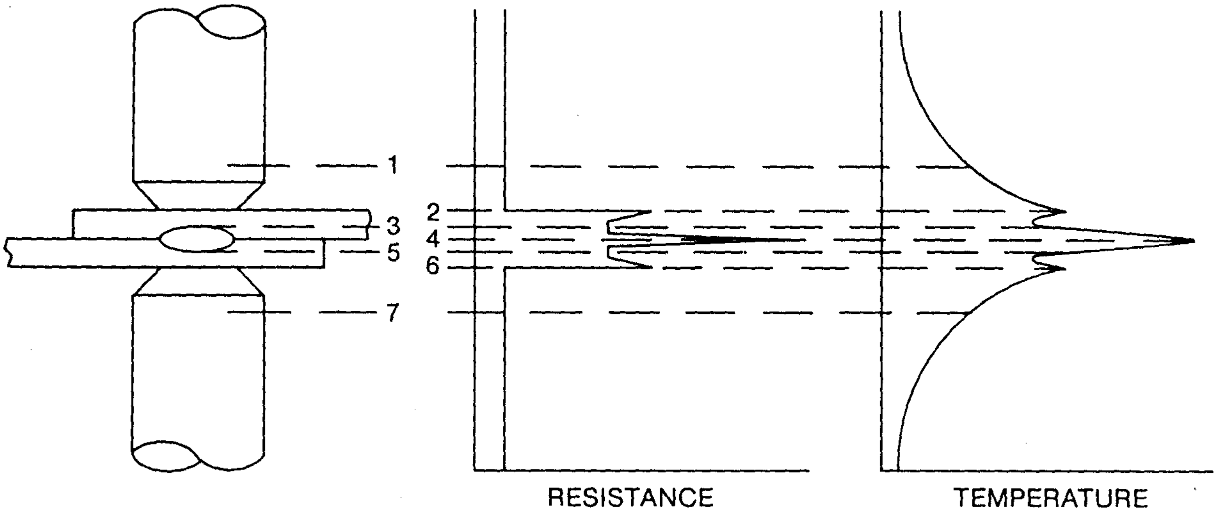


Figure 17.2–Graphs of Resistance and Temperature as a Function of Location in the Diagrammed Circuit

most rapidly developed at that location. Points of next lower resistance are 2 and 6. The temperature rises rapidly at these points also, but not as fast as at 4. After about 20 percent of the weld time, the heat gradient may conform to the profile shown in Figure 17.2. Heat generated at 2 and 6 is rapidly dissipated into the adjacent water-cooled electrodes 1 and 7. The heat at 4 is dissipated much more slowly into the base metal. Therefore, while the welding current continues, the rate of temperature rise at plane 4 will be much more rapid than at 2 and 6. The welding temperature is indicated on the chart at the right of Figure 17.2, by the number of dots within the drawing leading to the matching curve.

In a well-controlled weld, the welding temperature will first be reached at numerous point contacts at the interface that melt and with time quickly grow into a nugget.

Factors that affect the amount of heat generated in the weld joint by a given current for a unit of weld time are (1) the electrical resistances within the metal being welded and the electrodes, (2) the contact resistances between the workpieces and between the electrodes and the workpieces, and (3) the heat lost to the workpieces and the electrodes.

Effect of Welding Current. In the formula, $Q = I^2Rt$, current has a greater effect on the generation of heat than either resistance or time. Therefore, it is an important variable to be controlled. Two factors that cause variation in welding current are fluctuations in power line voltage and variations in the impedance of the secondary circuit with AC machines. Impedance variations are caused by changes in circuit geometry or by the introduction of varying masses of magnetic metals into the secondary loop of the machine. Direct current machines are not significantly affected by magnetic metals in the secondary loop and are little affected by circuit geometry.

In addition to variations in welding current magnitude, current density may vary at the weld interface. This can result from shunting of current through preceding welds and contact points other than those at the weld. An increase in electrode face area, or projection size in the case of projection welding, will decrease current density and welding heat. This may cause a significant decrease in weld strength.

A minimum current density for a finite time is required to produce fusion at the interface. Sufficient heat must be generated to overcome the losses to the adjacent base metal and the electrodes.

Weld nugget size and strength increase rapidly with increasing current density. Excessive current density will cause molten metal expulsion (resulting in internal voids), weld cracking, and lower mechanical strength properties. Typical variations in shear strength of spot welds as a function of current magnitude are shown in Figure 17.3. In the case of spot and seam welding, excessive current will overheat the base metal and result in deep indentations in the parts and, it will cause overheating and rapid deterioration of the electrodes.

Effect of Weld Time. The rate of heat generation must be such that welds with adequate strength will be produced without excessive electrode heating and rapid deterioration. The total heat developed is proportional to weld time. Essentially, heat is lost by conduction into the surrounding base metal and the electrodes; a very small amount is lost by radiation. These losses increase with increases in weld time and in metal temperature, but they are essentially uncontrollable.

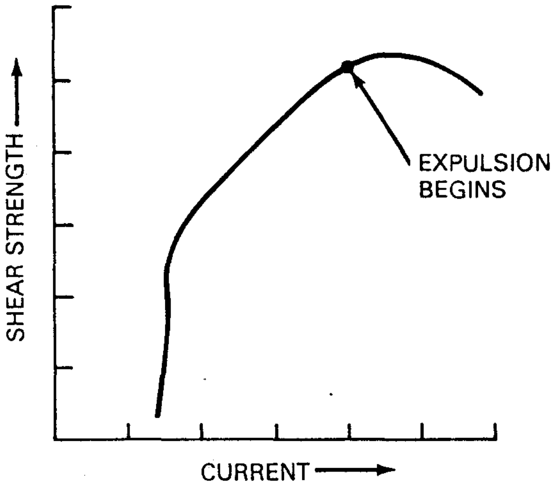


Figure 17.3–Effect of Welding Current on Spot Weld Shear Strength

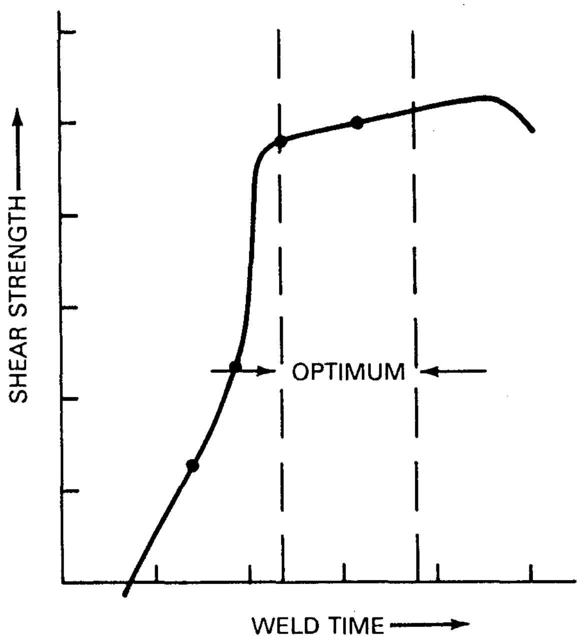


Figure 17.4–Tensile-Shear Strength as a Function of Weld Time

During a spot welding operation, some minimum time is required to reach melting temperature at some suitable current density. If current is continued, the temperature at plane 4 in the weld nugget will far exceed the melting temperature, and the internal pressure may expel molten metal from the joint. Generated gases or metal vapor may be expelled together with minute metal particles. If the work surfaces are scaly or pitted, gases and particles may also be expelled at planes 2 and 6.

Excessively long weld time will have the same effect as excessive amperage on the base metal and electrodes. Furthermore, the weld heat-affected zone will extend farther into the base metal.

In most cases, the heat losses at some point during an extended welding interval will equal the heat input; temperatures will stabilize. An example of the relationship between weld time and spot weld shear strength is shown in Figure 17.4, assuming all other conditions remain constant.

To a certain extent, weld time and amperage may be complementary. The total heat may be changed by adjusting either the amperage or the weld time. Heat transfer is a function of time and the development of the proper nugget size requires a minimum length of time, regardless of amperage.

When spot welding heavy plates, welding current is commonly applied in several relatively short impulses without removal of electrode force. The purpose of pulsing the current is to gradually build up the heat at the interface between the workpieces. The amperage needed to accomplish welding can rapidly melt the metal if the heat pulse time is too long, resulting in expulsion.

Effect of Welding Pressure. The resistance *R* in the heat formula is influenced by welding pressure through its effect on contact resistance at the interface between the workpieces. Welding pressure is produced by the force exerted on the joint by the electrodes. Electrode force is considered to be the net dynamic force of the electrodes upon the work, and it is the resultant pressure produced by this force that affects the contact resistance.

Pieces to be spot, seam, or projection welded must be clamped tightly together at the weld location to enable the passage of the current. Everything else being equal, as the electrode force or welding pressure is increased, the amperage will also increase up to some limiting value. The effect on the total heat generated, however, may be the reverse. As the pressure is increased, the contact resistance and the heat generated at the interface will decrease. To increase the heat to the previous level, amperage or weld time must be increased to compensate for the reduced resistance.

The surfaces of metal components, on a microscopic scale, are a series of peaks and valleys. When they are subjected to light pressure, the actual metal-to-metal contact will be only at the contacting peaks, a small percentage of the area. Contact resistance will be high. As the pressure is increased, the high spots are depressed and the actual metal-to-metal contact area is increased, thus decreasing the contact resistance. In most applications, the electrode material is softer than the workpieces; consequently, the application of a suitable electrode force will produce better contact at the electrode-to-work interfaces than at the interface between the workpieces.

Influence of Electrodes. Electrodes play a vital role in the generation of heat because they conduct the welding current to the work. In the case of spot and seam welding, the electrode contact area largely controls the welding current density and the resulting weld size. Electrodes must have good electrical conductivity, but they must also have adequate strength and hardness to resist deformation caused by repeated applications of high electrode force. Deformation or "mushrooming" of the electrode face increases the contact area and decreases both current density and welding pressure. Weld quality will deteriorate as tip deformation proceeds; consequently, the electrodes must be reshaped or replaced at intervals to maintain adequate heat generation for acceptable weld properties.

When the electrodes are slow in following a sudden decrease in total work thickness, a momentary reduction in pressure will occur. If this happens while the welding current is on, interface contact resistance at locations 2, 4, and 6 and the rate of heat generation will increase. An excessive heating rate at the three contacting surfaces tends to cause overheating and violent expulsion of molten metal. Molten metal is retained at each interface by a ring of unfused metal surrounding the weld nugget. A momentary reduction in electrode force permits the internal metal pressure to rupture this surrounding ring of unfused metal. Internal voids or excessive electrode indentation may result. Weld properties may fall below acceptable levels, and electrode wear will be greater than normal.

Influence of Surface Condition. The surface condition of the parts influences heat generation because contact resistance is affected by oxides, dirt, oil, and other foreign matter on the surfaces. The most uniform weld properties are obtained when the surfaces are clean.

The welding of parts with a nonuniform coating of oxides, scale, or other foreign matter on the surface causes variations in contact resistance. This produces inconsistencies in heat generation. Heavy scale on the work surfaces may also become embedded in the electrode faces, causing rapid electrode deterioration. Oil and grease will pick up dirt which also will contribute to electrode deterioration.

Influence of Metal Composition. The electrical resistivity of a metal directly influences resistance heating during welding. In high-conductivity metals such as silver and copper, little heat is developed even under high-current densities. The small amount of heat generated is rapidly transmitted into the surrounding work and the electrodes.

The composition of a metal determines its specific heat, melting temperature, latent heat of fusion, and thermal conductivity. These properties govern the amount of heat required to melt the metal and produce a weld. However, the amounts of heat necessary to raise unit masses of most commercial metals to their fusion temperatures are very nearly the same. For example, stainless steel and aluminum require the same Btu's per pound (joules per gram) to reach fusion temperature, even though they differ widely in spot welding characteristics. As a result, the electrical and thermal conductivities become dominant. The conductivities of aluminum are about ten times greater than those of stainless steel. Consequently, the heat lost into the electrodes and surrounding metal is greater with aluminum. Accordingly the welding current for aluminum must be considerably greater than that for stainless steel.

Heat Balance

HEAT BALANCE OCCURS when the depths of fusion (penetration) in the two workpieces are approximately the same. The majority of spot and seam welding applications are confined to the welding of equal thicknesses of the same metal, with electrodes of the same alloy, shape, and size. Heat balance in these cases is automatic; however, in many applications, the heat generated in the parts is unbalanced.

Heat balance may be affected by the following:

(1) Relative electrical and thermal conductivities of the metals to be joined
(2) Relative geometry of the parts at the joint
(3) Thermal and electrical conductivities of the electrodes
(4) Geometry of the electrodes

Heating will be unbalanced when pieces to be welded have significantly different compositions, different thicknesses, or both. The unbalance can be minimized in many cases by part design, electrode material and design, or projection location (in the case of projection welding). Heat balance can also be improved by using the shortest weld time and lowest current that will produce acceptable welds.

Heat Dissipation

DURING WELDING, HEAT is lost by conduction into the adjacent base metal and the electrodes, as shown in Figure 17.5. This heat dissipation continues at varying rates during current application and afterward, until the weld has cooled to room temperature. It may be divided into two phases: (1) during the time of current application, and (2) after the cessation of current. The extent of the first phase depends upon the composition and mass of the workpieces, the welding time, and the external cooling means. The composition and mass of the workpieces are determined by the design. External cooling depends upon the welding setup and the welding cycle.

The heat generated by a given amperage is inversely proportional to the electrical conductivity of the base metal. The thermal conductivity and temperature of the base metal determine the rate at which heat is dissipated or conducted from the weld zone.[1] In most cases, the thermal

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[1] Heat flow in welding is discussed in the *Welding Handbook*, Vol. 1, 8th Ed.

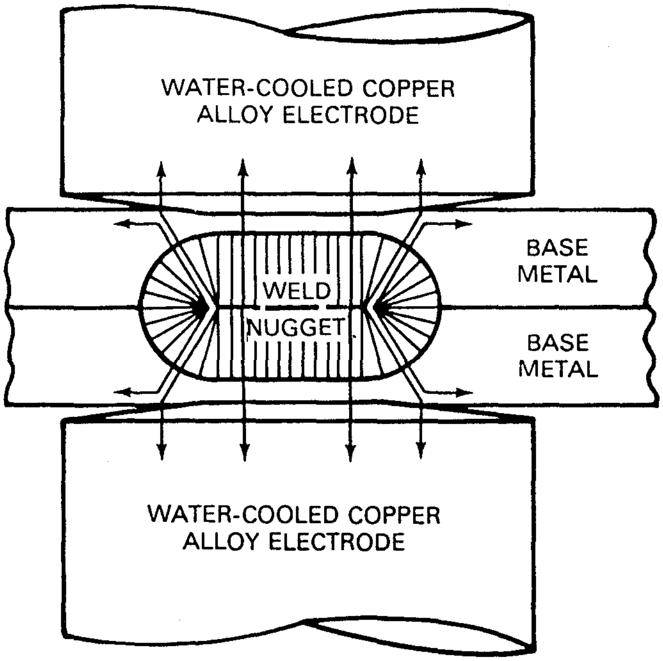

Figure 17.5–Heat Dissipation During Resistance Welding into the Surrounding Base Metal and Electrodes

and electrical conductivities of a metal are similar. In a high-conductivity metal, such as copper or silver, high amperage is needed to produce a weld and compensate for the heat that is dissipated rapidly into the adjacent base metal and the electrodes. Spot, seam, and projection welding of these metals is very difficult.

If the electrodes remain in contact with the work after weld current ceases, they rapidly cool the weld nugget. The rate of heat dissipation into the surrounding base metal decreases with longer welding times because a larger volume of base metal will have been heated. This reduces the temperature gradient between the base metal and the weld nugget. For thick sheets of metal where long welding times are generally required, the cooling rates will be slower than with thin sheets and short weld times.

If the electrodes are removed from the weld too quickly after the welding current is turned off, problems may result. With thin sheets, this procedure may cause excessive warpage. With thick sheets, adequate time is needed to cool and solidify the large weld nugget while under pressure. It is usually best, therefore, to have the electrodes in contact with the work until the weld cools to a temperature where it is strong enough to sustain any loading imposed when the pressure is released.

The cooling time for a seam weld nugget is short when the electrodes are rotated continuously. Therefore, welding is commonly done with water flowing over the workpieces to remove the heat as rapidly as possible.

It is not always good practice to cool the weld zone rapidly. With quench-hardenable alloy steels, it is usually best to retract the electrodes as quickly as possible to minimize heat dissipation to the electrodes, and thus to retard the cooling rate of the weld.

WELDING CYCLE

THE WELDING CYCLE for spot, seam, and projection welding consists basically of four phases:

(1) Squeeze time - the time interval between timer initiation and the first application of current; the time interval is to assure that the electrodes contact the work and establish the full electrode force before welding current is applied.

(2) Weld time - the time that welding current is applied to the work in making a weld in single-impulse welding.

(3) Hold time - the time during which force is maintained to the work after the last impulse of current ends; during this time, the weld nugget solidifies and is cooled until it has adequate strength.

(4) Off time - the time during which the electrodes are off the work and the work is moved to the next weld location; the term is generally applied where the welding cycle is repetitive.

Figure 17.6 shows a basic welding cycle. One or more of the following features may be added to this basic cycle to improve the physical and mechanical properties of the weld zone:

(1) Precompression force to seat the electrodes and workpieces together
(2) Preheat to reduce the thermal gradient in the metal at the start of weld time
(3) Forging force to consolidate the weld nugget
(4) Quench and temper times to produce the desired weld strength properties in hardenable alloy steels
(5) Postheat to refine the weld grain size in steels
(6) Current decay to retard cooling on aluminum

In some applications, the welding current is supplied intermittently during a weld interval time; it is on during heat time and ceases during cool time. Figure 17.7 shows the sequence of operations in a more complex welding cycle.

WELDING CURRENT

BOTH ALTERNATING CURRENT (ac) and direct current (dc) are used to produce spot, seam, and projection welds. The welding machine transforms line power to low voltage, high amperage welding power. Some applications use single phase ac of the same frequency as the power line, usually 60 Hz. Direct current is used for applications that require high amperage because the load can be balanced on a 3-phase power line. Its use also reduces the power losses in

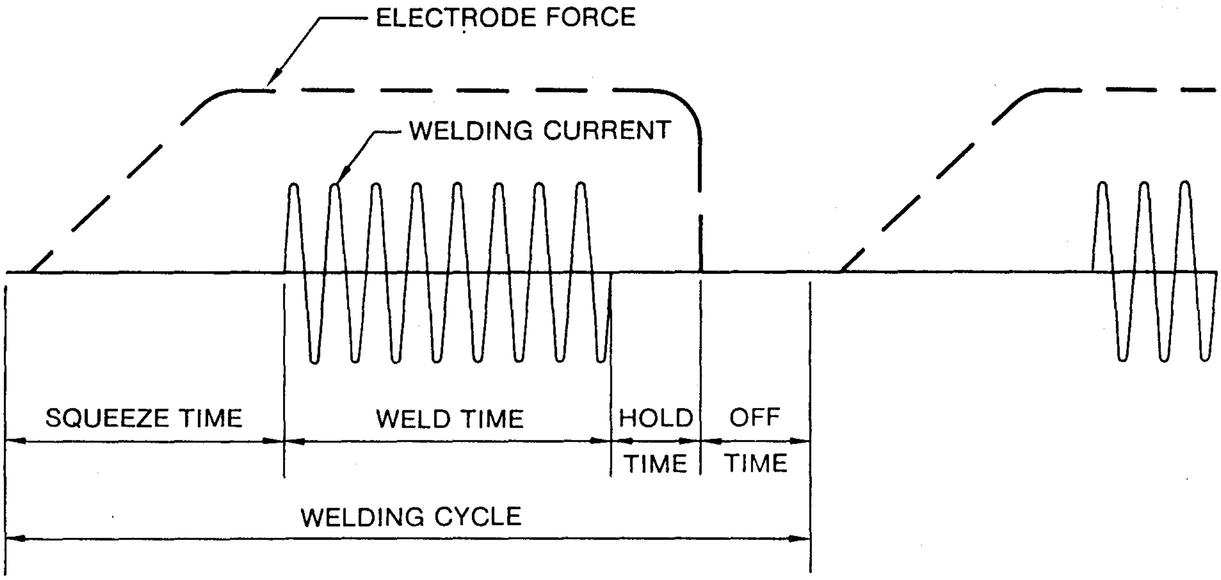

Figure 17.6–Basic Single Impulse Welding Cycle for Spot and Projection Welding

the secondary circuit. Direct current may be essentially constant for a timed period or in the form of a high-peaked pulse. The latter is normally produced from stored electrical energy.

Current Programming

WITH DIRECT ENERGY machines, the rate of current rise and fall can be programmed. The current rise period is commonly called *upslope time* and the current fall period is called *downslope time* (see Figure 17.7). These features are available on machines equipped with electronic control systems.

Upslope is generally used to avoid overheating and expulsion of metal at the beginning of weld time, when the base metal interface resistance is high. Downslope is used to control weld nugget solidification, to avoid cracking in metals that are quench-hardenable or subject to hot tearing.

Prior to welding, the base metal can be preheated using a low current. Following the formation of the weld nugget, the current can be reduced to some lower value for postheating of the weld zone. This may be part of the weld interval, as shown in Figure 17.7, or a separate application of current following a quench time period.

WELD TIME

THE TIME OF current application, or weld time for other than stored energy power, is controlled by electronic, mechanical, manual, or pneumatic means. Times commonly range from one half cycle (1/120 sec.) for very thin sheets to several seconds for thick plates. For the capacitor or magnetic type of stored energy machines, the weld time is determined by the electrical constant of the system.

Single Impulse Welding

THE USE OF one continuous application of current to make an individual weld is called *single impulse welding* (see Figure 17.6). Up or down current slope may be included in the time period.

Multiple Impulse Welding

MULTIPLE IMPULSE WELDING consists of two or more pulses of current separated by a preset cool time (see Figure 17.7). This sequence is used to control the rate of heating at the interface while spot welding relatively thick steel sheet.

ELECTRODE FORCE

COMPLETION OF THE electrical circuit through the electrodes and the work is assured by the application of electrode force. This force is produced by hydraulic, pneumatic, magnetic, or mechanical devices. The pressure developed at the interfaces depends upon the area of the electrode faces in contact with the workpieces. The functions of this force or pressure are to (1) bring the various interfaces into intimate contact, (2) reduce initial contact resistance at the interfaces, (3) suppress the expulsion of

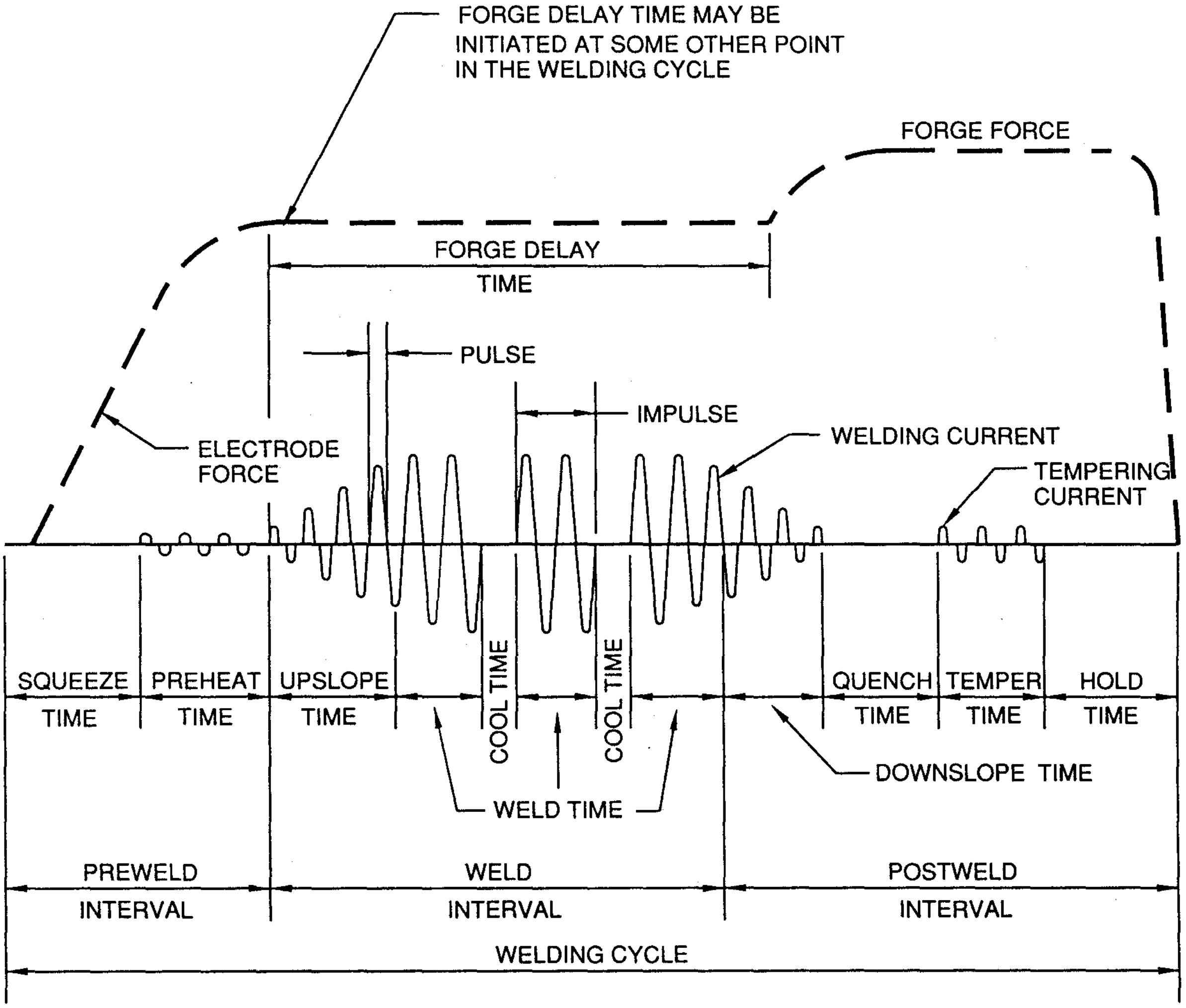

Figure 17.7–Enhanced Welding Cycle which Includes: Preheat Time, Upslope Time, Downslope Time, Quench Time, Temper Time, and Forging Force

molten weld metal from the joint, and (4) consolidate the weld nugget.

Forces may be applied during the welding cycle as follows:

(1) A constant weld force

(2) Precompression and weld forces - a high initial level to reduce initial contact resistance and bring the parts into intimate contact, followed by a lower level for welding

(3) Precompression, weld, and forging forces - the first two levels as described in (2), followed by a forging force near the end of the weld time; forging is used to reduce porosity and hot cracking in the weld nugget

(4) Weld and forging forces

EQUIPMENT

SPOT, SEAM, AND projection welding equipment consists of three basic elements: an electrical circuit, the control equipment, and a mechanical system.[2]

ELECTRICAL CIRCUIT

THIS CIRCUIT COMPRISES a welding transformer, a primary contactor, and a secondary circuit. The secondary circuit includes the electrodes that conduct the welding current to the work, and the work itself. In some cases, a means of storing electrical energy is also included in the circuit. Both alternating current and direct current are used for resistance welding. The welding machine converts 60 Hz line power to low voltage, high amperage power in the secondary circuit of the welding machine.

Alternating Current

SOME RESISTANCE WELDING machines produce single-phase alternating current (ac) of the same frequency as the power line, usually 60 Hz. These machines contain a single-phase transformer that provides the high welding currents required at low voltage. Depending upon the thickness and type of material to be welded, currents may range from 1000 to 100 000 amperes. A typical electrical circuit designed for this type of machine is shown in Figure 17.8.

Direct Current

WELDING MACHINES MAY produce direct current of continuous polarity, pulses of current of alternating polarity, or high-peaked pulses of current. The latter type is produced by stored electrical energy.

Rectifier Type Machines. These machines are direct energy types, in that ac power from the plant distribution system passes through a welding transformer and is then rectified to dc power. Silicon diode rectifiers are widely used in secondary circuits because of their inherent reliability and efficiency. The system can be single phase; however, one of the advantages of direct current systems is the ability to use a three-phase transformer to feed the rectifier system in the secondary circuit. This makes it possible to use balanced three-phase line power.

Frequency Converter Machines. This type of machine has a special welding transformer with a three-phase primary and a single-phase secondary. The primary current is controlled by ignitron tubes or silicon-controlled rectifiers (SCRs). Half cycles of three-phase power, either positive or negative, are conducted to the transformer for a timed period that depends upon the transformer design. The transformer output is a pulse of direct current. By switching the polarity of the primary half cycles, the polar-

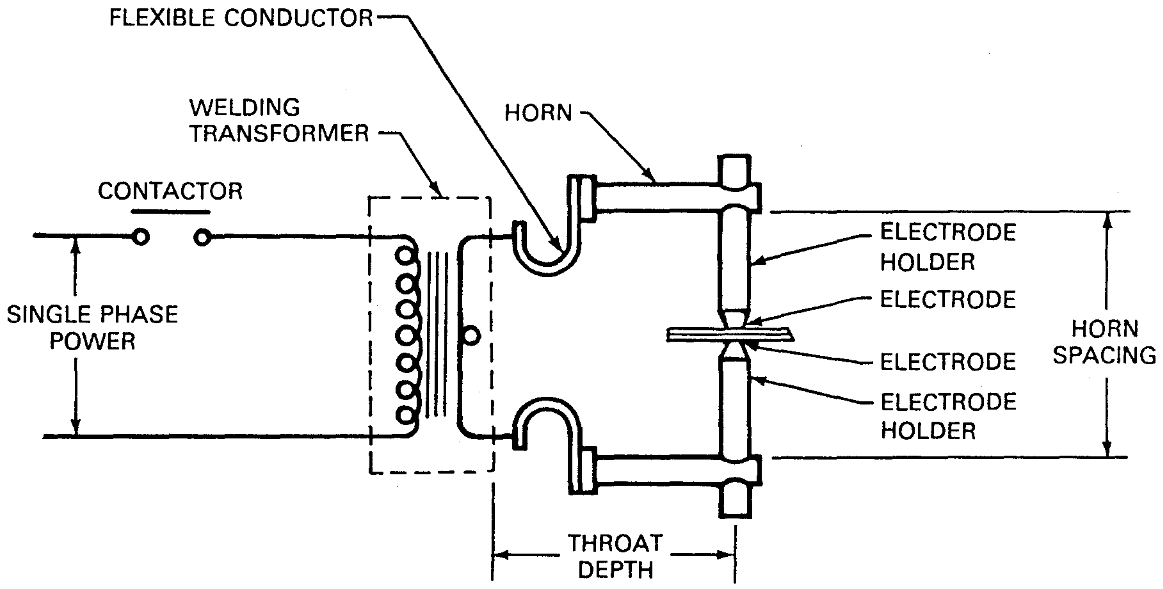

Figure 17.8—Typical Single-Phase Spot Welding Circuit

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[2] Resistance welding equipment is covered in Chapter 19.

ity of the secondary current is reversed. A weld may be made with one or more dc pulses.

Stored Energy Machines. Stored energy machines are of electrostatic design. They draw power from a single-phase system, store it, and then discharge it in a very short pulse period to make the weld. These machines draw power from the supply line over a relatively long time between welds, accumulating power to deliver to the electrodes during a short weld time.

The equipment for electrostatic stored energy welding consists primarily of a bank of capacitors, a circuit for charging these capacitors to a predetermined voltage, and a system for discharging the capacitors through a suitable welding transformer. High- voltage capacitors are generally used, the most common varying from 1500 to 3000 volts.

ELECTRODES

RESISTANCE WELDING ELECTRODES[3] perform four functions:

(1) Conduct the welding current to the work, and for spot and seam welding, fix the current density in the weld zone. In projection welding, the current density is determined by the size, shape, and number of projections.

(2) Transmit a force to the workpieces.

(3) Dissipate part of the heat from the weld zone.

(4) Maintain relative alignment and position of the workpieces in projection welding.

If the application of pressure were not involved, electrode material selection could be made almost entirely on the basis of electrical and thermal conductivity. Since the electrodes are subjected to forces that are often of considerable magnitude, they must be capable of withstanding the imposed stresses at elevated temperatures without excessive deformation. Proper electrode shape is important because the current must be confined to a fixed area to achieve needed current density.

When only one spot or seam weld is to be made at a time, only one pair of electrodes is required. In this case, the force and current are applied to each weld by shaped electrodes. Several closely spaced projection welds can be made with one pair of welding dies (electrodes).

Electrodes of several copper alloys with satisfactory physical and mechanical properties are available commercially. Generally speaking, the harder the alloy, the lower are its electrical and thermal conductivities. The choice of a suitable alloy for any application is based on a compromise of its electrical and thermal properties with its mechanical qualities. Electrodes selected for aluminum welding, for instance, should have high conductivity at the expense of high compressive strength, to minimize sticking of electrodes to the work. Electrodes for welding stainless steel, on the other hand, should sacrifice high conductivity to obtain good compressive strength, to withstand the required electrode force.

Resistance to deformation or mushrooming depends upon the proportional limit and hardness of the electrode alloy. The proportional limit is largely established by heat treatment. The temperature of the electrode face is the governing factor, because this is where softening takes place.

The sizes and shapes of electrodes are usually determined by the sheet thickness and the metal to be welded.

CONTROL EQUIPMENT

WELDING CONTROLS MAY provide one or more of the following principal functions:

(1) Initiate and terminate current to the welding transformer

(2) Control the magnitude of the current.

(3) Actuate and release the electrode force mechanism at the proper times

They may be divided into three groups based on their purposes: welding contactors, timing and sequencing controls, other current controls and regulators.

A welding contactor connects and disconnects the primary power and the welding transformer. Electronic contactors use silicon-controlled rectifiers (SCRs), ignitron tubes, or thyratron tubes to interrupt the primary current.

The timing and sequence control establishes the welding sequence and the duration of each function of the sequence. This includes application of electrode force and current, as well as the time intervals following each function.

The welding current output of a machine is controlled by transformer taps, or an electronic heat control, or both. An electronic heat control is used in conjunction with ignitron tubes or SCRs. It controls current by delaying the firing of the ignitron tubes or SCRs during each half cycle (1/120 sec.). Varying the firing delay time can be used to gradually increase or decrease the primary (rms) amperage. This provides upslope and downslope control of welding current.

Transformer taps are used to change the number of primary turns connected across the ac power line. This changes the turns ratio of the transformer, with an increase or decrease in open circuit secondary voltage. Decreasing the turns ratio will increase the open circuit secondary voltage, the primary current, and the welding current.

MECHANICAL SYSTEMS

SPOT, SEAM, AND projection welding machines have essentially the same types of mechanical operation. The electrodes approach and retract from the work at controlled

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[3] Resistance welding electrodes are discussed more fully in Chapter 19.

times and rates. Electrode force is applied by hydraulic, pneumatic, magnetic, or mechanical means. The rate of electrode approach must be rapid, but controlled, so that the electrode faces are not deformed from repeated blows. The locally heated weld metal expands and contracts rapidly during the welding cycle and the electrodes must follow this movement to maintain welding pressure and electrical contact. The ability of the machine to follow motion is influenced by the mass of the moving parts, or their inertia, and by friction between the moving parts and the machine frame.

If the pressure between the electrodes and work drops rapidly during weld time, the contact surfaces of the electrodes and workpieces may overheat and result in burning or pitting of the electrode faces. The electrodes may stick to the work and, in some cases, the surfaces of the parts that are being welded may vaporize from the very high energy.

The electrode force used during the melting of the weld nugget may not be adequate to consolidate the weld metal and to prevent internal porosity or cracking. Multilevel force machines may be employed to provide a high forging pressure during weld solidification. The magnitude of this pressure should suit the composition and thickness of the metal and the geometry of the parts. The forging pressure is often two to three times the welding pressure. Since the weld cools from the periphery inward, the forging pressure must be applied at or close to the current termination time.

SURFACE PREPARATION

FOR ALL TYPES of resistance welding, the condition of the surfaces of the parts to be welded largely controls how consistent the weld quality will be. The contact resistance of the faying surfaces has a significant influence on the amount of welding heat generated; hence, the electrical resistance of these surfaces must be highly uniform for consistent results. They must be free of high-resistance materials such as paint, scale, thick oxides, and heavy oil and grease. If it is necessary to use a primer paint on the faying surfaces prior to welding, as is sometimes the case, the welding operation must be performed immediately after applying the primer, or special conducting primers must be used. For best results, the primer should be as thin as possible so that the electrode force will displace it and give metal-to-metal contact.

Paint should never be applied to outside base metal surfaces before welding, because it will reduce electrode life and produce poor surface appearance. Heavy scale should be removed by mechanical or chemical methods. Light oil on steel is not harmful unless it has picked up dust or grit. Drawing compounds containing mineral fillers should be removed before welding.

The methods used for preparing surfaces for resistance welding differ for various metals and alloys. A brief description of surface conditions and methods of cleaning follows.

ALUMINUM

THE CHEMICAL AFFINITY of aluminum for oxygen causes it to become coated with a thin film of oxide whenever it is exposed to air. The thin oxide film that forms on a freshly cleaned aluminum surface does not cause sufficient resistance to be troublesome for resistance welding. The permissible holding period, or elapsed time between cleaning and welding, may vary from 8 to 48 hours or more, depending upon the cleaning process used, cleanliness of the shop, the particular alloy, and the application.

An aluminum surface may be mechanically cleaned for resistance welding with a fine grade of abrasive cloth, fine steel wool, or a fine wire brush. Clad aluminum may also be cleaned by mechanical means, but care must be taken not to damage the cladding. Numerous commercial chemical cleaners are available for aluminum. Chemical cleaning is usually preferred in large volume production for reasons of economy as well as uniformity and control.

MAGNESIUM

CLEANING MAGNESIUM ALLOYS is particularly important since they readily alloy with copper at elevated temperatures. The contact resistance between the electrode and the work must be kept as low as possible. Magnesium alloys are supplied coated with an oil or are chrome-pickled, to protect the metal from oxidation during shipment and storage. To obtain sound and consistent welds, the protective coating must be removed to facilitate the removal of residual magnesium oxide.

COPPER

CLEANING OF COPPER alloys is important. The beryllium-coppers and aluminum-bronzes are particularly difficult to clean by chemical means. Mechanical means are preferred. In some instances, a flash coating of tin is applied to produce a uniformly higher surface resistance than pure copper would have.

NICKEL

NICKEL AND ITS alloys demand high standards of material cleanliness for successful resistance welding. The presence of grease, dirt, oil, and paint increases the probability of sulfur embrittlement during welding, and will result in defective welds. Oxide removal is necessary if heavy oxides are present from prior thermal treatments. Machining, grinding, blasting, or pickling may be employed. Wire brushing is not satisfactory.

TITANIUM

BEFORE WELDING, THE surfaces of titanium parts should be scrupulously clean. Materials such as oil, grease, dirt, oxides and paint can adversely affect both weld consistency and chemical composition. Titanium and titanium alloys react with many elements and compounds at welding temperatures. Contamination by oxygen, hydrogen, nitrogen, and carbon, which enter the microstructure interstitially, can significantly reduce weld ductility and toughness. Scale-free surfaces may be welded either after degreasing or after degreasing plus acid pickling. The surfaces may be degreased with acetone, methylethylketone, or a dilute solution of sodium hydroxide. Chlorinated solvents should not be used. Titanium and its alloys are susceptibile to stress corrosion.

Pickling may be used to remove light oxide scale before welding. Pickling is usually performed with HF-HNO_3 solutions containing two to five percent HF and 30 to 40 percent HNO_3 by volume, balance water.

STEELS

PLAIN CARBON AND low alloy steels have relatively low resistance to corrosion in ordinary atmosphere; hence, these metals are usually protected by a thin oil film during shipment, storage, and processing. This oil film has no harmful effects on the weld, provided the oily surfaces are not contaminated with shop dirt or other poorly conductive or dielectric materials.

Steels are supplied with various surface finishes. Some of the more common are (1) hot-rolled, unpickled; (2) hot-rolled, pickled, and oiled; and (3) cold-rolled with or without an anneal. Unpickled hot-rolled steel must be pickled or mechanically cleaned prior to welding. Hot-rolled pickled steel is weldable in the as-received condition, except for possible wiping to remove loose dirt. Cold-rolled steel presents the best welding surface and, if properly protected by oil, requires no cleaning prior to welding other than wiping to remove loose dirt.

High alloy steels and stainless steels are noncorrosive and usually require no involved cleaning before resistance welding. When exposed to elevated temperatures, stainless steels will acquire an oxide film; the thickness depends upon the temperature and time of exposure. The scale is an oxide of chromium which is effectively removed by pickling. Oil and grease should be removed with solvents or by vapor degreasing prior to welding.

COATED STEELS

THE COATINGS AND platings applied to carbon steel to provide corrosion resistance or for decoration lend themselves satisfactorily to resistance welding with few exceptions. In general, good results may be obtained without special cleaning processes.

Welding of aluminized steel results in less expulsion and pickup if the surfaces are wire brushed.

Phosphate coatings increase the electrical resistance of the surfaces to a degree that welding current cannot pass through the sheets with low welding pressures. Higher pressures will produce welds, but slight variations in coating thickness may prevent welding.

SURFACE PREPARATION CONTROL

SURFACE PREPARATION CONTROL can be maintained by periodically measuring the room temperature contact resistance of the workpieces immediately following cleaning. The measurement is most readily taken tip to tip between two RW electrodes, through two or more thicknesses of metal. Unit surface resistance varies inversely with pressure, temperature, and area of contact. The test conditions must be specified, to make the measurements significant in control of surface cleanliness.

RESISTANCE SPOT WELDING

APPLICATIONS

RESISTANCE SPOT WELDING (RSW) is used to fabricate sheet metal assemblies up to about 0.125 in. (3.2 mm) thickness, when the design permits the use of lap joints and leak tight seams will not be required. Occasionally the process is used to join steel plates 1/4 in. (6.35 mm) thick or thicker; however, loading of such joints is limited and the joint overlap adds weight and cost to the assembly when compared to the cost of an arc welded butt joint.

The process is used in preference to mechanical fastening, such as riveting or screwing, when disassembly for maintenance is not required. It is much faster and more economical because separate fasteners are not needed for assembly.

Spot welding is used extensively for joining low carbon steel sheet metal components for automobiles, cabinets, furniture, and similar products. Stainless steel, aluminum, and copper alloys are commonly spot welded commercially.

ADVANTAGES AND LIMITATIONS

THE MAJOR ADVANTAGES of resistance spot welding are its high speed and adaptability for automation in high-rate production of sheet metal assemblies. Spot welding is also economical in many job shop operations, because it is faster than arc welding or brazing and requires less skill to perform.

The process also has some limitations:

(1) Disassembly for maintenance or repair is very difficult.

(2) A lap joint adds weight and material cost to the product, when compared to a butt joint.

(3) The equipment costs are generally higher than the costs of most arc welding equipment.

(4) The short time, high-current power requirement produces unfavorable line power demands, particularly with single phase machines.

(5) Spot welds have low tensile and fatigue strengths, because of the notch around the periphery of the nugget between the sheets.

(6) The full strength of the sheet cannot prevail across a spot welded joint, because fusion is intermittent and loading is eccentric due to the overlap.

PROCESS VARIATIONS

VARIATIONS OF THE resistance spot welding process differ in the application of welding current and pressure, and the arrangement of the secondary circuit.

Direct and Indirect Welding

DIRECT WELDING IS a resistance welding secondary circuit variation in which welding current and electrode force are applied to the workpieces by directly opposing electrodes.

Indirect welding is a variation in which the welding current paths are through the workpieces away from, as well as at, the spot weld locations. Typical arrangements for direct and indirect spot welding are shown schematically in Figure 17.9. Figures 17.9 (A), (B), and (C) apply to direct resistance welding. In Figure 17.9 (A), direct welding is done using electrodes with similar geometries. A larger electrode against one workpiece in Figure 17.9 (B) provides an increased contact surface area for applications requiring better welding heat balance, or in order to reduce the marking on the lower sheet by the electrodes. The larger electrode surface area will conduct heat away from the weld joint more rapidly. Figure 17.9 (C) is a schematic of two or more electrodes connected in series to a single transformer. Electrode arrangements such as this can make spot welds in rapid succession with one set of electrodes in contact with the work at a time. This arrangement is economical with respect to equipment costs.

Figures 17.9 (D) through (G) represent indirect resistance welding arrangements. A backing plate arrangement in Figure 17.9 (D) provides a current path and pressure when the backing plate is made of a conducting material. If the backing plate is non-conductive, the plate only provides welding pressure, and the current path will be from the top electrode, through the faying surface location, along the lower workpiece to the return connection further down the joint. Figure (E) is similar to (D) with the exception that the non-pressure electrode is away from the lap joint. Current may be through a conducting backing plate between the electrodes, or through the base material between the electrodes. Figures 17.9 (F) and (G) are similar to the joints in (E) and (D), but are for spot welding high-resistance materials which require higher voltages. The two secondary circuits are in series, and are connected to two transformers. The primary circuits may be connected either in series or in parallel. The two secondary circuits provide the sum of their respective voltages at the spot welds.

Parallel and Series Welding

PARALLEL AND SERIES resistance welding are secondary circuit variations used for multiple spot welding applications. Examples of parallel and series welding arrangements are shown schematically in Figure 17.10.

Parallel welding arrangements divide and conduct the secondary current through the workpieces and electrodes in parallel electrical paths, simultaneously forming spot welds. Figure 17.10 (A) and (B) represent parallel welding arrangements. In Figure (A), the welding current is from a single transformer with multiple electrodes in the secondary circuit in parallel. Figure (B) represents a parallel welding system operating with a three-phase primary. This particular system is limited to three work stations.

In series welding (Figures 17.10 C and D), the secondary circuit current is conducted through the workpieces and the electrodes in a series electrical path, simultaneously forming multiple spot welds at the electrode locations. A series welding arrangement requires equal resistance values at the faying surfaces in order to obtain uniform heating at each spot weld. When spot welding with two electrodes in series, a portion of the current will travel through the adjacent workpiece from one electrode to the other, bypassing the faying surfaces. This shunted current does not contribute to the spot weld, and must be taken into account when developing a series spot welding procedure.

HEAT BALANCE

HEAT BALANCE IN a spot weld occurs when the depths of fusion in the workpieces are approximately the same. Problems with heat balance arise when joints are made using metals of different thicknesses, different electrical conductivities, or a combination of both. Electrode configurations and compositions can be used to overcome unbalanced heating to some extent, as shown in Figure 17.11. This sketch illustrates general methods for over-

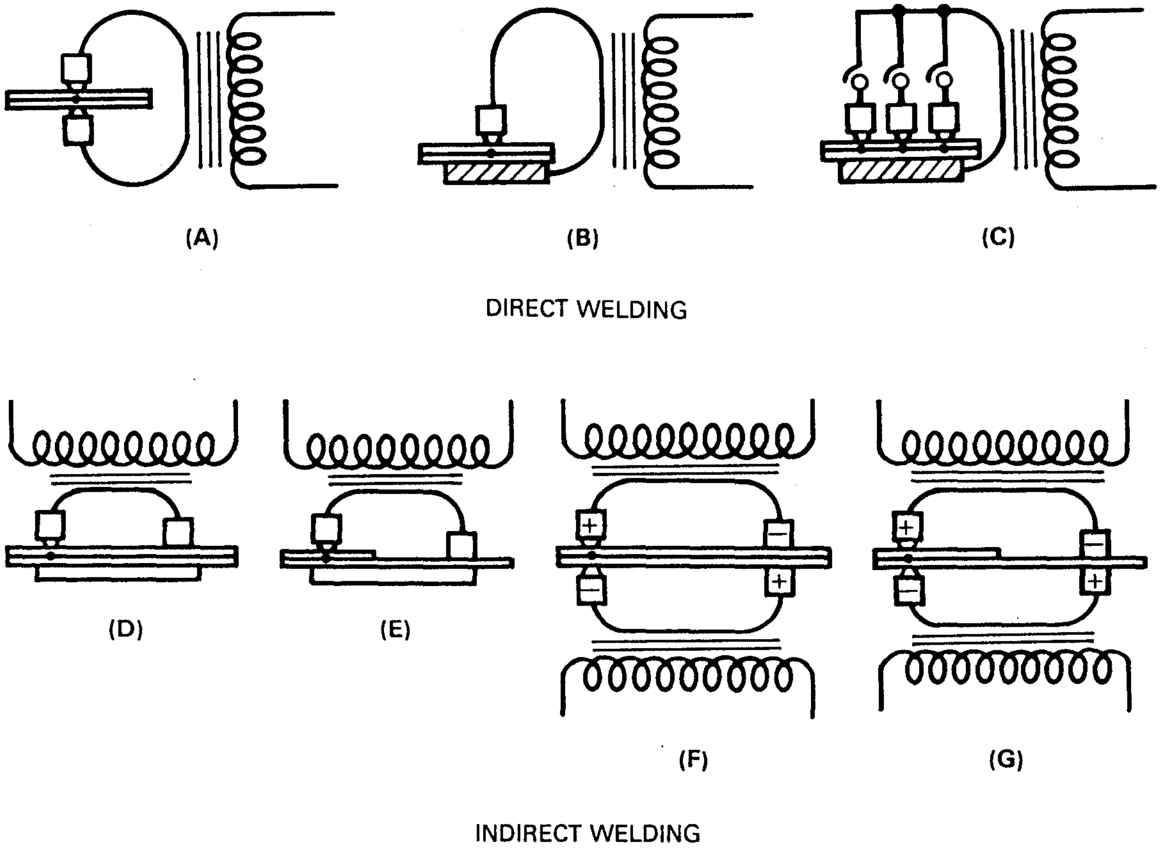


Figure 17.9–Typical Secondary Circuit Arrangements for Direct and Indirect Resistance Spot Welding

coming improper joint heating involving base metals with different electrical conductivities.

In Figure 17.11 (A), an electrode with a smaller face area is used on the metal having the higher conductivity. The smaller contact area will increase the current density in the higher conducting metal. Less heat is conducted away from the joint by the base metal and the electrode. More heat is generated in the workpiece, and the fusion area will shift from the lower conducting metal towards the higher conducting metal. An alternative would be to apply an electrode with higher resistance against the higher-conducting metal, in order to limit the heat loss through that electrode [Figure 17.11 (B)]. Figure 17.11 (C) presents the combination of a higher-resistance electrode and a smaller electrode face area applied to the more conductive metal. Better heat balance can also be obtained by increasing the thickness of the more conductive metal, as seen in Figure 17.11 (D), resulting in an increase in the effective resistance of that sheet.

Spot welding metals with similar electrical characteristics but differing thicknesses will also result in uneven joint heating. The thicker workpiece will exhibit a higher resistance (lower conductivity) than the thinner sheet, resulting in deeper penetration into the thicker sheet. The heat balance can be improved by decreasing the current density in the thicker sheet, by decreasing the heat loss from the thinner sheet, or by a combination of both. Applying a large diameter electrode on the thicker sheet will concentrate the current density into the thinner metal, shifting the nugget penetration deeper into the thinner sheet.

In order to effectively spot weld two or more dissimilar thicknesses of the same metal, a maximum section-thickness ratio of the outer sheets is suggested. For carbon steels the suggested maximum section-thickness ratio is 4 to 1. Joining three different thicknesses of carbon steel using pointed electrodes, an outer sheet thickness ratio of 2.5 to 1 is suggested. To accommodate joints with higher thickness ratios, altering the electrode face diameter and the electrode composition are important methods of balancing the heat produced in each member of the joint.

In multiple layers of dissimilar thicknesses, a long weld time permits more uniform distribution of heat in the asymmetrical resistance path between the electrodes. Cor-

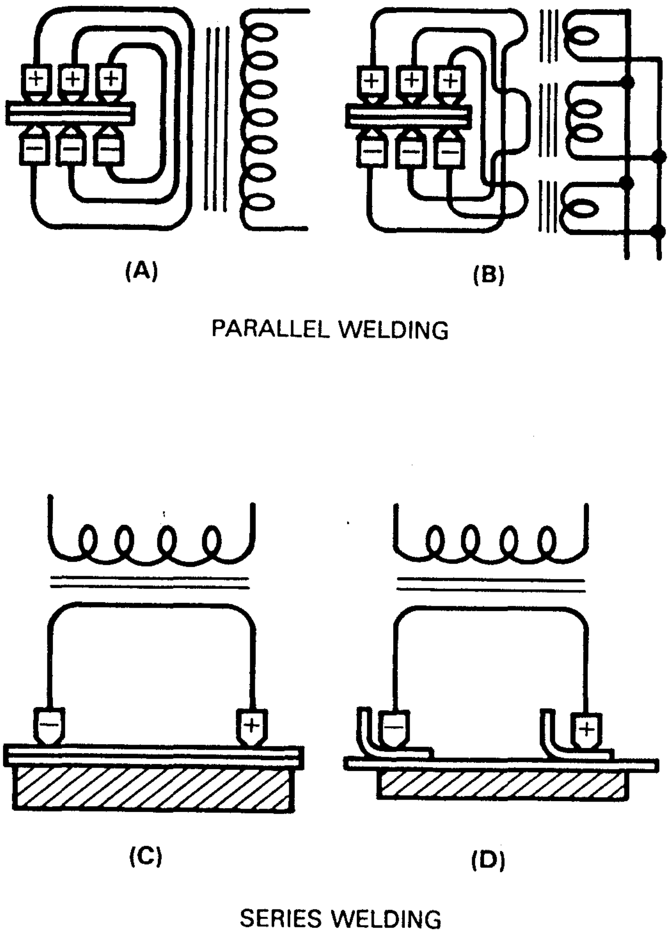


Figure 17.10–Typical Secondary Arrangements for Direct Multiple Spot Welding

rect heat balance may be obtained by using multiple impulse (pulsation) welding, or a single impulse of continuous current for an equivalent time.

JOINT DESIGN

THE JOINT DESIGN in all cases of spot welding consists of a lap joint.

One or more of the welded members may be part flanges, or formed sections such as angles and channels. The use of standard resistance welding machines, portable welding guns, and special-purpose machines must be considered when designing the lap joint configuration. The joint design for indirect welding must allow access to both sides of the joint by the electrodes or backup dies.

Factors that should be considered when designing for spot welding include:

(1) Edge distance
(2) Joint overlap
(3) Fit-up
(4) Weld spacing
(5) Joint accessibility
(6) Surface marking
(7) Weld strength

Edge Distance

THE EDGE DISTANCE is the distance from the center of the weld nugget to the edge of the sheet. Enough base metal must be available to resist the expulsion of molten metal from the joint. Spot welds made too close to the edge of one or both members will cause the base metal at the edge of the member to overheat and upset outward. See Figure 17.12. The restraint by the base metal at the edge on the molten nugget is reduced and expulsion of molten metal may occur due to the high internal pressure in the molten nugget. The weld nugget may be unsound, the electrode indentation excessive, and the weld strength low. The required minimum edge distance is a function of base metal composition and strength, section thicknesses, electrode face contour, and the welding cycle.

Joint Overlap

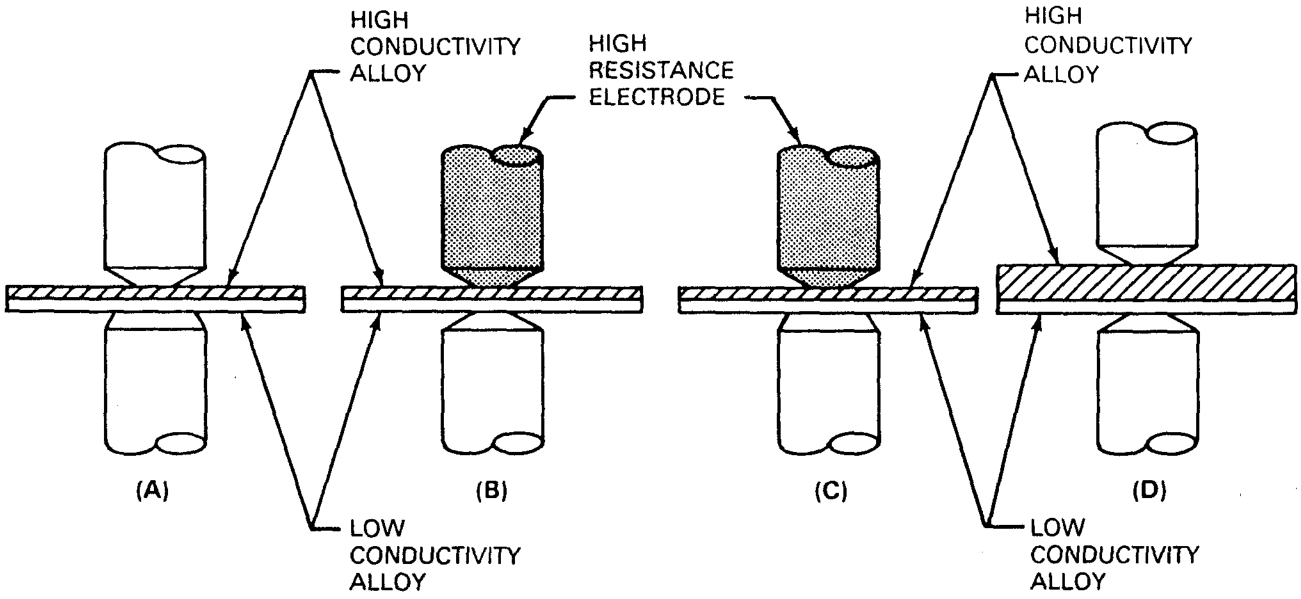
THE MINIMUM PERMISSIBLE joint overlap is twice the minimum edge distance. The overlap must include the base metal requirement for avoiding edge overheating and expulsion for both sheet members. Other factors such as electrode clearance, however, may require a larger overlap. If the overlap is too small, the edge distance will automatically be insufficient, as sketched in Figure 17.12.

Fit-Up

THE MATING PARTS should fit together along the joint with very little or no gap between them. Any force required to overcome gaps in the joint reduces the effective welding force. The force required to close the joint may vary as welding progresses, and consequently may change the actual welding force. The ultimate result may be significant variations in the strengths of the individual welds.

Weld Spacing

WHEN NUMEROUS SPOT welds are made successively along a joint, a portion of the secondary current shunts through the adjacent welds. The shunting of the current must be considered when establishing the distance between adja-



(A) ELECTRODE WITH SMALLER FACE AREA AGAINST HIGH-CONDUCTIVITY ALLOY
(B) HIGH-ELECTRICAL RESISTANCE ELECTRODE AGAINST HIGH-CONDUCTIVITY ALLOY
(C) SAME AS B. WITH ADDITION OF LARGER ELECTRODE FACE AGAINST LOW-CONDUCTIVITY MATERIAL
(D) INCREASE THICKNESS OF HIGH-CONDUCTIVITY WORKPIECE

Figure 17.11–Typical Techniques for Improving Joint Heat Balance When Spot Welding Metals with Different Electrical Conductivities

cent spot welds and when establishing the welding machine settings.

The division of current will depend primarily upon the ratio of the resistances of the two paths, one through the adjacent welds and the other across the interface between the sheets. If the path length through the adjacent weld is long compared to the joint thickness, that resistance will be high compared to the resistance of the joint, and the shunting effect will be negligible. The minimum spacing between spot welds is related to the conductivity and thickness of the base metal, the diameter of the weld nugget, and the cleanliness of the faying surfaces. For example, metals with higher conductivities or thicker sections will require greater spacing between spot welds. The suggested minimum spacing between adjacent spot welds increases when joining three or more sheets. The spot spacing for a weld joining three thicknesses is generally 30 percent greater than the spacing required for welding two sections of the thicker outer sheet. Current levels may be increased in order to provide more current to the weld and so offset the shunting effects; however, the higher heat inputs may cause expulsion if applied to the first spot weld, which is unshunted. An auxiliary weld timer or current control may be provided to produce the first spot weld using lower heat input.

Joint Accessibility

THE JOINT DESIGN should consider the size and shape of commercially available electrodes and electrode holders, as well as the type of spot welding equipment on which the welding will be done. Each side of the weld joint should be accessible to the electrodes mounted on the welding machine or to backup dies in the case of indirect welding. See Chapter 19 for information on electrodes and electrode holder designs.

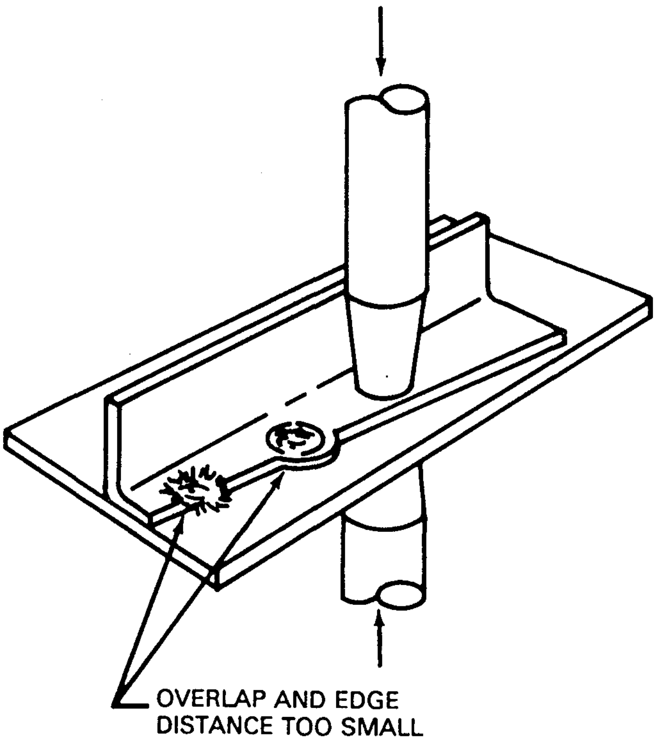


Figure 17.12–Effect of Improper Overlap and Edge Distance

Surface Marking

SURFACE MARKING RESULTS from workpiece shrinkage, caused by a combination of the heat of welding and electrode penetration into the surface of the workpiece.

When the welding current is on, the work is resistance heated locally and tries to expand in all directions. Because of the pressure exerted by the electrodes, expansion transverse to the plane of the sheets is restricted. As the weld cools, contraction takes place almost entirely in the transverse direction and produces concave surfaces or marks at the electrode locations. See Figure 17.13. This weld shrinkage is not to be confused with excessive electrode indentation into the work caused by improper welding procedures. The contraction shrinkage seldom exceeds a few thousandths of an inch.

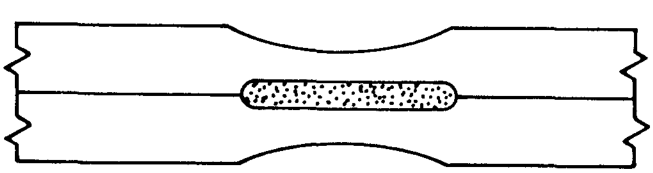


Figure 17.13–Surface Irregularity Produced by Spot Welding

A circular ridge around the spot weld concavity occurs when the expanding workpiece upsets in the plane of the sheets around the electrode face. See Figure 17.13. This ridge is caused by the relatively high electrode force and will occur to some extent with all shaped electrodes.

After some finishing operations, such as painting, the marks may be very conspicuous. It is difficult to eliminate the marks completely, but they can be reduced materially by modifying the welding procedure. For example, the depth of fusion into the sheet can be minimized by welding in the shortest practical time.

Various techniques are used to minimize these markings. The common method is to use a large flat-faced electrode against the *show side* of the joint. (The show side of the joint is the side that is visable when the assembly is in use.) This electrode should be made of a hard copper alloy to minimize wear. Another technique is to use indirect welding arrangements such as those shown in Figures 17.9 and 17.14.

Surface marking may also occur when an electrode or its holder accidentally contacts the workpiece adjacent to where the spot weld is to be made. Resultant arcing may produce a small pit in the work which is undesirable in some applications. If localized melting occurs as a result of the contact, cracks may result in some materials.

Electrode misalignment, skidding, or deflection of the supporting machine component under load may also result in undesirable surface marking. Localized overheating and electrode deflection will not be a problem if the proper joint design, electrodes, and equipment are used.

Weld Strength

THE STRENGTH OF a single spot weld in shear is determined by the cross-sectional area of the nugget in the plane of the faying surfaces. Strength tests for spot welds are discussed in Chapter 12, Volume 1 of the 8th Edition of the *Welding Handbook*. For additional information on spot weld test procedures, see AWS C1.1, *Recommended Practices for Resistance Welding.*

Lap joints tested with the weld in shear will experience an eccentricity of loading resulting in rotation of the joint at the weld as the test load increases. Resistance to joint rotation increases with increasing sheet thicknesses. The joint may fail either by shear through the nugget, or by tearing of the base metal adjacent to the weld nugget. See Figure 17.15. Normally, low weld strengths are associated with weld nugget shear failure, and high strengths are associated with base metal tearing. A minimum nugget diameter is required in order to obtain failure by base metal tear-

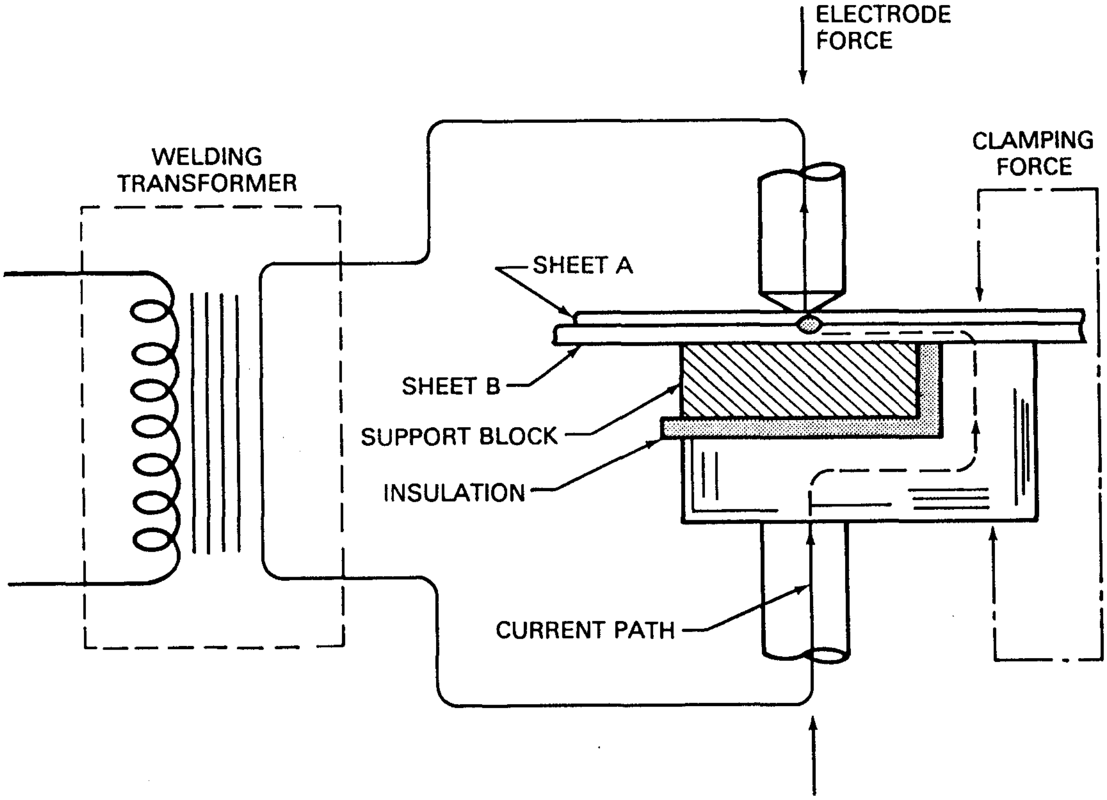


Figure 17.14–Application of Indirect Welding to Minimize Marking on One Side

ing. The minimum nugget diameter is unique to the type of base material, surface condition, and, if applicable, coating type.

Increasing the nugget diameter above this minimum value may provide some increase in the weld strength. Figure 17.16 shows the slight increase in strength values for low carbon steel as the nugget size increases.

Spot welds have relatively low strengths when stressed in tension by loading transverse to the plane of the sheets. This is due to the sharp notch between the sheets at the periphery of the weld nugget; consequently, spot welded joints should not be loaded in this manner.

The strength of multiple spot welded joints is dependent upon material thickness, spot weld spacing, and weld pattern. The spacing between adjacent spot welds may alter the joint weld strength due to current shunting through previous welds. As the spacing between adjacent spot welds decreases, the joint shear strength may decrease.

Figure 17.17 shows the effect of shunt distance (spot spacing) on tensile shear strength of spot welds. Data were taken from welds made on 1/4 in. (6.3 mm) thick by 3 in. (76 mm) wide strips of mild steel. All welds were made with one shunt circuit. Average shear strength of twenty-four welds was 17 570 lbs (8000 kg).

To obtain a desired joint strength, the number of required welds must satisfy minimum spacing requirements in order to minimize current shunting effects. A staggered weld pattern of multiple rows of welds rather than a rectangular pattern will provide better strengths, by distributing the load more efficiently among the spot welds.

To summarize the relationship between resistance spot welding variables and joint strength, Table 17.1 lists suggested resistance spot welding variables for welding uncoated low carbon steel, showing the resultant minimum shear strengths and the nugget "button" diameters.

ELECTRODE MAINTENANCE

MAINTENANCE OF ELECTRODES is necessary for the production of consistent welds. An abnormal increase in the size of the electrode faces contacting the work is detrimental to strength and quality. For example, if a 1/4 in.

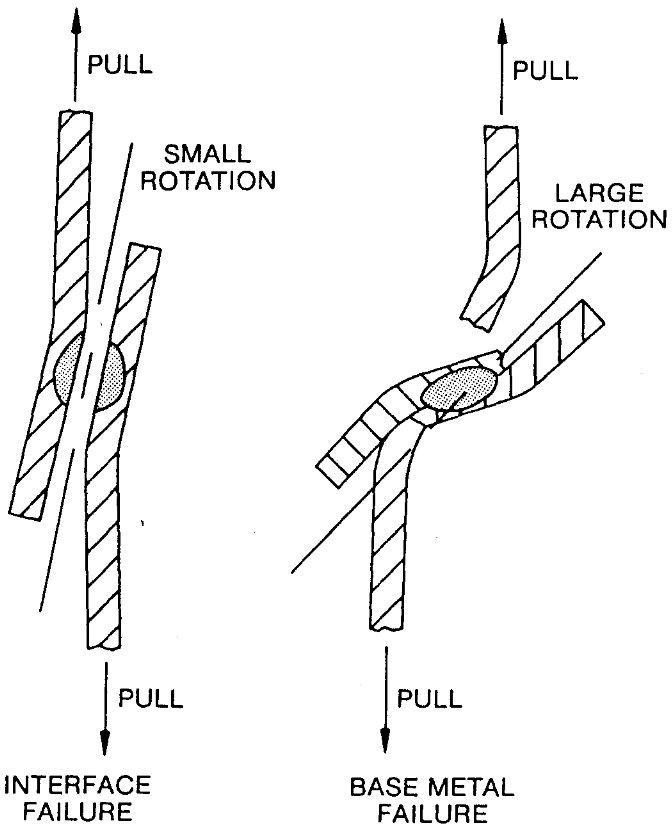


Figure 17.15–Failure Types in Tensile Shear Test as a Function of Rotation

(6.35 mm) diameter electrode face is allowed to increase to 5/16 in. (7.94 mm) diameter by mushrooming, the contact area will increase 50 per cent, with a corresponding decrease in current density and pressure. Depending somewhat upon the weld schedule, the result may be weak or defective welds. A danger sign is the production of poorly shaped spots, which may be caused by the following:

(1) Noncircular electrode faces
(2) Too large a flat face on the electrode
(3) Concavity or convexity of the electrode face
(4) Misalignment of the electrodes with respect to the work

Correct electrode alignment is relatively easy to maintain with stationary welding machines and proper supporting fixtures; however, misalignment is common with portable gun type machines. The seriousness of this condition is dependent upon the ease with which the equipment can be manipulated and correctly positioned for welding. It is likely that the electrodes will have longer life between dressings on positioned work(stationary machines) than on nonpositioned work(portable welding guns).

WELDBONDING

WELDBONDING IS A combination of resistance spot welding and adhesive bonding. Paste or film adhesive is placed between the members to be joined, and resistance welds are then made through the adhesive layer. The adhesive is allowed to cure either at ambient temperature or heated in an oven, as required by the adhesive manufacturer. The spot welds principally hold the joint together during curing; they are fewer in number than otherwise required and so do not contribute greatly to the strength of the joint. Common structures joined by weldbonding are found in the aerospace and transportation industries. Weldbonding is used to attach beaded panels to aircraft skins, and aircraft or truck skins to channels, angles, and other types of reinforcement.

The adhesive, whether paste or film type, can be applied to one or both joint surfaces. The electrode force during welding squeezes out the adhesive at the spot weld locations, creating a current path through the sheets. The adhesive must have good wetting and flow characteristics, in order to bond the faying surfaces securely. Premature curing of the adhesive, during or prior to spot welding, may hamper proper adhesive movement and result in high resistance between the faying surfaces. High resistance may impede weld current, or result in excessive heating and subsequent metal expulsion. Application of a precompression electrode force prior to the welding cycle may help displace the adhesive at each weld site.

Weldbonding improves the fatigue life and durability of the joint over that obtained with spot welding alone. The process may also improve stress distribution, joint rigidity, and buckling resistance in thin sheets. The adhesive in the joint dampens vibration and noise, and provides some corrosion resistance. In some aircraft components, greater cost effectiveness is obtainable with weldbonding than with mechanical fastening or adhesive bonding alone.

Disadvantages of weldbonding, in most applications, include the additional costs of the adhesive, the added curing operation, and the time and labor costs for cleaning the components, treating the surfaces, and applying the adhesive. In addition, operating temperatures for the component are limited to the effective service temperature of the adhesive.

The presence of adhesive in the joint makes welding more difficult, and may contribute to significant variations in weld quality. Regardless of welding conditions, not all of the adhesive will be displaced from between the sheets, and therefore the contact resistance will be higher than with clean sheets.

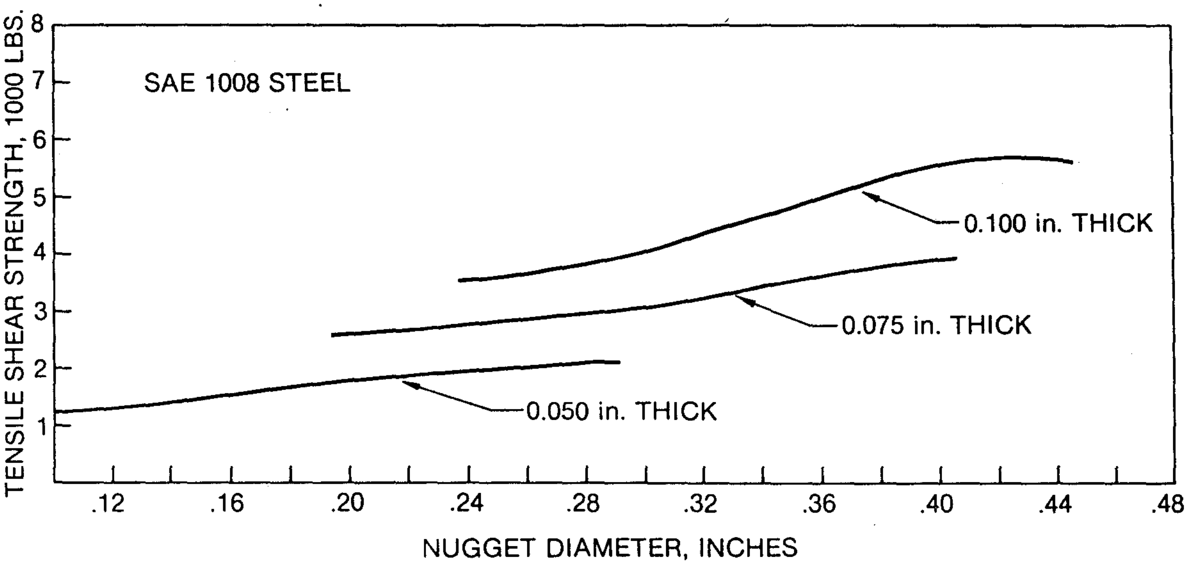


Figure 17.16–Effect of Nugget Size and Sheet Thickness on Tensile Shear Strength, Failure Occuring by Base Metal Tear Out

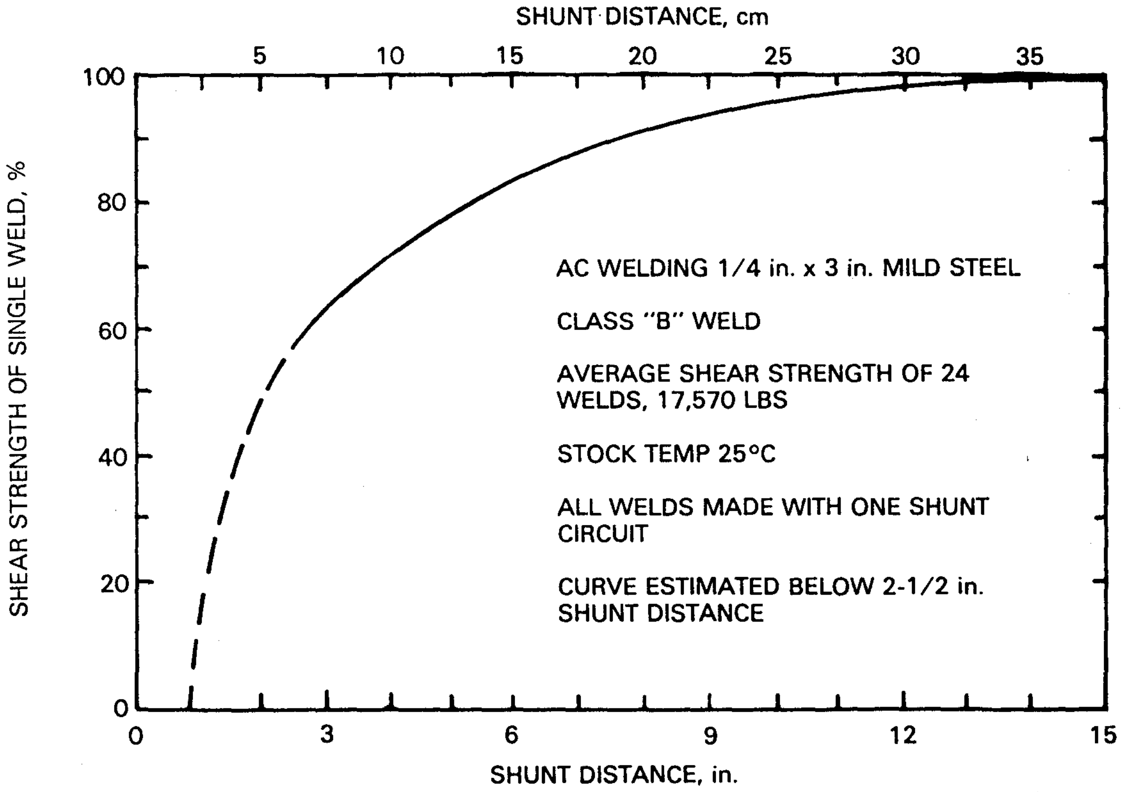


Figure 17.17–The Effect of Shunt Distance (Spot Spacing) on Tensile Shear Strength Loss

Table 17.1
Suggested Schedules for Spot Welding Uncoated Low Carbon Steel Sheet

	Electrode				Weld	Welding	Minimum	Minimum Weld Spacing		Minimum	
Thickness in.	Face Dia., in.	Shape *	Bevel Angle, Degrees**	Force, lb	Time, (60Hz) cy	Current, (Approx.) A	Contact Overlap, in.	2 stack, in.	3 stack, in.	Shear Strength, lb	Button Dia., in.
0.020	0.188	E,A,B	45	400	7	8,500	0.44	0.38	0.62	320	0.10
0.025	0.188	E,A,B	45	450	8	9,500	0.47	0.62	0.88	450	0.12
0.030	0.250	E,A,B	45	500	9	10,500	0.47	0.62	0.88	575	0.14
0.035	0.250	E,A,B	45	600	9	11,500	0.53	0.75	1.06	750	0.16
0.040	0.250	E,A,B	45	700	10	12,500	0.53	0.75	1.06	925	0.18
0.045	0.250	E,A,B	45	750	11	13,000	0.59	0.94	1.18	1150	0.19
0.050	0.312	E,A,B	30	800	12	13,500	0.59	0.94	1.18	1350	0.20
0.055	0.312	E,A,B	30	900	13	14,000	0.63	1.06	1.31	1680	0.21
0.060	0.312	E,A,B	30	1000	14	15,000	0.63	1.06	1.31	1850	0.23
0.070	0.312	E,A,B	30	1200	16	16,000	0.66	1.18	1.50	2300	0.25
0.080	0.312	E,A,B	30	1400	18	17,000	0.72	1.38	1.60	2700	0.26
0.090	0.375	E,A,B	30	1600	20	18,000	0.78	1.56	1.88	3450	0.27
0.105	0.375	E,A,B	30	1800	23	19,500	0.84	1.68	2.00	4150	0.28
0.120	0.375	E,A,B	30	2100	26	21,000	0.88	1.81	2.50	5000	0.30

* Shape Definitions: E = Truncated Cone
A = •A• Nose Pointed
B = 3 in. Radius

** Applies to truncated cone electrodes only and is measured from the plane of the electrode face.

Notes:
1. For intermediate thicknesses, force and weld time may be interpolated.
2. Minimum weld spacing is measured from centerline to centerline.
3. The data within this table were supplied by the AWS D8 Committee and represent an average of typical variables used by the automotive industry.

RESISTANCE SEAM WELDING

APPLICATIONS

A RESISTANCE SEAM weld (RSEW) is made on overlapping workpieces and is a continuous weld formed by overlapping weld nuggets, by a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by its resistance to the welding current.

Seam welds are typically used to produce continuous gas- or liquid-tight joints in sheet assemblies, such as automotive gasoline tanks. The process is also used to weld longitudinal seams in structural tubular sections that do not require leak-tight seams. In most applications, two wheel electrodes, or one translating wheel and a stationary mandrel, are used to provide the current and pressure for resistance seam welding (Figure 17.18). Seam welds can also be produced using spot welding electrodes; this requires the purposeful overlapping of the spot welds in order to obtain a leak-tight seam weld. Overlapping spot welding requires an increase in power after the first spot weld, to offset the shunting effect in order to obtain adequate nugget formation as welding progresses.

ADVANTAGES AND LIMITATIONS

RESISTANCE SEAM WELDING has the same advantages and limitations as resistance spot welding. An additional advantage is the ability to produce a continuous leak-tight weld.

Seam welds must be made in a straight or uniformly curved path. Abrupt changes in welding direction or in joint contour along the path cannot be welded leaktight. This limits the design of the assembly.

Strength properties of seam welded lap joints are generally lower than those of fusion welded butt joints, due to the eccentricity of loading on lap joints and the built-in notch along the nugget at the sheet interface.

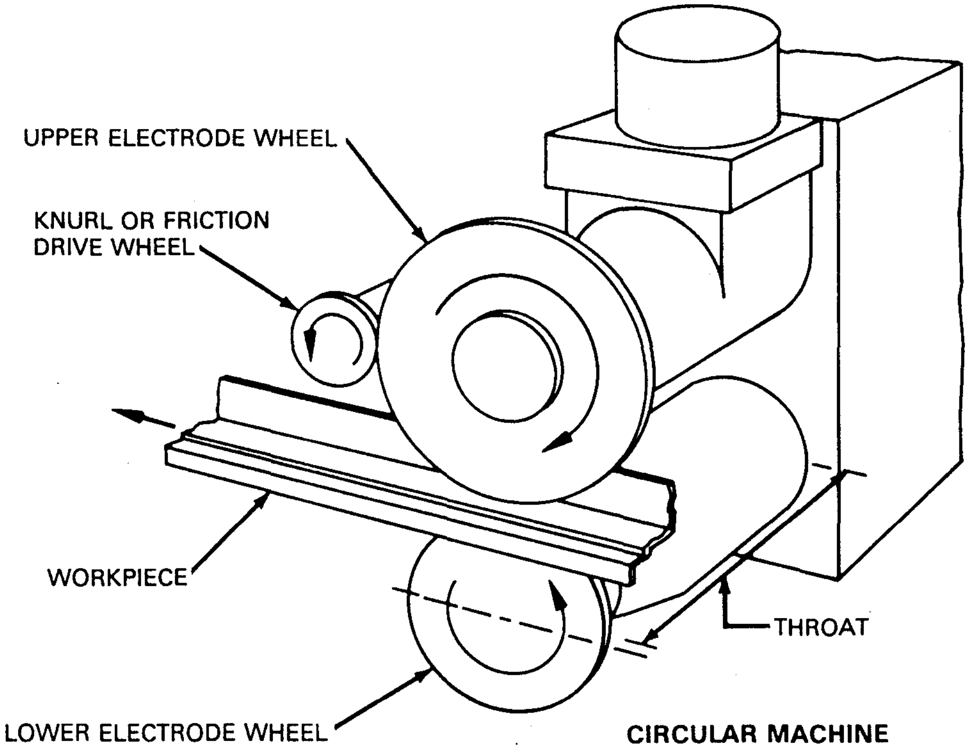


Figure 17.18–Position of Electrode Wheels on Resistance Seam Welder

PROCESS VARIATIONS

RESISTANCE SEAM WELDING variations are shown in Figure 17.19.

Lap Seam Welding

LAP JOINTS CAN be seam welded using two wheel electrodes [Figure 17.19 (A)] or with one wheel and a mandrel. The minimum joint overlap is the same as for spot welding, namely twice the minimum edge distance (distance from the center of the weld nugget to the edge of the sheet).

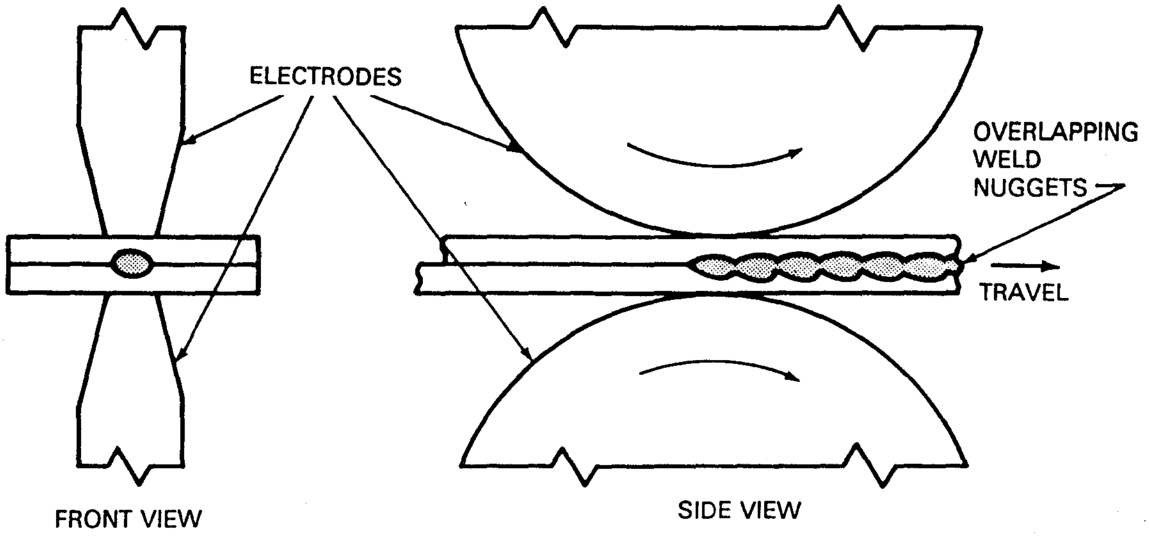
Mash Seam Welding

MASH SEAM WELDING is a resistance welding variation that makes a lap joint primarily by high-temperature plastic forming and diffusion, as opposed to melting and solidification. The joint thickness after welding is less than the original assembled thickness.

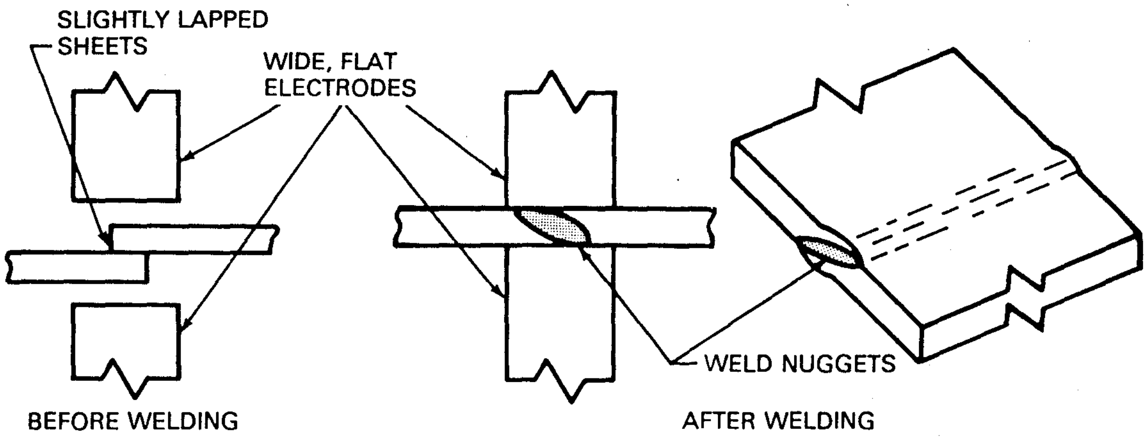
Mash seam welding [Figure 17.19 (B)] requires considerably less over lap than the conventional lap joint. The overlap is about 1 to 1.5 times the sheet thickness, with proper welding procedures. Wide, flat-faced wheel electrodes, which completely cover the overlap, are used. Mash seam welding requires high electrode force, continuous welding current, and accurate control of force, current, welding speed, overlap, and joint thickness in order to obtain consistent welding characteristics. Overlap is maintained at close tolerances, usually by rigidly clamping or tack welding the pieces.

Typically, the exposed or show side of the welded component is placed against a mandrel which acts as an electrode and supports the members to be joined. A welding wheel electrode is applied to the side of the joint that does not show. The show surface of the joint must be mashed as nearly flat as possible so that it will present a good appearance. Proper positioning of the wheel with respect to the joint is required to obtain a smooth weld face. Some polishing of the weld area may be required before painting or coating, when the appearance of the finished product is important.

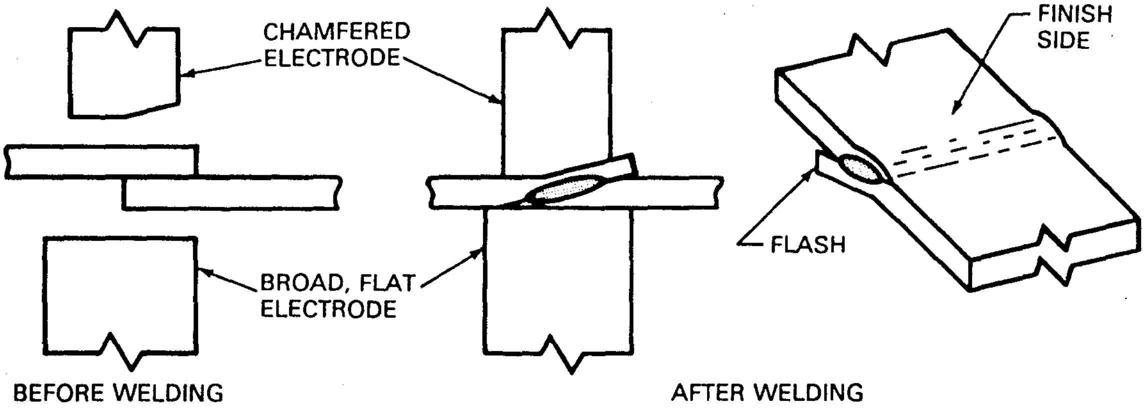
Mash seam welding produces continuous seams, which have good appearance and are free of crevices. Crevice-free joints are necessary in applications having strict contamination or cleanliness requirements, such as joints in food containers or refrigerator liners.



(A) LAP SEAM WELD



(B) MASH SEAM WELD



(C) METAL FINISH SEAM WELD

Figure 17.19–Resistance Seam Welding Variations

Disadvantages of the mash seam welding process include the following:

(1) Offset at the joint, due to the inability of the process to completely flatten the seam
(2) Distortion: the inherent lateral flow of metal as it is welded is restrained by fixturing or by tack welds
(3) Very rigid fixturing, required to resist weld distortion

In order to obtain acceptable welds, the materials to be joined by mash seam welding must have wide plastic temperature ranges. Low carbon steel and stainless steel can be mash seam welded for certain applications.

Metal Finish Seam Welding

LAP AND MASH seam welds differ with respect to the amount of forging, or, as the name implies, mash down. The lap weld has practically no mash down, while the thickness of a mash seam weld approaches that of one sheet thickness. In metal finish seam welding, mash down occurs on only one side of the joint (Figure 17.19C), and is a compromise between lap and mash seam welding.

The amount of deformation, or mash, is affected by the geometry of one electrode wheel face and the position of the joint with respect to that face. The wheel face is beveled on one side of the midpoint (Figure 17.20). This varies the amount of deformation across the joint. Good surface finish can be produced on the side of the joint against the flat wheel by using proper welding procedures.

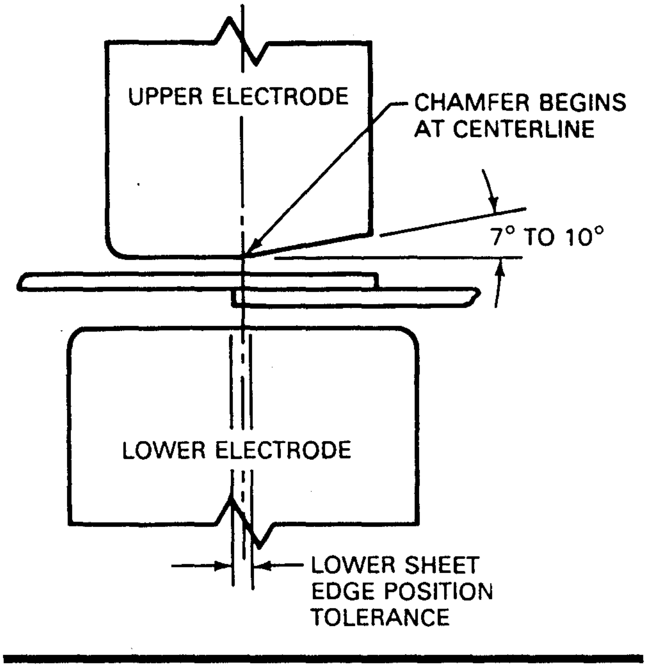


Figure 17.20–Electrode Face Contour and Joint Position for Metal Finish Seam Welding

The location of the edge of the sheet contacting the flat-faced electrode, relative to the bevel on the other electrode, must be held within close tolerance (Figure 17.20). With 0.031 in.(0.8 mm) thick low carbon steel sheet, for example, the edge must be within 0.016 in. (0.4 mm) of center. The overlap distance is not critical.

Higher amperage and electrode force are required than those for mash seam welding, because of the greater overlap distance. Materials that are easily mash seam welded (those with wide plastic temperature ranges) are also easily welded using the metal finish seam welding variation.

Electrode Wire Seam Welding

THE ELECTRODE WIRE seam welding process uses an intermediate wire electrode between each wheel electrode and the workpiece (Figure 17.21). The electrode wire seam welding process is used almost exclusively for seam welding of tin mill products to fabricate cans. The copper wire travels around the wheel electrodes at the welding speed. The copper wire electrode provides a continuously renewed surface, but it is not consumed in the welding operation. The tin build-up which would occur on a copper wheel electrode is avoided. The copper wire electrode may have a circular or flat cross section.

The process requires specially designed welding systems. The seam welds may be made with two wheel electrodes, or one wheel electrode and a mandrel electrode.

The temperature range of an electrode wire seam weld should provide good solid phase bonding and not exceed the melting point of the base material. If the seam weld reaches temperatures greater than the melting point of the base metal, spikes or splashes of molten metal are expelled from the seam weld. Splashes of material can lead to corrosion of the welded component, and are, therefore, undesirable. Electrode wire seam welding has small tolerance for temperature variation. Variations in welding temperature resulting from fluctuations in electrical power or electrode pressure, and changes in overlap distances are usually acceptable.

Butt Joint Seam Welding

BUTT JOINT SEAM welding is done with the edges of the sheets forming a butt joint. A thin, narrow strip of metal, fed between the workpieces and the wheel electrode, is welded to one or both sides of the joint. The metal strip bridges the gap between the workpieces, distributes the welding current to both sheet edges, offers added electrical resistance, and contains the molten weld nugget as the nugget forms. The strip serves as a filler metal and produces a flush or slightly reinforced weld joint. See Figure 17.22.

Strip electrode configurations can be circular, triangular, or flat. The metal strip must be guided accurately and centered on the joint to secure even current distribution to both sheet edges. The strip may be roll spot welded to the

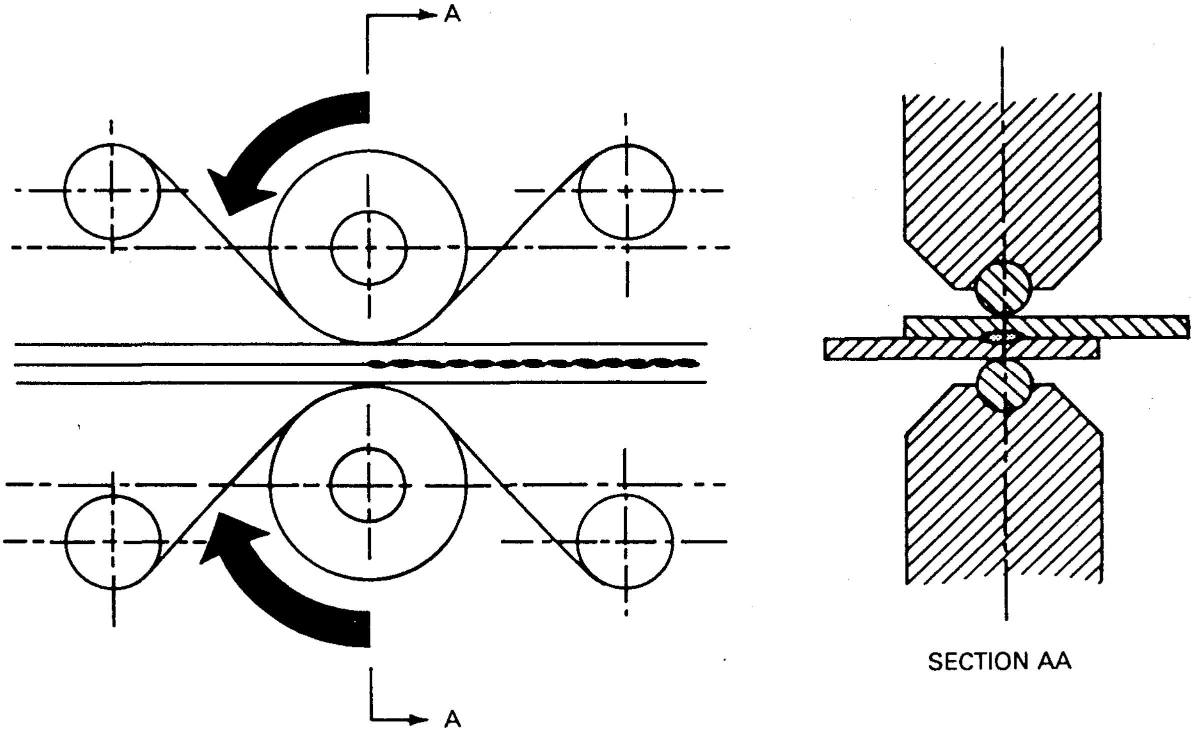


Figure 17.21–Electrode Wire Seam Weld

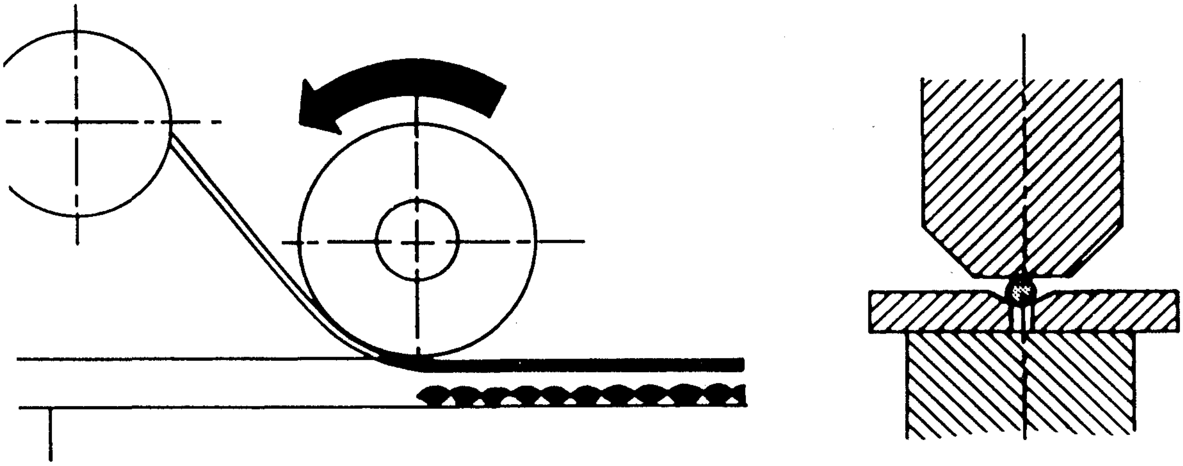


Figure 17.22–Butt Joint Seam Weld

sheets at low power before the joint is seam welded. Very little forging of the joint during welding is required; therefore, there is lower distortion of the joint compared to lap seam welding. The travel speed for butt joint seam welding of low-carbon steel is comparable to that for lap seam welding. Welding procedures must ensure welding of the strips over their entire width, in order to avoid reduced corrosion resistance.

Other Types of Seam Welding

AS WITH SPOT welding, two seam welds can be made in series, using two weld heads. The two heads may be mounted side by side or in tandem. Two seams can be welded with the same welding current, and power demand will be only slightly greater than for a single weld.

A tandem wheel arrangement can reduce welding time by 50 percent, since both halves of a joint can be welded simultaneously. Thus, for a joint 72 in. (182 cm) long, two welding heads can be placed 36 in. (91 cm) apart, with the welding current path through the work from one wheel electrode to the other. A third continuous electrode is used on the other side of the joint. The full length of the joint can be welded with only 36 in. (91 cm) of travel.

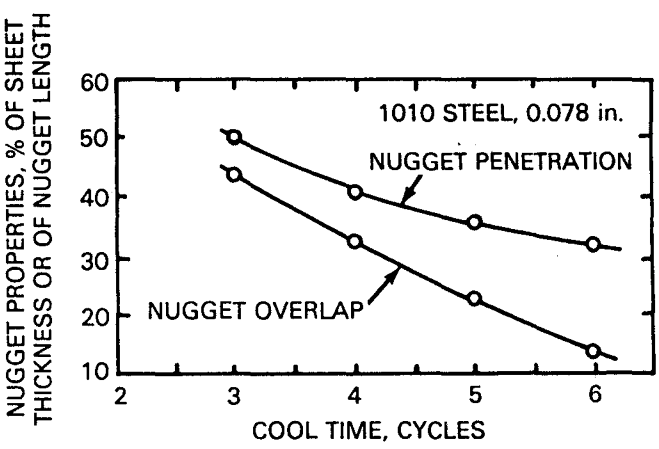
HEAT BALANCE

THE SEAM WELDING of dissimilar metals or unequal thicknesses presents the same heat balance problems as with spot welding. The techniques for improving joint heat balance are similar. On workpieces requiring a lower current density or faster cooling, the contact area between the work and the electrode can be enlarged by increasing the diameter or width of the wheel electrode. As an alternative, one of the electrode wheels or mandrels may be made of an alloy of higher thermal conductivity in order to facilitate heat conduction from the workpiece via the electrode.

WELDING CYCLE

RESISTANCE SEAM WELDS typically require higher welding currents than resistance spot welds, due to the shunting of the welding current through previously made welds.

The resistance welding current is normally supplied in timed pulses (heating times) which are separated by periods of cool times (hold times). A weld nugget is produced during each pulse of current. For a given welding speed and heating-cooling cycle, the welding current determines the depth of weld penetration. The welding-current schedule and weld speed control the weld nugget overlap. As the welding speed increases, the ratio of heating time to cool time must be increased in order to maintain weld nugget overlapping. The heat time controls the size of the weld nugget. Figure 17.23 shows the effect that cool time has on weld nugget penetration (macrosection perpendicular to weld centerline) and weld overlap (macrosection parallel to weld centerline).



NOTE: WELDING CONDITIONS: HEAT TIME, 6 CYCLES; ELECTRODE FORCE, 1500 LB; WELDING CURRENT, 18 950 A; WELDING SPEED, 55 in./MIN.
(SOURCE: RWMA BULLETIN 23)

Figure 17.23–Effects of Cool Time on Nugget Penetration and Nugget Overlap in Seam Welding

Welding currents higher than those required to obtain proper joint properties may result in excessive indentation, or burning of the welded workpieces. Short heating times, or fast weld speeds, require higher current levels for proper weld nugget formation, but may produce greater electrode wear.

Either pulsed (intermittent) current or continuous alternating current is used for resistance seam welding. As an example of the lap seam welding process, Table 17.2 provides suggested resistance seam welding conditions for welding uncoated low carbon steel sheet.

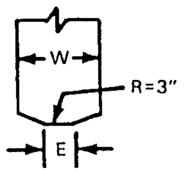
Pulsed Current

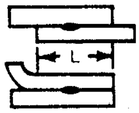
PULSED CURRENT IS usually desirable for most seam welding operations for the following reasons:

(1) Good control of the heat is obtained.
(2) Each weld nugget in the seam is allowed to cool under pressure.
(3) Distortion of the work parts is minimized.
(4) It is easy to control expulsion or burning.
(5) Sound welds with better surface appearance are possible.

To produce a leak-tight seam, the nuggets should overlap 15 to 20 percent of the nugget diameter. For maximum

Table 17.2
Suggested Schedules for Seam Welding Uncoated Low Carbon Steel Sheet





	Electrode Width and Shape (in.)								Minimum Contact Overlap
Thickness	W, Min.	E, Max.	Force (lb.)	On Time (cycles) (60 per second)	Off Time (cycles)	Weld Speed (in./min.)	Welds Per Inch	Current (Amp.)	(in.)
0.010	0.380	0.18	400	2	1	80	15.0	8000	0.38
0.021	0.380	0.19	550	2	2	75	12.0	11000	0.44
0.031	0.500	0.25	900	3	2	72	10.0	13000	0.50
0.040	0.500	0.25	980	3	3	67	9.0	15000	0.50
0.050	0.500	0.31	1050	4	3	65	8.0	16500	0.56
0.062	0.500	0.31	1200	4	4	63	7.0	17500	0.62
0.078	0.062	0.38	1500	6	5	55	6.0	19000	0.69
0.094	0.062	0.44	1700	7	6	50	5.5	20000	0.75
0.109	0.750	0.50	1950	9	6	48	5.0	21000	0.81
0.125	0.750	0.50	2200	11	7	45	4.5	22000	0.88

Notes:
1. Type of steel - SAE 1010
2. Material should be free from scale, oxides, paint, grease and oil.
3. Welding conditions determined by thickness outside piece "T".
4. Data for total thickness of pile-up not exceeding 4 "T". Maximum ratio between thicknesses; 3 to 1.
5. Electrode material. Class 2
   Minimum conductivity - 75% of Copper
   Minimum hardness - 75 Rockwell "B"
6. For large assemblies minimum contacting overlap indicated should be increased 30 percent.

strength, the overlap should be 40 to 50 percent. The size of the nugget will depend upon the heat time for a given welding speed and current. The amount of overlap will depend upon the cool time.

For a particular metal and sheet thickness, the number of welds (nuggets) per inch that can be produced economically will fall within a range. In general, as the sheet thickness decreases, the number of welds per unit of length must increase to obtain a strong, leak-tight seam weld. The ratio of welds per inch to welds per minute will establish the welding speed in inches per minute. The number of welds per minute is the number of cycles of ac per minute, divided by the sum of the heat and cool times (in cycles) for a single weld.

To obtain the minimum number of welds per inch that will produce the required seam at a given welding speed, the heat time and welding current should be adjusted to give the required weld nugget geometry. The cool time should then be set to give the necessary nugget overlap. Since decreasing cool time may increase the heat buildup, nugget penetration may increase.

Roll Spot Welding

ROLL SPOT WELDING consists of making a series of spaced spot welds in a row with a seam welding machine without retracting the electrode or removing the electrode force between welds. Electrode wheel rotation may or may not be stopped during the welding cycle. The radius of the wheel electrode, the contour of its face, and the weld time influence the shape of the nugget. The nugget is usually oval-shaped.

The weld spacing is obtained by adjustment of cool time with the wheel electrodes continuously rotating at a set speed. Hold time is effectively zero. Roll spot welding may also be done with interrupted electrode rotation when a hold time period is needed to consolidate the weld nugget as it cools.

When continuously moving electrodes are employed, as is commonly the case, weld time is usually shorter and welding amperage higher than those used for conventional spot welding. The higher amperage employed may sometimes require the use of a higher electrode force. Otherwise, recommended practices for spot welding apply.

Continuous Current

WITH LOW CARBON steel, welding current can be applied continuously along the length of the seam with high travel speeds, if the current wave form available will produce the proper nugget size and spacing. In this case weld quality is secondary to high- production requirements. Continuous current can be used for sheet up to and including 0.040 in. (1 mm) thickness. Above this thickness, surface condition has a significant effect on welding, and electrode life is short. Continuous current welds in a particular thickness can be made over a wide range of speeds. For example, two thicknesses of 0.040-in.(1 mm.) steel stock can be welded at speeds ranging from 105 to 310 in./min. (44 to 131 mm/s). The required amperage increases with speed.

A problem that may arise when using continuous alternating current operations is arcing between the wheel electrode and a localized region of the weld assembly on the exit side of the electrode. The arcing may produce superficial melting of the sheet surface and the electrode. In steels, the rapid cooling of molten metal that results from workpiece-to-electrode arcing, can result in brittle martensite formation. The localized martensitic microstructure may provide initiation sites for crack formation.

WELDING SPEED

THE SPEED OF welding depends upon the metal being welded, stock thickness, and the weld strength and quality requirements. In general, permissible welding speeds are much lower with stainless steels and nonferrous metals, because of restrictions on heating rate to avoid weld metal expulsion.

In some applications, it is necessary to stop the movement of the electrodes and work as each weld nugget is made. This is usually the case for sections over 0.188 in. (4.78 mm) thick, and for metals that require postheating or forging cycles to produce the desired weld properties. Interrupted motion significantly reduces welding speed because of the relatively long time required for each weld.

With continuous motion, the welding current must be increased and heat time decreased as welding speed is increased to maintain weld quality and joint strength. There is a speed beyond which the required welding current may cause undesirable surface burning and electrode pickup. This will accelerate electrode wear.

ELECTRODES

SEAM WELDING ELECTRODES are normally wheels with diameters ranging from 2 to 24 in. (50 to 600 mm). Common sizes have diameters of 7 to 12 in. (175 to 300 mm) and widths of 0.375 to 0.75 in. (10 to 19 mm).

The width of the weld cross section at the interface of the two workpieces should range from 1.5 to 3 times the thickness of the thinner member. The ratio of weld width to sheet thickness normally decreases as the thickness increases. The weld width is always slightly less than the electrode face width when commercial welding schedules are used.

For more information on seam welding electrodes, see Chapter 19, "Resistance Welding Equipment".

EXTERNAL COOLING

FLOOD COOLING, IMMERSION, or mist cooling is commonly used with seam welding. This is generally in addition to any internal cooling of the components in the secondary circuit of the welding machine. When external cooling is not used, electrode wear and distortion of the work may be excessive. For welding nonferrous metals and stainless steel, clean tap water is satisfactory. For ordinary steels, a 5 percent borax solution is commonly used to minimize corrosion.

JOINT DESIGN

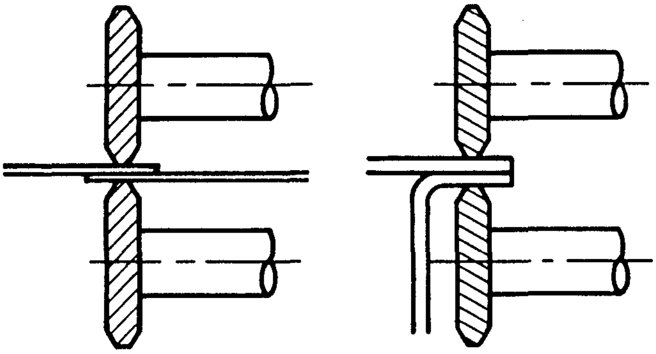
THE VARIOUS REQUIREMENTS that must be met in designing spot welded joints apply to seam welded joints. With seam welding, electrode design together with mounting and leak-tightness requirements place some limitations on design.

The wheel-type electrodes are relatively large and require unobstructed access to the joint. Since the electrodes rotate during welding, they cannot be inserted into small recesses or internal corners. External flanges must change direction over large radii in order to produce a strong, leaktight seam weld. Joint designs that incorporate corners having small radii may result in welding problems when resistance seam welding. Decreased welding speeds are sometimes required in order to maintain weld quality.

Figure 17.24 presents some common designs of seam welded joints. They are similar to those used for spot welding applications. The lap joint (Figure 17.24A) is the most common design. The workpiece edges must overlap sufficiently to prevent expulsion of the weld metal from the edges of the workpiece. Excessive overlapping however, may entrap dirt or moisture within the joint, and may cause subsequent manufacturing or service problems. Lap seam welds are used for the longitudinal seams in cans, buckets, water tanks, mufflers, and large diameter, thin-walled pipes.

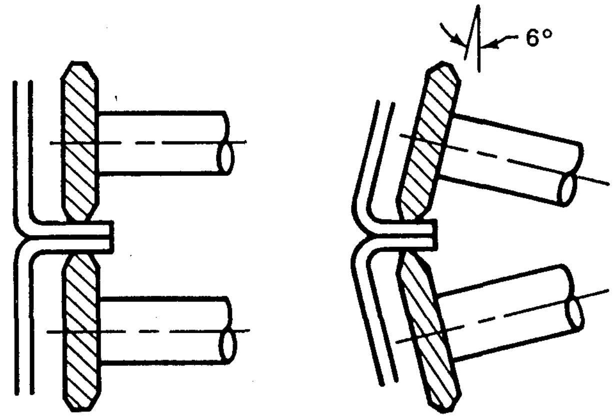
Flange joints are forms of lap joints. The design in Figure 17.24 (B), in which one of the pieces is straight, is commonly used to weld flanged ends to containers of various types. In Figure 17.24 (C), both pieces are flanged. This design is used to join the two sections of automotive gasoline tanks. Often the flanged pieces are dished to obtain added strength, in which case it is necessary to mount one or both wheels at an angle to clear the work, as shown in Figure 17.24 (D). A practical limit is 6 degrees because greater angles cause excessive bearing thrust.

Specialized workpiece designs may require the adjustment of the shape and contour of the wheel electrode. Workpieces that contain regularly spaced contours may be welded with notched or segmented wheel electrodes (Figure 17.25).



(A) LAP JOINT

(B) FLANGED JOINT



(C) FLANGED JOINT

(D) ANGLED WHEEL ELECTRODE

Figure 17.24–Examples of Resistance Seam Welded Joints

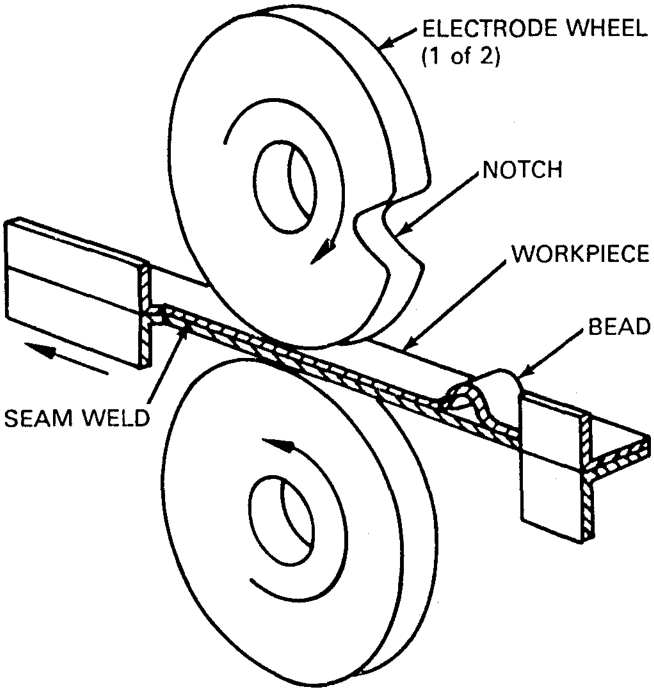


Figure 17.25–Notched Electrode Wheel for Seam Welding of a Workpiece Having Obstructions in the Path of the Wheel

PROJECTION WELDING

APPLICATIONS

PROJECTION WELDING IS primarily used to join a stamped, forged, or machined part to another part. One or more projections are produced on the parts during the forming operations. Fasteners or mounting devices, such as bolts, nuts, pins, brackets, and handles, can be projection welded to a sheet metal part. Projection welding is especially useful for producing several weld nuggets simultaneously between two parts. Marking of one part can be minimized by placing the projections on the other part.

The process is generally used for section thicknesses ranging from 0.02 to 0.125 in. (0.5 to 3.2 mm) thick. Thinner sections require special welding machines capable of following the rapid collapse of the projections. Various carbon and alloy steels and some nickel alloys can be projection welded.

ADVANTAGES AND LIMITATIONS

IN GENERAL, PROJECTION welding can be used instead of spot welding to join small parts to each other and to larger parts. Selection of one method over another depends upon the ecomonics, advantages, and limitations of the two processes. The chief advantages of projection welding include the following:

(1) A number of welds can be made simultaneously in one welding cycle of the machine. The limitation on the

number of welds is the ability to apply uniform electrode force and welding current to each projection.

(2) Less overlap and closer weld spacings are possible, because the current is concentrated by the projection, and shunting through adjacent welds is not a problem.

(3) Thickness ratios of at least 6 to 1 are possible, because of the flexibility in projection size and location. The projections are normally placed on the thicker section.

(4) Projection welds can be located with greater accuracy and consistency than spot welds, and the welds are generally more consistent because of the uniformity of the projections. As a result, projection welds can be smaller in size than spot welds.

(5) Projection welding generally results in better appearance, on the side without the projection, than spot welding can produce. The most deformation and greatest temperature rise occur in the part with the projection, leaving the other part relatively cool and free of distortion, particularly on the exposed surface.

(6) Large, flat-faced electrodes are used; consequently, electrode wear is much less than that with spot welding and this reduces maintenance costs. In some cases, the fixturing or part locators are combined with the welding dies or electrodes when joining small parts together.

(7) Oil, rust, scale, and coatings are less of a problem than with spot welding, because the tip of the projection tends to break through the foreign material early in the welding cycle; however, weld quality will be better with clean surfaces.

The most important limitations of projection welding are the following:

(1) The forming of projections may require an additional operation unless the parts are press-formed to design shape.

(2) With multiple welds, accurate control of projection height and precise alignment of the welding dies are necessary to equalize the electrode force and welding current.

(3) With sheet metal, the process is limited to thicknesses in which projections with acceptable characteristics (see Projection Designs - Sheet Metal) can be formed, and for which suitable welding equipment is available.

(4) Multiple welds must be made simultaneously, which requires higher capacity equipment than does spot welding. This also limits the practical size of the component that contains the projections.

TYPES OF JOINTS

AS WITH SPOT and seam welding, projection welding can be used to produce lap joints. The number and shape of the projections depend upon the requirements for joint strength.

Circular or annular ring projections can be used to weld parts requiring either gas-tight or water-tight seals, or to obtain a larger area weld than button-type projections can provide.

PROJECTION DESIGNS

THE MEANS OF producing projections depends upon the material in which they are to be produced. Projections in sheet metal parts are generally made by embossing, as opposed to projections formed in solid metal pieces which are made by either machining or forging. In the case of stamped parts, projections are generally located on the edge of the stamping.

The purpose of a projection is to localize the heat and pressure at a specific location on the joint. The projection design determines the current density. Various types of projection designs are shown in Figure 17.26.

Sheet Metal

A PROJECTION DESIGN for sheet metal should meet the following requirements:

(1) Be sufficiently rigid to support the initial electrode force before welding current is applied.

(2) Have adequate mass to heat a spot on the other surface to welding temperature. If too small, the projection will collapse before the other surface is adequately heated.

(3) Collapse without metal expulsion between the sheets or sheet separation after welding.

(4) Be easy to form and not be partially sheared from the sheet during the forming operation. Such projections may be weak and the resulting welds may be easily torn from the sheet on loading.

(5) Cause little distortion of the part during forming or welding.

The general design of a projection suitable for steel sheet is shown in Figure 17.27. This design avoids the tendency for the forming operation to shear the sheet or to significantly thin the projection wall. The designs of the punch and die that form this projection shape are illustrated in Figure 17.28. The projection sizes recommended for various sheet thicknesses, and the punch and die dimensions to produce the projections, are given in Table 17.3.

Projections may be elongated to increase nugget size, and thus the strength of the weld. In this case, the contact between the projection and the mating section is linear. Elongated projections are generally used for the thicker sheet gages.

On thin sheet, an annular projection of small diameter may be used instead of a round projection. The annular projection has greater stiffness to resist collapse when electrode force is applied.

Machined or Forged Parts

ANNULAR PROJECTIONS ARE frequently used on forged parts to carry heavy loads and for applications that require a pressure- tight joint around a hole between two parts. Such preparation also produces a high-strength weld when a large stud or boss is welded to thin sheet metal. Figure

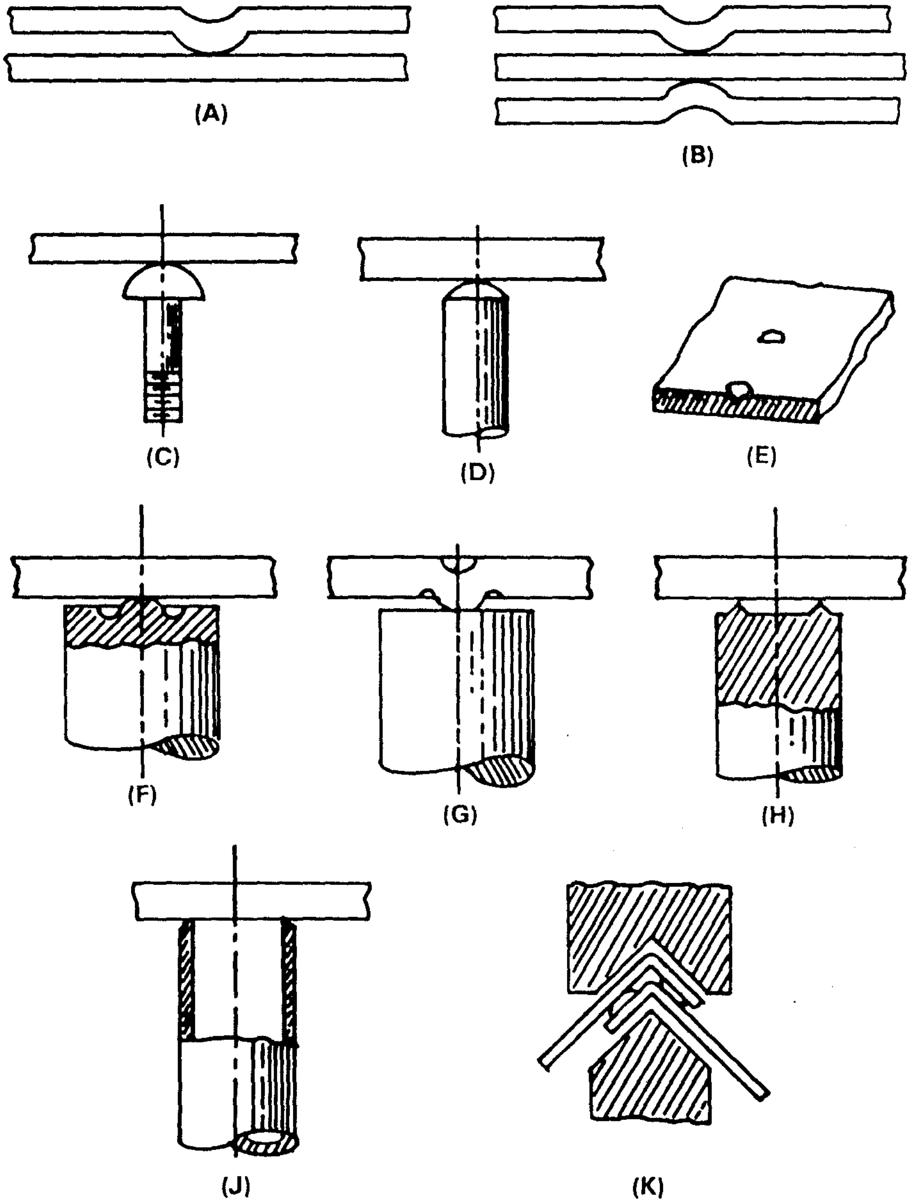


Figure 17.26–Examples of Various Projection Designs.

17.29 shows two applications of annular projections. The summit of the circular ridge should be rounded, particularly with heavy sections, to improve heat balance. Relief, as shown in Figure 17.29(C), should be provided at the base of the projection, for the upset metal to fill as the projection collapses. This will assure a tight joint without a gap, as shown in Figure 17.29(D).

Various designs of weld fasteners are available commercially for projection welding applications. Typical examples are shown in Figure 17.30. Projection designs and their number depend upon the application.

HEAT BALANCE

THE FOLLOWING FACTORS affect heat balance:

(1) Projection design and location
(2) Thickness of the sections

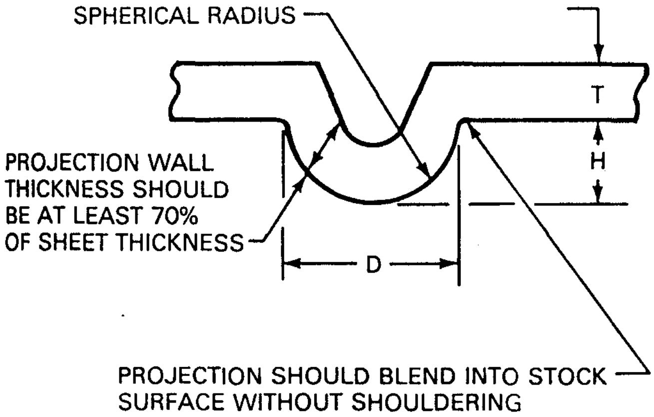


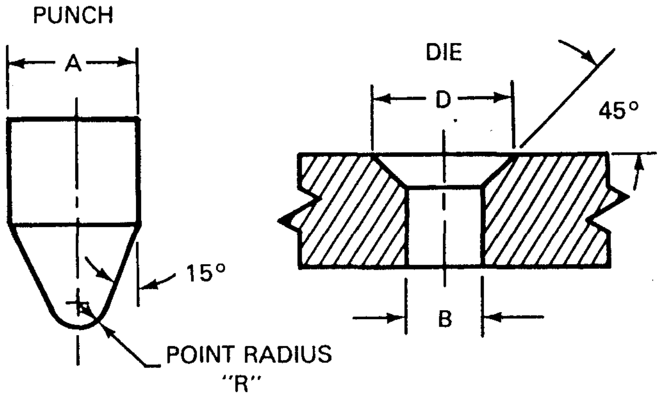
Figure 17.27–Basic Design of a Projection Placed in Steel Sheet

(3) Thermal and electrical conductivities of the metal being welded

(4) Heating rate

(5) Electrode alloy

The distribution of heat in the two sections being projection welded together must be reasonably uniform to obtain strong welds, as in spot welding. The major portion of the heat develops in the projections during projection welding. Consequently, heat balance is generally easier to obtain in projection welding than in spot welding; however, it may be complicated by simultaneously making multiple projection welds. Uniform division of welding current and electrode force is necessary to obtain even heating of all projections. Since the current paths through the projections are in parallel, any variation in resistance between the projections will cause the current to be distributed unequally.



MATERIAL: TOOL STEEL HARDENED TO 50-52 RC

Figure 17.28–Basic Design of a Punch and Die to Form Projections of the Type Shown in Figure 17.27 in Sheet Steel

Projections must be designed to support the electrode force needed to obtain good electrical contact with the

Table 17.3
Punch and Die Dimensions for Spherical Dome Projections (Refer to Figure 17.28)

	Projection		Punch		Die	
Thickness (T)	Height, H Within 2%	Diameter, D Within 5%	Diameter A	Point Radius, R Within 0.002	Hole Diameter, B Within 0.005	Chamber Diameter
0.022-0.034	0.025	0.090	0.375	0.031	0.076	0.090
0.036-0.043	0.035	0.110	0.375	0.047	0.089	0.110
0.049-0.054	0.038	0.140	0.375	0.047	0.104	0.130
0.061-0.067	0.042	0.150	0.375	0.062	0.120	0.150
0.077	0.048	0.180	0.375	0.062	0.144	0.180
0.092	0.050	0.210	0.500	0.078	0.172	0.210
0.107	0.055	0.240	0.500	0.078	0.196	0.240
0.123	0.058	0.270	0.500	0.094	0.221	0.270
0.135	0.062	0.300	0.500	01.09	0.250	0.300
0.153	0.062	0.330	0.500	0.125	0.270	0.330
0.164	0.068	0.350	0.500	0.141	0.297	0.360
0.179	0.080	0.390	0.500	0.156	0.328	0.390
0.195	0.084	0.410	0.500	0.156	0.338	0.410
0.210	0.092	0.440	0.500	0.187	0.358	0.440
0.225	0.100	0.470	0.500	0.187	0.368	0.470
0.245	0.112	0.530	0.500	0.187	0.406	0.530

All dimensions are in inches.

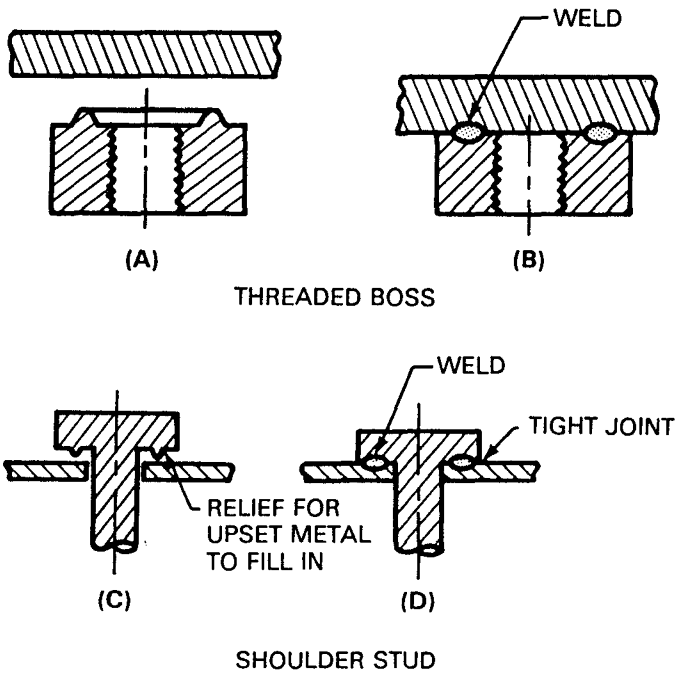


Figure 17.29–Application of Projection Welding Using Annular Projections

mating part, and to collapse when heated. With multiple projections, slight variations in projection heights can affect heat balance. This may occur as a result of wear of the projection-forming punches.

Heat balance in dissimilar thickness materials is maintained by placing the projection in the thicker of the pieces to be welded. The size of the projection is based upon the requirements for heating the thinner section. Similarly, to maintain heat balance in materials of dissimilar conductivity, the projection is located in the piece of higher conductivity (lower resistivity). The choice of electrode alloy determines the conductivity of the electrode, which can also affect heat balance.

WELDING CYCLE

Welding Current

THE CURRENT FOR each projection is generally less than that required to produce a spot weld in the same thickness of that same metal. The projection will heat rapidly and excessive current will melt it and result in expulsion; however, the current must be at least high enough to create fusion before the projection has completely collapsed.

For multiple projections, the total welding current will approximately equal the current for one projection multiplied by the number of projections. Some adjustment may be required to account for normal projection tolerances, part designs, and the impedance of the secondary circuit.

Weld Time

WELD TIME IS about the same for single or multiple projections of the same design. Although a short weld time may be desirable from a production standpoint, it will require correspondingly higher amperage. This may cause overheating and metal expulsion. In general, longer weld times and lower amperages are used for projection welding than those for spot welding.

In some cases, multiple impulse welding may be advantageous to control heating rate. This is helpful with thick sections and with metals of low thermal conductivity.

Electrode Force

THE ELECTRODE FORCE used for projection welding will depend upon the metal being welded, the projection design, and the number of projections in the joint. The force should be adequate to flatten the projections completely when they reach welding temperature, and so to bring the workpieces in contact. Excessive force will prematurely collapse the projections and the weld nuggets will be ring-shaped, with incomplete fusion in the center.

The welding machine must be capable of mechanically following the work with the electrodes as the projections collapse. Slow follow-up will permit metal expulsion before the workpieces are together.

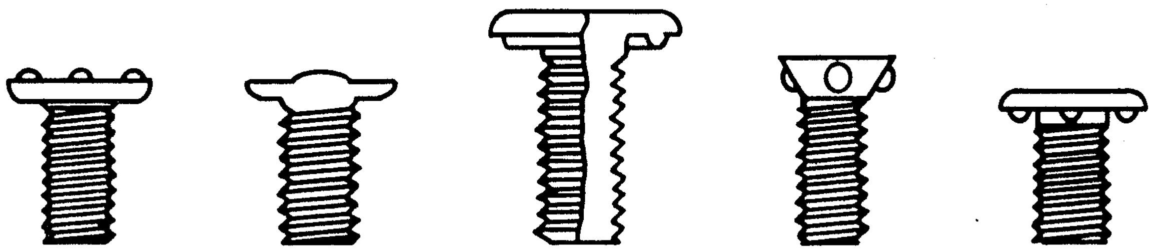
The sequence of events during the formation of a projection weld is shown schematically in Figure 17.31. In Figure 17.31(A), the projection is shown in contact with the mating sheet. In Figure 17.31(B), the current has started to heat the projection to welding temperature. The electrode force causes the heated projection to collapse rapidly and then fusion takes place as shown in Figure 17.31(C). The completed weld is shown in Figure 17.31(D).

ELECTRODES AND WELDING DIES

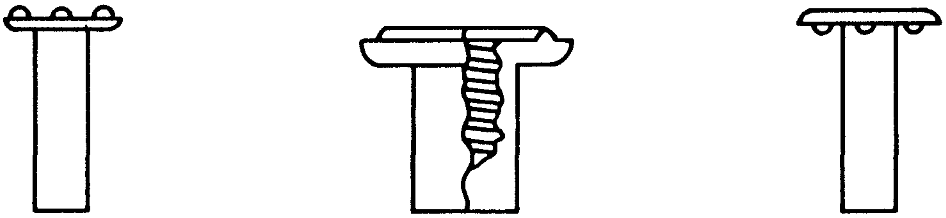
THE AREAS OF parts to be joined are frequently flat except for the projections. In such cases, large flat-faced electrodes are used. When the surfaces to be contacted are contoured, the electrodes are fitted to them. With such electrodes, the electrode force can be applied without distorting the parts, and the welding current can be introduced without overheating the contact areas.

For a single projection, the electrode face diameter should be at least twice the diameter of the projection. With multiple projections, the electrode face should extend a minimum of one projection diameter beyond the boundry of the projection pattern.

The best electrode material is one that is sufficiently hard (to minimize wear) but does not crack or cause surface burning of the part. If burning or cracking is encoun-



(A) WELD BOLTS



(B) WELD PINS

(C) WELD NUTS AND PADS

Figure 17.30—Typical Commercially Available Projection Weld Fasteners

tered, a softer alloy of higher conductivity should be used. With multiple projections, electrode wear can upset the balance of welding current and electrode force on the projections. Then the strength and quality of the welds may become unacceptable.

Electrodes for large production requirements often have inserts of Resistance Welder Manufacturers Association (RWMA) Group B material at the points of greatest wear. In some cases, it is more economical and equally satisfactory to use one-piece electrodes of RWMA Group A, Class 3 alloy.

Welding electrodes and locating dies for projection welding are usually combined. With the proper dies, it is possible to attain accuracy with projection welding equal to that of any other assembly process. The welding dies should meet the following requirements:

(1) Provide accurate positioning of the parts
(2) Permit rapid loading and unloading
(3) Have no alternative path for the welding current
(4) For ac welding, be made of nonmagnetic materials
(5) Be properly designed for operator safety

The dies must be mounted solidly on the welding machine. The parts are mated in one die and all the welds are made at once with one operation of the machine. One part may be located in relation to the other by punching holes in one, with semipunchings in the other to match. The projections can usually be embossed or forged in the same operation.

In some designs, insulated pins or sleeves may be used in the electrode or dies to position and align the parts. Simple examples are shown in Figures 17.32 and 17.33.

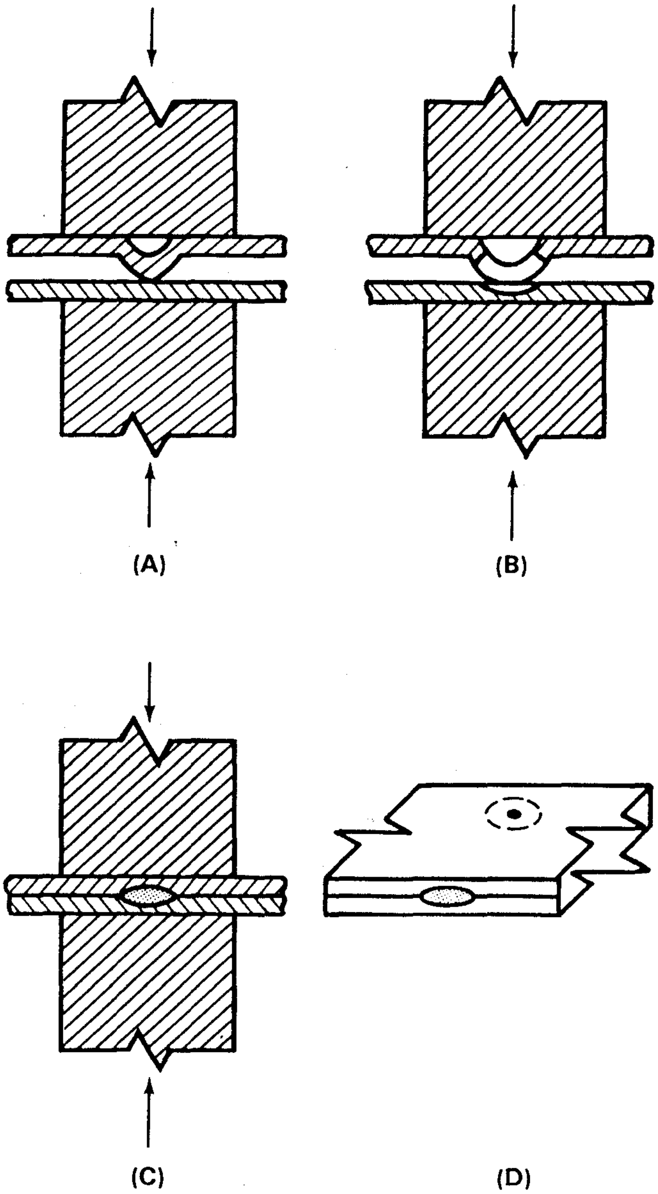


Figure 17.31–Sequence of Events During the Formation of a Projection Weld

When the small part of an assembly can be placed on the bottom and the large part on top, it is a simple matter to hold the small part in a recessed lower electrode such as shown in Figure 17.34. When it is desired to locate a small part on top of a larger part, a problem exists. Sometimes the small part can be located and held by a removable device and then welded with a flat upper electrode. Parts that nest into the upper electrode may be held by spring clips attached to the electrode. Figure 17.35 shows a spring-loaded retainer through the side of the electrode, holding a bolt for welding. Vacuum may also be used to hold small parts in the upper electrode or die when part design permits.

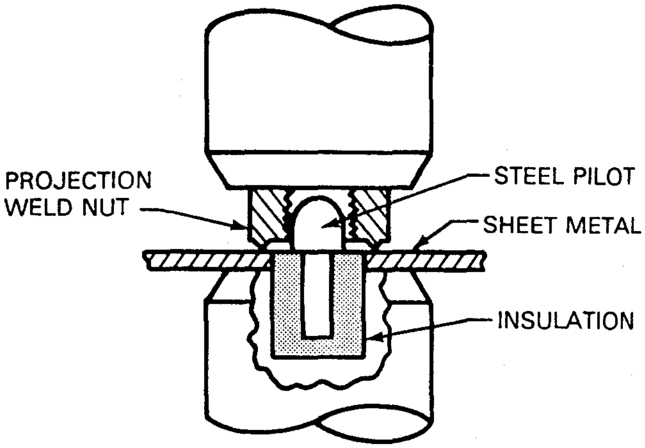


Figure 17.32–Use of an Insulating Pin to Locate a Weld Nut

The success of projection welding operations in production with respect to the electrodes depends largely upon the proper selection of materials, proper installation, and proper maintenance. If the dies are correctly designed and constructed, the installation is next in importance. First, the platens of the welding machine must be parallel to each other and perpendicular to the motion of the ram. The platens should also be smooth, clean, and free of nicks and pit marks. If they are not, the platens should be removed and machined smooth and flat before installation of the

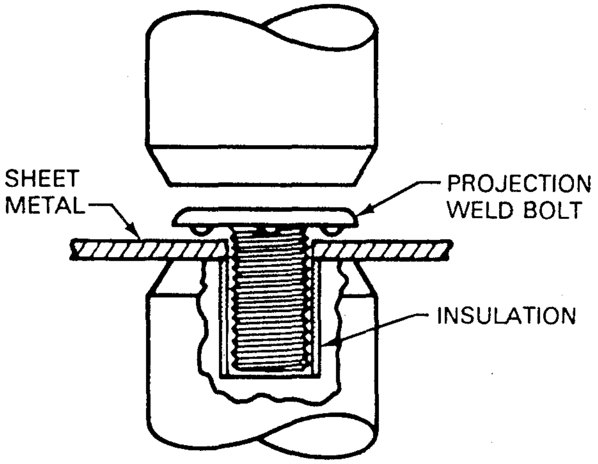


Figure 17.33–Positioning a Weld Bolt with an Insulating Sleeve

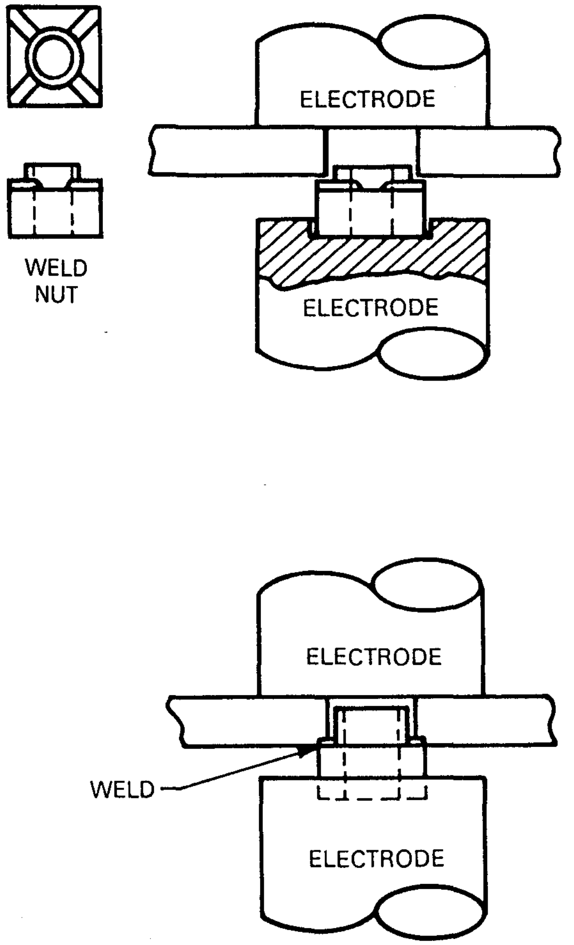


Figure 17.34—Use of a Recessed Electrode to Position a Weld Nut

dies. The check for parallelism of the platens should be made under intended operating forces. This can best be done by placing a steel block with smooth parallel faces between the platens, applying the intended electrode force, and then checking for gap with feeler gages.

The next step is to check the bases of the die blocks. They must be clean, smooth, flat, and free from burrs and nicks. If not, they should be machined.

The dies are then installed on the machine. Most machines have tee slots at right angles to one another in the two platens to permit universal alignment of the dies. After the dies are properly lined up, they should be clamped securely to the platens. With the work in place in the dies, the position of the ram or knee of the machine should be adjusted for the proper stroke, including the necessary allowance for upset of the projections.

If the tips of the projections are in one plane and of uniform height, the setup is ready for trial welds. Nonuniformity of current or force on the projections may be caused by the following:

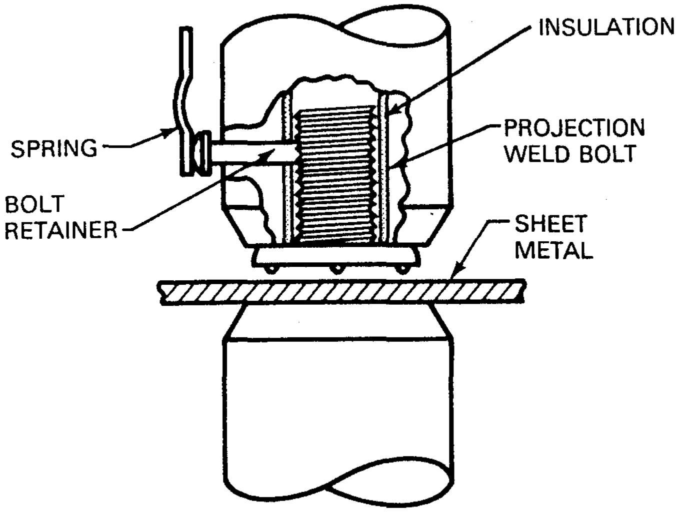


Figure 17.35—Holding a Bolt in the Upper Electrode with a Spring Retainer

(1) Shunting of current through locators
(2) Unequal secondary circuit path lengths
(3) Excessive play in the welding head
(4) Too much deflection in the knee of the machine

The use of shims between die components or between dies and platens should be avoided. If shims must be used, they should be only clean, annealed, pure copper sheets, of sufficient area to carry the secondary current.

If projections are located on curved or angled surfaces, accurate templates should be provided for checking the dies. Note that when curved parts are welded, or two or more parts are welded to others, the mill tolerances for the metal thicknesses involved may cause problems. These tolerances must be provided for in the design of the parts and the arrangement of the projections.

JOINT DESIGN

LAP JOINT DESIGNS for projection welding are similar to those for spot welding. In general, joint overlap and edge distances for projection welding can be less than for spot welding. Most applications use multiple projections where the minimum distance between projections should be twice the projection diameter.

Part design at the joint location may be significantly limited because the welding electrodes normally contact several projections simultaneously. The electrodes must be mounted rigidly on the welding machine, and the supporting members must be strong enough to minimize deflection when electrode force is applied. Press type welding machines are commonly used for projection welding applications.

Fit-up is important with multiple projection welding. Each projection must be in contact with the mating surface to accomplish a weld. Uniformity of projection heights is a factor in good fit-up. The welding dies must be carefully designed and accurately manufactured to mate with the parts at the weld locations. They should not need to deform the parts to obtain good fit-up.

Where surface marking of one part must be minimized, the projections should be placed in the other part. A large, flat electrode on the show side of the joint should prevent electrode marking, although slight shrinkage may occur at each projection weld. This may be visible after some finishing operations.

When projection welds are used to attach other fasteners such as weld nuts and bolts, they must contain a sufficient number of projections to carry the design load. The design should be proven by applicable mechanical testing. Production quality control should be programmed to ensure that weld quality does not drop below the design standards.

CROSS WIRE WELDING

General Principles

RESISTANCE WELDING OF crossed wires is, in effect, a form of projection welding. In practice, it usually consists of welding a number of parallel wires at right angles to one or more other wires or rods. There are many specific ways to perform the welding operation, depending upon production requirements, but the final finished product is essentially the same regardless of the method used. Figure 17.36 shows a section of a typical cross wire weld.

Crossed-wire products include such items as stove and refrigerator racks, grills of all kinds, lamp shade frames, poultry equipment, wire baskets, fencing, grating, and concrete reinforcing mesh.

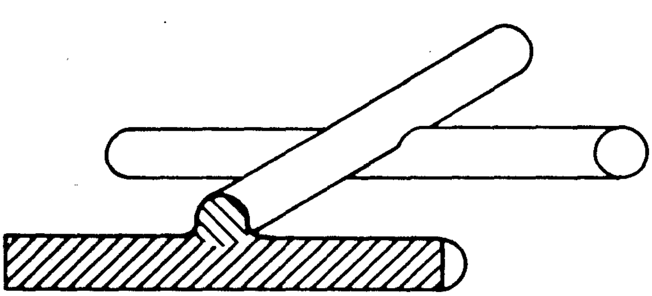


Figure 17.36–Section of a Typical Cross Wire Weld

Wire racks may be welded in a press-type projection welding machine or in special automatic indexing machines, with hopper feed and a separate gun for each weld.

Concrete reinforcing mesh is made on continuous machines. The stay wires are fed either from wire reels on the side of the machine or from magazines of cut wire. The welded mesh is either rolled into coils, like fencing, or cut into mats and then stacked and bundled.

As in spot and projection welding, the wire or rod should be clean and free from scale or rust, dirt, paint, heavy grease, or other high-resistance coatings. Plated or galvanized wire or rods may be used, but the coating at the weld will be destroyed.

Wire Materials

LOW CARBON STEEL wire is the wire most commonly welded. Typical machine settings for cross wire welding of this type of material are tabulated in Table 17.4. Next in importance are stainless steel and copper-nickel wires. Copper-nickel alloy wires will require about the same weld time and amperage as carbon steel wires, and about twice the electrode force. Stainless steel wires will require about the same weld time also, but 60 percent of the amperage, and 2.5 times the electrode force.

Welding Technique

NORMALLY, CROSS WIRE welds are not dressed after welding. Therefore, the major consideration may be appearance, with strength secondary in importance for some applications.

In setting up the welding machine, consideration must be given to the following:

(1) Design strength
(2) Appearance
(3) Welding electrodes
(4) Electrode force
(5) Weld time
(6) Welding current (heat)

The particular application will determine which is most important, strength or appearance, when setting up for a particular crossed wire welding application. It is normally assumed that high-strength welds with an acceptable appearance are desired.

The required electrode force, welding current, and weld time depend greatly upon the amount that the wires or rods are to be compressed together. This condition is called *setdown*. It is the ratio of the decrease in joint height to the diameter of the smaller wire. Weld strength generally increases as "setdown" percent increases.

The welding electrodes must be of the proper material and shape, with provision for water cooling. RWMA Class II alloy electrodes usually have acceptable life, although electrode facings of harder alloys are sometimes used for special applications. Although flat electrodes are commonly used for cross wire welding, certain advantages are gained by shaping them to mate with the wires or rods being welded. Shaped electrodes provide better contact between the electrode and the work.

The electrode force depends upon the wire diameter, the specified setdown, the desired appearance, and the weld-design strength. The electrode force will affect the appearance of the weld. The values given in Table 17.4 will produce welds with good appearance. Lower weld strengths than those shown in the table will result if higher forces are used without decreasing the weld time and increasing the welding current.

The weld time needed will depend upon the diameter of the wire to be welded. For best results, the values shown in the table should be used.

The welding current depends upon the diameter and the specified setdown. It should be slightly less than that which will result in spitting or expulsion of hot metal.

Table 17.4
Conditions for Cross Wire Welding of Low Carbon Steel Wire

	Cold Drawn Wire				Hot Drawn Wire			
Wire Diameter in.	Weld Time, Cycles	Electrode Force, lbs.	Weld Current, A	Weld Strength, lbs.	Weld Time, Cycles	Electrode Force, lbs.	Weld Current, A	Weld Strength, lbs.
	15% Setdown					15% Setdown		
1/16	5	100	600	450	5	100	600	350
1/8	10	125	1800	975	10	125	1850	750
3/16	17	360	3300	2000	17	360	3500	1500
1/4	23	580	4500	3700	23	580	4900	2800
5/16	30	825	6200	5100	30	825	6600	4600
3/8	40	1100	7400	6700	40	1100	7700	6200
7/16	50	1400	9300	9600	50	1400	10000	8800
1/2	60	1700	10300	12200	60	1700	11000	11500
	30% Setdown					30% Setdown		
1/16	5	150	800	500	5	150	800	400
1/8	10	260	2650	1125	10	260	2770	850
3/16	17	600	5000	2400	17	600	5100	1700
1/4	23	850	6700	4200	23	850	7100	3000
5/16	30	1450	9300	6100	30	1450	9600	5000
3/8	40	2060	11300	8350	40	2060	11800	6800
7/16	50	2900	13800	11300	50	2900	14000	9600
1/2	60	3400	15800	13600	60	3400	16500	12400
	50% Setdown					50% Setdown		
1/16	5	200	1000	550	5	200	1000	450
1/8	10	350	3400	1250	10	350	3500	900
3/16	17	750	6000	2500	17	750	6300	1800
1/4	23	1240	8600	4400	23	1240	9000	3100
5/16	30	2000	11400	6500	30	2000	12000	5300
3/8	40	3000	14400	8800	40	3000	14900	7200
7/16	50	4450	17400	11900	50	4450	18000	10200
1/2	60	5300	21000	14600	60	5300	22000	13000

$$\text{Setdown \%} = \frac{\text{Decrease in joint height}}{\text{Diameter of smaller wire}} + 100$$

METALS WELDED

PROPERTIES INFLUENCING WELDABILITY

THE FOLLOWING PROPERTIES of metals have a bearing on their resistance weldability:

(1) Electrical resistivity
(2) Thermal conductivity
(3) Thermal expansion
(4) Hardness and strength
(5) Oxidation resistance
(6) Plastic temperature range
(7) Metallurgical properties

Electrical Resistivity

WORKPIECE RESISTIVITY IS probably the most important welding property, from an RW standpoint, since the heat generated by the welding current is directly proportional to resistance. More current is required to generate heat for a metal of low resistivity than one of high resistivity. A metal such as pure copper is difficult to resistance weld, because of its low electrical resistivity. In addition, current shunting through adjacent welds is more significant in metals of low resistivity than in those of high resistivity. Therefore, metals of high electrical resistivity are considered more weldable than those of low resistivity. High currents also require large transformers and power lines which increase equipment costs.

Thermal Conductivity

THERMAL CONDUCTIVITY IS important because part of the heat generated during resistance welding is lost through conduction into the base metal. This loss must be overcome by greater power input. Therefore, metals of high heat conductivity are less weldable than those of low conductivity. Thermal conductivity and electrical conductivity of the various metals closely parallel one another. Aluminum, for instance, is a good conductor of both heat and electricity, while stainless steel is a poor conductor of both.

Thermal Expansion

THE COEFFICIENT OF thermal expansion is a measure of the change in dimensions that takes place with a temperature change. When the coefficient of thermal expansion is large, warping and buckling of welded assemblies can be expected.

Hardness And Strength

THE HARDNESS AND strength of metals are important to resistance welding. Soft metals can be indented easily by the electrodes. Hard, strong metals require high electrode forces, which in turn require electrodes with high hardness and strength to prevent rapid deformation of the electrodes. Metals that retain their strength at elevated temperatures may require the use of welding machines capable of applying a forging force to the weld.

Oxidation Resistance

ALL COMMONLY USED metals oxidize in air, some more readily than others. The surface oxide normally has high electrical resistance. Surface oxide films generally reduce the resistance weldability of metals. In spot and seam welding, they can cause surface flashing, pickup of metal on the electrode, and poor surface appearance. If the oxide film thickness varies from one part to another, inconsistent weld strength may result.

Aluminum alloys form surface oxides rapidly. Therefore, welding must be done within a short time after deoxidation cleaning to avoid significant variations in surface contact resistance. In contrast, preweld deoxidation cleaning is usually not necessary for stainless steel after being cleaned at the mill prior to packaging and shipping. Whether preweld deoxidation cleaning is necessary depends upon the amount of oxide present and how it will affect weld properties. Surface resistance measurements may be used to confirm cleanliness. In any case, all mill scale, heavy oxide from prior heat treatment, and extraneous material, such as paint, drawing compounds, or grease, should be removed prior to resistance welding.

Plastic Temperature Range

IF THE METAL melts and flows in a narrow temperature range, the welding variables must be more closely controlled than with a metal having a wide plastic temperature range. This property may have considerable bearing on the welding procedure and equipment. Aluminum alloys have narrow plastic ranges and require precise control of welding current, electrode force, and electrode follow-up during welding; projection welding of aluminum is not done commercially. Low carbon steel has a wide plastic range; it is easily resistance welded.

Metallurgical Properties

WITH RESISTANCE WELDING, a small volume of metal is heated to its forging or melting temperature in a short time. The heated metal is then cooled rapidly by the electrodes and surrounding metal. Cold-worked metal will be annealed in the areas exposed to this thermal cycle. In contrast, the rapid cooling will cause hardening in some steels. High carbon steel may harden so rapidly that the welds crack. A tempering cycle following the weld cycle is needed to avoid this cracking. For optimum mechanical properties in the weld region, the heat treatable alloys must be properly postweld heat-treated.

LOW CARBON STEEL

LOW CARBON STEELS generally contain less than 0.25 percent carbon. The overall resistance weldability of these steels is good. Their electrical resistivity is average. Hardenability is low. Welds with good strength can be obtained over a wide range of current, electrode force, and weld time settings.

HARDENABLE STEELS

MEDIUM CARBON STEELS may contain from 0.25 to 0.55 percent carbon; high carbon steels may contain 0.55 to 1.0 percent carbon. Low alloy steels contain up to 5.5 percent total alloying elements including cobalt, nickel, molybdenum, chromium, vandium, tungsten, aluminum, and copper.

Alloying additions produce certain desirable properties in steels. The steels may respond to heat treatment, and they may be hard and brittle unless a postheat tempering cycle is employed. With seam welding, that requires that travel stop after each weld nugget is formed to apply the postheat tempering cycle. Special controls are available to perform this function on standard machines.

In general, hardenable steels are less weldable, because of their hardenability, than low carbon steel.

STAINLESS STEELS

STAINLESS STEELS CONTAIN relatively large amounts of chromium or chromium and nickel as alloying elements. They are divided into three groups: martensitic, ferritic, and austenitic types. Whether a stainless steel is hardenable depends upon the amounts of carbon, chromium, and nickel present.

Ferritic and Martensitic Types

THESE STEELS MAY be hardenable (martensitic types) or nonhardenable (ferritic types). Both types have poor resistance weldability. When resistance welding the hardenable types, the precautions given for high carbon and low alloy steels should be followed. The nonhardenable types have low ductility and a characteristic coarse-grained structure in the weld region. These steels are generally not suitable for applications where a ductile weld is required. With the martensitic types, a postweld heat treatment improves weld ductility. However, postweld heat treatment of the ferritic types is not beneficial.

Austenitic Type

THERE ARE A number of austenitic stainless steels, each having suitable properties for particular uses. The ones most common contain 18 percent chromium, 8 percent nickel, and approximately 0.10 percent carbon. The nonstabilized ones are susceptible to carbide precipitation if heated for an appreciable time between 800 to 1600°F; with short weld times they can be resistance welded without producing harmful carbide precipitation.

These alloys require less current than is required for low carbon steels, since their electrical resistances are about seven times greater. Relatively high electrode forces are needed because of their high strengths at elevated temperatures. Austenitic stainless steels have higher coefficients of thermal expansion than carbon steels. As a result, seam welded assemblies may warp excessively. Distortion may be reduced by using welding schedules that lower the total heat input.

NICKEL-BASE ALLOYS

GENERALLY, NICKEL-BASE ALLOYS are readily joined by resistance welding. However, the cast precipitation-hardenable nickel-base alloys, e.g., Alloy 713C, with low ductility, are normally difficult to resistance weld without cracking. High electrode forces are needed because of the high strength of nickel-base alloys at elevated temperatures. These alloys are subject to embrittlement by sulfur, lead, and other low-melting-point metals when exposed to them at high temperatures. Oils, grease, lubricants, marking materials, and other foreign materials which might contain sulfur or lead must removed from the parts prior to welding, or weld cracking may occur. Pickling prior to welding will only be necessary if a significant amount of oxide is present, recognized by surface discoloration.

Pure nickel can be welded rather easily. Some mechanical sticking of electrodes may be experienced because of the high electrical conductivity of nickel. A restricted dome electrode with 170 degree cone angle is recommended for spot welding.

Monel 400 is an alloy approximately two-thirds nickel and one-third copper. It has higher electrical resistivity and strength than low carbon steel. Therefore, somewhat lower welding current and higher electrode force are required for this alloy than for low carbon steel.

Monel K-500, which can be age-hardened at 1000°F (538°C), has higher electrical resistivity and strength but lower thermal conductivity than Monel 400. Therefore, lower welding currents but higher electrode forces are required for Monel K-500 than for Monel 400. Monel K-500 will crack in the age-hardened condition if subjected to appreciable tensile stress at 1100°F (595°C); spot, seam, and projection welding should be done on annealed material.

Inconel 600 contains approximately 78 percent nickel, 15 percent chromium, and 7 percent iron. It also has higher electrical resistivity and strength but lower thermal conductivity than Monel 400. Therefore, lower welding currents and higher electrode forces are required for this alloy than for Monel 400. Inconel 600 can be readily resistance welded using procedures similar to those for stainless steels.

Inconel X-750, Inconel 718, and Inconel 722 are age-hardenable alloys. They possess high strengths at elevated temperatures, and have high electrical resistances. Relatively low welding currents and high electrode forces are needed for these alloys. Projection welding can be readily accomplished with machines having adequate force capacity. These Inconels should be welded in the solution annealed condition.

COPPER ALLOYS

COPPER ALLOYS HAVE a wide range of weldability that varies almost inversely with their electrical resistance. When the resistance is low, they are difficult to weld; when the resistance is high, they are rather easy to weld. Machines having adequate current capacity and moderate forces are necessary. Because of the narrow plastic range of these alloys, machines with low inertia heads should be used to provide a faster follow-up of the upper electrode to maintain pressure on the joint, to prevent metal expulsion. The machines should be capable of accurate control of welding current, time, and electrode force, because of the sensitivity of these alloys to variations in welding conditions. Shorter welding times are recommended to prevent metal expulsion and welding the electrode to the work. Fusing of the electrodes with the workpiece can be reduced by using electrodes faced with a refractory metal.

Copper-zinc alloys (brasses) become easier to weld with increasing zinc content, because the electrical resistivity increases. The red brasses are difficult to weld, while the brasses with high zinc content can be welded throughout a range of welding conditions, even though the required energy input is high compared with that for carbon steel.

Copper-tin alloys (phosphor bronze), copper-silicon alloys (silicon bronze), and copper-aluminum (aluminum bronze) are relatively easy to weld because of their relatively high electrical resistance. These alloys, particularly phosphor bronze, have a tendency to be hot short, which may result in cracking in the weld.

ALUMINUM AND MAGNESIUM ALLOYS

ALL COMMERCIAL ALUMINUM and magnesium alloys that are produced in the form of sheet and extrusions may be spot and seam welded, provided the thicknesses involved are not too great. Proper welding equipment, correct surface preparation, and suitable welding procedures are necessary to produce satisfactory welds.

Aluminum and magnesium alloys have high thermal and electrical conductivities. Therefore, high welding currents and short welding times are needed. Machines with low inertia heads should be used for spot and seam welding because these alloys soften rapidly at welding temperature. Rapid acceleration of the welding head is necessary to maintain contact between the electrodes and work to prevent expulsion. Projection welding of aluminum and magnesium is not done commercially because they are plastic in narrow temperature ranges.

TITANIUM ALLOYS

TITANIUM AND ITS alloys can be readily resistance welded. Resistance welding is facilitated by their relatively low electrical and thermal conductivities. Although titanium and titanium alloys are very sensitive to embrittlement, caused by reaction with air at fusion welding temperatures, they can be resistance welded without inert-gas shielding: during resistance welding, the molten weld metal is completely surrounded by the base metal, thus protecting it from contamination; furthermore the welding time is short.

COATED AND PLATED STEELS

MANY PLATED AND coated steels can be spot, seam, or projection welded, but the weld quality usually is affected by the composition and thickness of the coating. Coatings on steel are usually applied for corrosion resistance, decoration, or a combination of these. Welding procedures should assure reasonable preservation of the coating function as well as produce welds of adequate strength. Strength requirements usually require machine settings similar to those for bare carbon steel. Adjustments to compensate for the coating will be determined by a number of factors, including its effect on contact resistance, acceptable electrode indentation, tendency of the coating to alloy with the base metal, and tendency of the electrode to weld to the work.

Coating thickness is the most important variable affecting the weldability of these steels. When coating thickness presents problems in welding, better quality welds can often be obtained by decreasing the coating thickness. A weld nugget of the desired size may be obtained without too much disturbance of the outside surfaces by using higher welding current, greater electrode force, and shorter weld time than for the same thickness of bare steel. However, it is difficult to prevent alloying and metal pickup around the periphery of the electrode face, particularly with low-melting-point coatings such as lead, tin, and zinc. Short welding times, good tip maintenance, and attention to electrode cooling are the best preventive measures.

WELDING SCHEDULES

When setting up for welding a particular metal and joint design, a schedule must be established to produce welds that meet the design specifications. Previous experience can provide a starting point for the initial setup. If the application is a new one, reference to published information on the welding of the material by the designated process will serve as a guide for the initial setup.

Sample welds should be made and tested while changing one process variable at a time within a range, to establish an acceptable value for that variable. It may be necessary to establish the effect of one variable at several levels of another. For example, weld or heat time and electrode force may be evaluated at several levels of current. Visual examination and destructive test results can be used to select an appropriate welding schedule. Finally, first production parts, or simulations thereof, should be welded and destructively tested. Final adjustments are then made to the welding schedule to meet design or specification requirements.

Starting schedules for many commercial alloys may be available from the equipment manufacturer. Some may also be found in the following publications:

(1) AWS C1.1, Recommended Practices for Resistance Welding

(2) AWS C1.3, Recommended Practices for Resistance Welding Coated Low Carbon Steels

(3) AWS D8.5, Recommended Practices for Automotive Portable Gun Resistance Spot Welding

(4) AWS D8.7, Recommended Practices for Automotive Weld Quality, Resistance Spot Welding

(5) Resistance Welding Manual, 4th Ed., Resistance Welder Manufacturers Association, 1989

(6) Metals Handbook, Vol. 6, 9th Ed., ASM International, 1983.

WELD QUALITY

THE WELD QUALITY required depends primarily upon the application. In applications such as aircraft and space vehicles, the weld quality must meet the requirements of rather stringent specifications. In other applications, such as automobiles, the requirements are less stringent. Generally, the quality of resistance spot, seam, and projection welds is determined based on the following:

(1) Surface appearance
(2) Weld size
(3) Penetration
(4) Strength and ductility
(5) Internal discontinuities
(6) Sheet separation and expulsion

Unfortunately, weld nugget size and penetration, two factors with the strongest influence on weld strengths, cannot be determined by nondestructive inspections. In addition, the commonly used destructive metallographic examination and the tensile shear test of sample welds each have inherent limitations. The designer should be aware of these shortcomings when considering resistance spot, seam, or projection welding for an application.

Some success has been achieved in application of monitoring or adaptive controls, e.g., those based on measuring the thermal expansion of the developing weld nugget and surrounding base metal during heating and melting, to assure producing consistently acceptable resistance welds. Such successes may compensate for the lack of nondestructive inspectability of weld nugget size and penetration, as well as the inherent limitations of destructive testing of sample welds.

SURFACE APPEARANCE

NORMALLY, THE SURFACE appearance of a spot, seam, or projection weld should be relatively smooth. It should be round or oval in the case of a contoured workpiece, and free from surface fusion, electrode deposit, pits, cracks, excessive electrode indentation, or any other condition that indicates improper electrode maintenance or operation. Table 17.5 lists some of the more common undesirable surface conditions, their causes, and the effects on weld quality.

WELD SIZE

THE DIAMETER OR width of the fused zone must meet the requirements of the appropriate specifications or design criteria. Table 17.6 lists the required diameter of fused zone for various workpiece thicknesses. In the absence of such requirements, either accepted shop practices or the following general rules should be used.

(1) Spot welds that are reliably reproduced under normal production conditions should have a minimum nugget diameter of 3.5 to 4 times the thickness of the thinner outside part.

(2) The individual nuggets in a leak-tight seam weld should overlap a minimum of 25 percent. The diameter of nugget should be at least 3.5 to 4 times the thickness of the thinner outside part.

(3) Projection welds should have a nugget diameter equal to or larger than the diameter of the original projection.

There is a maximum limit to the nugget size of a spot, seam, or projection weld. Since this limit is usually controlled by the part configuration, cost, or practicality of making the weld, each user should establish this limit based on the design requirements and prevailing shop practices.

Table 17.5
Undesirable Surface Conditions for Spot Welds

Type	Cause	Effect
1. Deep electrode indentation	Improperly dressed electrode face; lack of control of electrode force; excessively high rate of heat generation due to high contact resistance (low electrode force)	Loss of weld strength due to reduction of metal thickness at the periphery of the weld area; bad appearance
2. Surface fusion (usually accompanied by deep electrode indentation)	Scaly or dirty metal; low electrode force; misalignment of work; high welding current; electrodes improperly dressed; improper sequencing of pressure and current	Undersize welds due to heavy expulsion of molten metal; large cavity in weld zone extending through to surface; increased cost of removing burrs from outer surface of work; poor electrode life and loss of production time from more frequent electrode dressings
3. Irregular shaped weld	Misalignment of work; bad electrode wear or improper electrode dressing; badly fitting parts; electrode bearing on the radius of the flange; skidding; improper surface cleaning of electrodes	Reduced weld strength due to change in interface contact area and expulsion of molten metal
4. Electrode deposit on work (usually accompanied by surface fusion)	Scaly or dirty material; low electrode force or high welding current; improper maintenance of electrode contacting face; improper electrode material; improper sequencing of electrode force and weld current	Bad appearance; reduced corrosion resistance; reduced weld strength if molten metal is expelled; reduced electrode life
5. Cracks, deep cavities, or pin holes	Removing the electrode force before welds are cooled from liquidus; excessive heat generation resulting in heavy expulsion of molten metal; poorly fitting parts requiring most of the electrode force to bring the faying surfaces into contact	Reduction of fatigue strength if weld is in tension or if crack or imperfection extends into the periphery of weld area; increase in corrosion due to accumulation of corrosive substances in cavity or crack

Table 17.6
Typical Required Minimum Weld Nugget Size (Diameter) for Various Sheet Thicknesses

Nominal Thickness of Thinner Sheet		Nugget Size		Nominal Thickness of Thinner Sheet		Nugget Size	
in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
0.001	(0.03)	0.010	(0.25)	0.036	(0.90)	0.160	(3.81)
0.002	(0.05)	0.015	(0.38)	0.040	(1.00)	0.160	(4.06)
0.003	(0.08)	0.020	(0.50)	0.045	(1.10)	0.170	(4.32)
0.004	(0.10)	0.030	(0.76)	0.050	(1.20)	0.180	(4.57)
0.005	(0.12)	0.035	(0.89)	0.056	(1.40)	0.190	(4.82)
0.006	(0.16)	0.040	(1.02)	0.063	(1.60)	0.200	(5.08)
0.007	(0.18)	0.045	(1.14)	0.071	(1.80)	0.210	(5.33)
0.008	(0.20)	0.050	(1.27)	0.080	(2.00)	0.225	(5.72)
0.010	(0.25)	0.060	(1.52)	0.090	(2.30)	0.240	(6.10)
0.012	(0.30)	0.070	(1.78)	0.100	(2.50)	0.250	(6.35)
0.016	(0.40)	0.085	(2.16)	0.112	(2.80)	0.260	(6.60)
0.018	(0.45)	0.090	(2.29)	0.125	(3.20)	0.280	(7.11)
0.020	(0.50)	0.100	(2.54)	0.140	(3.60)	0.300	(7.62)
0.022	(0.56)	0.105	(2.68)	0.160	(4.10)	0.320	(8.13)
0.025	(0.65)	0.120	(3.05)	0.180	(4.60)	0.340	(8.64)
0.028	(0.70)	0.130	(3.30)	0.190	(4.80)	0.350	(8.89)
0.032	(0.80)	0.140	(3.56)				

PENETRATION

PENETRATION IS THE depth to which the weld nugget extends into the pieces being welded. Generally, the acceptable minimum penetration is 20 percent of the thickness of the thinnr outside piece. If penetration is less than 20 percent, the weld is said to be cold, because the heat generated in the weld zone or joint interface was too small. Normally, the acceptable maximum penetration is 80 percent of the thickness of the thinner outside piece. Excessive penetration, e.g., 100 percent, will result in expulsion, deep indentation, and rapid electrode deterioration. Figure 17.37 shows normal, excessive, and insufficient penetration.

STRENGTH AND DUCTILITY

STRUCTURES JOINED BY spot, seam, and projection welds are usually designed so that the welds are loaded in shear when the parts are exposed to tension or compression loading. In some applications, the welds are loaded in tension, or a combination of tension and shear, but only where the direction of loading is normal to the plane of the joint. A seam weld may also be subjected to peeling action.

The strength requirements for spot and projection welds are normally specified in pounds (kilograms) per weld. For seam welds, the strength is usually specified in pounds per inch (kg/m) of joint length. These requirements are for a given sheet thickness. The strength of spot and projection welds increases as the nugget diameter increases, even though the average unit stress decreases. The unit stress decreases because of the increasing tendency for failure to occur at the edge of the nugget as its size increases. In low carbon steel, for example, the calculated average shear stress in good welds at fracture will vary from 10 to 60 ksi (69 to 414 MPa). Low values apply to relatively large welds, and high values to relatively small welds. In both instances, the actual tensile stress in the sheet at the weld periphery is at or near the ultimate tensile strength of the base metal. For this reason, the shear strength of circular welds tends to vary linearly with nugget diameter.

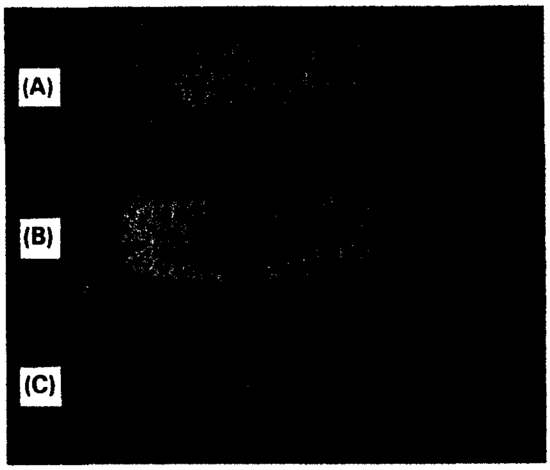


Figure 17.37–Penetration in Spot Welds

Single spot and projection welds are not strong in torsion where the axis of rotation is perpendicular to the plane of the welded parts. The torsional strength tends to vary with the cube of the nugget diameter. Little torsional deformation occurs with low ductility welds prior to failure. Angular displacements may vary from five to 180 degrees depending upon weld metal ductility. Torsion is normally used to shear welds across the interface to measure the nugget diameter, where the base metal is sufficiently thick.

The standard methods of measuring ductility, such as those that measure the percent elongation or reduction of area in a tensile test, are not adaptable to spot, seam, and projection welds. Hardness testing is the closest thing to ductility testing for these welds. It should be noted that although for a given alloy ductility decreases with increasing hardness, different alloys of the same hardness do not necessarily possess the same ductility.

Another method of indicating the ductility of a spot or projection weld is to determine the ratio of its direct tension-shear strength.[4] A weld with good ductility has a high ratio; a weld with poor ductility has a low ratio. Where this ratio is specified, 0.25 is usually the minimum for hardenable steel welds after tempering.

Various methods are available to minimize the hardening effect of rapid cooling in the welds. The following are some of these methods:

(1) Use long weld times to put heat into the work.
(2) Preheat the weld area with a preheat current.
(3) Temper the weld and heat-affected zones with a temper current at some interval after the weld time.
(4) Furnace anneal or temper the welded assembly.

INTERNAL DISCONTINUITIES

INTERNAL RESISTANCE WELD discontinuities include cracks, porosity, or spongy metal, large cavities, and, in some coated metals, metallic inclusions. Generally, these discontinuities will have no detrimental effect on the static or fatigue strength of a resistance weld if they are located entirely in the central portion of the weld nugget. This is true because the stresses are essentially zero in the central portion of the weld nugget. On the other hand, no defects should occur at the periphery of a weld, where the load stresses are highly concentrated. The high stresses at the weld periphery can be attributed to the high stress concen-

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[4] These tests are described in *Welding Handbook*, Vol. 1, 8th Ed. 390-394.

tration factor[5] associated with the overlapping joint geometry. Since high stress concentration can greatly reduce the fatigue strength or life of a metal, resistance spot, seam, and projection welding are not generally used for applications where the joint is subject to high cyclic load stresses.

Spot, seam, and projection welds in metal thicknesses of approximately 0.040 in. (1 mm) and greater may have small shrinkage porosity in the center of the weld nugget, as illustrated in Figure 17.38(A). This porosity is less pronounced in some welds than in others due to the difference in forging action of the electrodes on the hot metal. Porosity or cavities that result from heavy expulsion of molten metal, as shown in Figure 17.38(B), are much larger than shrinkage cavities. A certain number of expulsion cavities are usually expected in production welding of various metals. Heavy expulsion is a result of improper welding conditions.

Internal defects in spot, seam, and projection welds are generally caused by low electrode force, high welding current, poor fit-up, or inadequate overlap. They are also caused by excessive welding speeds or removing the electrode force too soon after welding current stops. When these conditions occur, the weld nugget is not properly forged during cooling.

When cracklike indications are observed in the heat-affected zone at low magnification, these indications should be examined at higher magnification to determine whether they are actual cracks or coring. As shown in Figure 17.39, a cored area is filled with material that has a dendritic structure. Coring appears to result from incipient melting or back filling of heat-affected zone cracks by the molten metal, based on the dendritic structure. Coring does not appear to affect the serviceability of the welded joint, based on the service experience of various resistance welded nickel-base alloy jet engine components, such as nozzles and combustor housings.

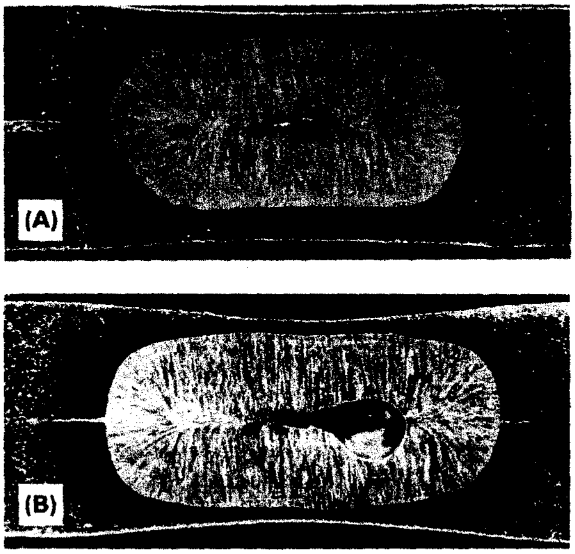

Figure 17.38–Shrinkage Cavities in Spot Welds

SHEET SEPARATION

SHEET SEPARATION OCCURS at the faying surfaces due to the expansion and contraction of the weld metal and the forging effect of the electrodes on the hot nugget. The amount of separation varies with the thickness of the sheet, increasing with greater thickness.

Excessive sheet separation results from the same causes as surface indentation, to which it is related. Improperly dressed electrode faces act as punches under high electrode force, which tends to decrease the joint thickness, upset the weld metal radially, and force the sheets up around the electrodes. Excessive sheet separation is illustrated in Figure 17.40 (note that one sheet is laminated).

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[5] A detailed of discussion of stress concentration factors can be found in R. E. Peterson's *Stress Concentration Factors*, John Wiley and Sons, New York, 1974.

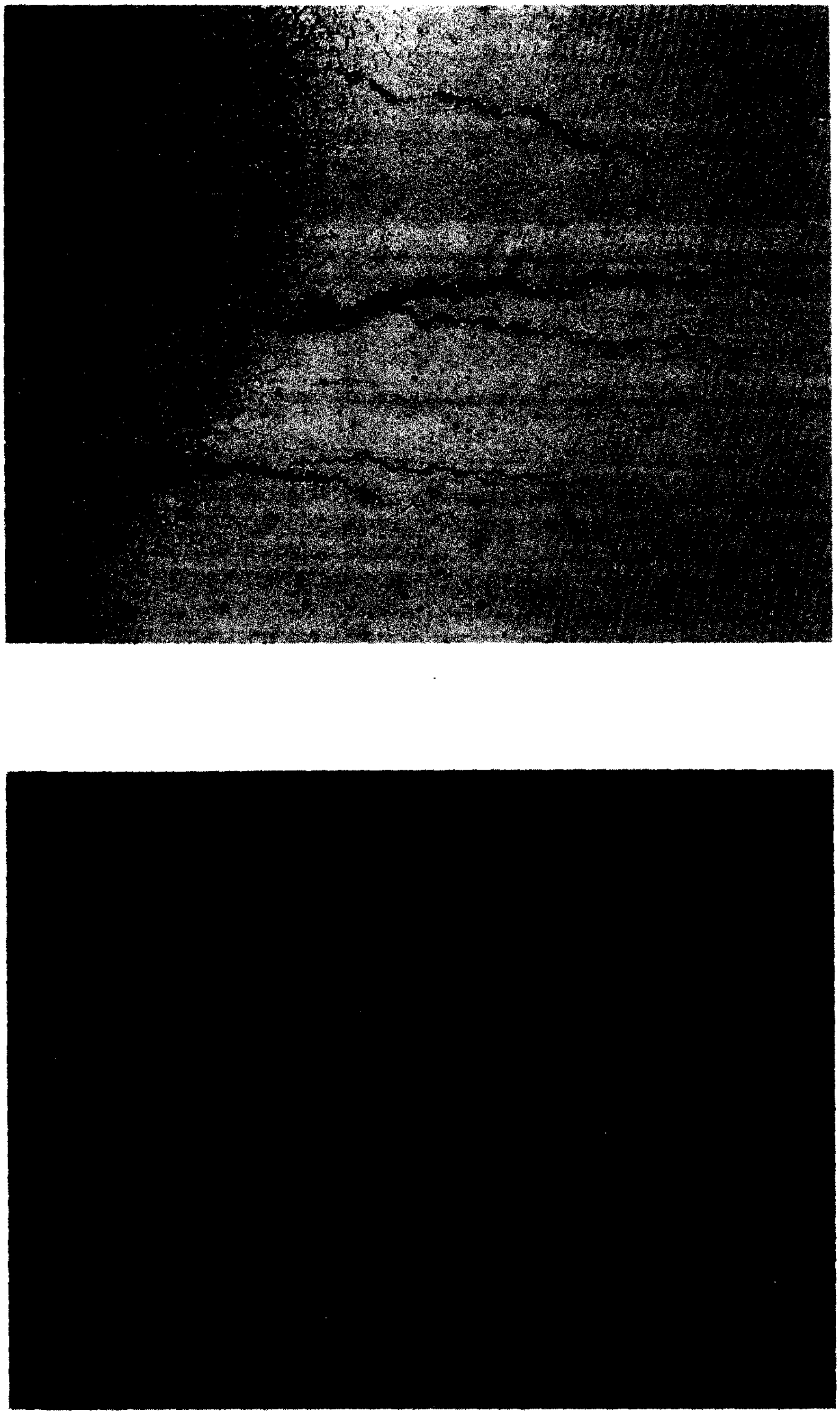

Figure 17.39–Coring in an Inconel 718 Seam Weld (Area Filled with Dendritic Material)

Figure 17.40–Excessive Sheet Separation (One Sheet Laminated)

SAFETY

SPOT, SEAM, AND projection welding may involve hazardous situations that can be avoided by taking the proper precautions outlined in the following section.

MECHANICAL

Guarding

INITIATING CONTROLS ON welding equipment, such as push buttons or switches, should be arranged or guarded to prevent the operator from inadvertently activating them.

In some multiple-gun welding machine installations, the operator's hands can be expected to pass under the point of operation. These machines should be effectively guarded by a suitable device, such as proximity-sensing gates, latches, blocks, barriers, or dual hand controls.

Stop Buttons

ONE OR MORE emergency stop buttons should be provided on all welding machines, with a minimum of one at each operator position.

PERSONAL EQUIPMENT

THE PROTECTIVE EQUIPMENT needed is dependent upon the particular welding application. The following equipment is generally needed for resistance welding:

(1) Eye protection, in the form of face shields or hardened lens goggles; face shields are the preferred form of protection

(2) Skin protection, provided by nonflammable gloves and clothing with the minimum number of pockets and cuffs in which hot or molten particles can lodge

(3) Protective footwear

ELECTRICAL

RESISTANCE WELDING EQUIPMENT should be designed to avoid accidental contact with parts of the system that are electrically hazardous. High-voltage components must have adequate electrical insulation and be completely enclosed. All doors, access panels, and control panels of resistance welding machines must be kept locked or interlocked, to prevent access by unauthorized persons. The interlocks must effectively interrupt power and discharge all high-voltage capacitors into a suitable resistive load when the door or panel is open. Additionally, a manually operated switch or suitable positive device should be provided to assure complete discharge of all high-voltage capacitors.

All electrical equipment must be suitably grounded and the transformer secondary may be grounded or provided with equivalent protection. External weld-initiating control circuits should operate at low voltage for portable equipment.

Additional information on safe practices for resistance welding is contained in ANSI Z49.1, *Safety in Welding and Cutting* (latest edition).

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CHAPTER 18

FLASH, UPSET, AND PERCUSSION WELDING

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CHAPTER 18

FLASH, UPSET, AND PERCUSSION WELDING

FLASH WELDING

FLASH, UPSET, AND percussion welding constitute a family of welding processes used to join parts of similar cross section by making a weld simultaneously across the entire joint area, without adding filler metal. Upset force is applied at some point before, during, or after the heating cycle to bring the parts into intimate contact. The method of heating and time of force application distinguish these three welding processes. Percussion welding may also be used to join the tip or end of a small part to a flat surface.

DEFINITION AND GENERAL DESCRIPTION

FLASH WELDING (FW) is a resistance welding process that produces a weld at the faying surfaces of a butt joint by a flashing action and by the application of pressure after heating is substantially completed. The flashing action, caused by the very high current densities at small contact points between the workpieces, forcibly expels material from the joint as the workpieces are slowly moved together. The weld is completed by a rapid upsetting of the workpieces.

Two parts to be joined are clamped in dies (electrodes) connected to the secondary of a resistance welding transformer. Voltage is applied as one part is advanced slowly toward the other. When contact occurs at surface irregularities, resistance heating occurs at these locations. High amperage causes rapid melting and vaporization of the metal at the points of contact, and then minute arcs form. This action is called "flashing". As the parts are moved together at a suitable rate, flashing continues until the faying surfaces are covered with molten metal and a short length of each part reaches forging temperature. A weld is then created by the application of an upset force to bring the molten faying surfaces in full contact and forge the parts together. Flashing voltage is terminated at the start of upset. The solidified metal expelled from the interface is called "flash".

PRINCIPLES OF OPERATION

THE BASIC STEPS in a flash welding sequence are as follows:

(1) Position the parts in the machine.
(2) Clamp the parts in the dies (electrodes).
(3) Apply the flashing voltage.
(4) Start platen motion to cause flashing.
(5) Flash at normal voltage.
(6) Terminate flashing.
(7) Upset the weld zone.
(8) Unclamp the weldment.
(9) Return the platen and unload.

Figure 18.1 illustrates these basic steps. Additional steps such as preheat, dual voltage flashing, postheat, and trimming of the flash may be added as the application dictates.

Flashing takes place between the faying surfaces as the movable part is advanced toward the stationary part. Heat is generated at the joint and the temperature of the parts increases with time. Flashing action (metal loss) increases with part temperature.

A graph relating part motion with time is known as the flashing pattern. In most cases, a flashing pattern should show an initial period of constant velocity motion of one part toward the other to facilitate the start of flashing. This

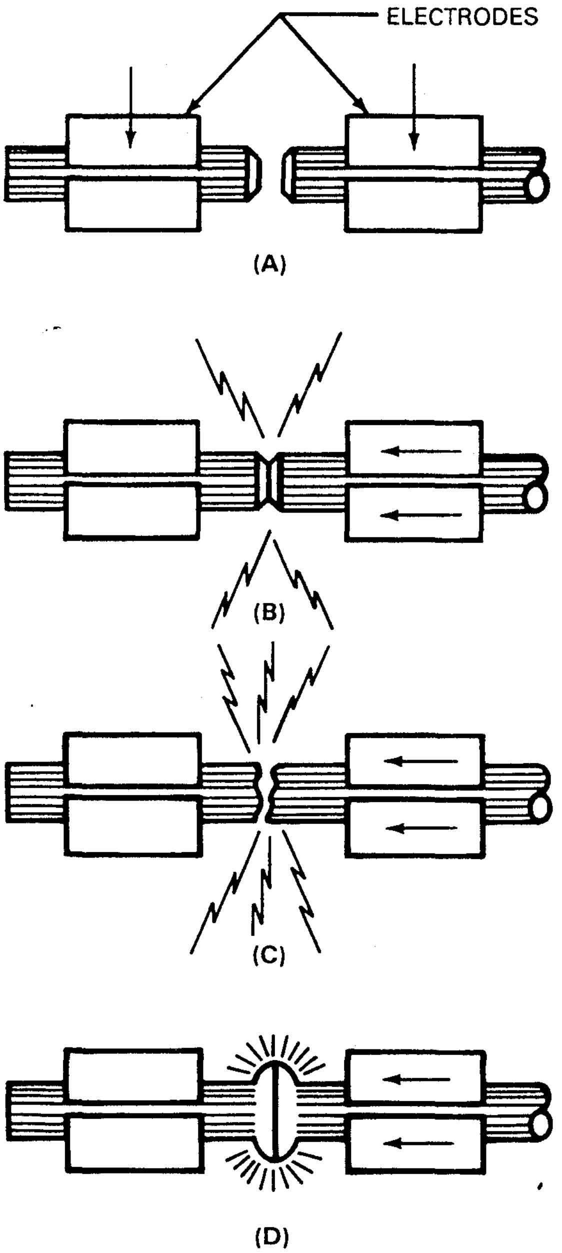

Figure 18.1–The Basic Steps in Flash Welding: (A) Position and Clamp the Parts; (B) Apply Flashing Voltage and Start Platen Motion; (C) Flash; (D) Upset and Terminate Current

linear motion should then merge into an accelerating motion which should closely approximate a parabolic curve. This pattern of motion is known as *parabolic flashing.*

To produce a strong joint with uniform upset, the temperature distribution across the joint should be uniform and the average temperature of the faying surface should be the melting temperature of the metal. Once these conditions are reached, further flashing is not necessary.

The steepness of the temperature gradient corresponding to a stable temperature distribution is a function of the part acceleration during parabolic flashing. In general, the higher the rate of part acceleration, the steeper is the stable temperature gradient produced. Thus, the shape of the temperature distribution curve in a particular application can be controlled by appropriate choice of flashing pattern. Since the compressive yield strength of a metal is temperature sensitive, the behavior of the metal during the upsetting portion of the welding cycle is markedly dependent upon the flashing pattern. Therefore, the choice of flashing pattern is extremely important for the production of sound flash welds. The minimum flashing distance is the amount of flashing required to produce a stable temperature distribution. From a practical standpoint, the flashing distance should be slightly greater than the minimum acceptable amount, to ensure that a stable temperature distribution is always achieved.

Upset occurs when a stable temperature distribution is achieved by flashing and the two parts are brought together rapidly. The movable parts should be accelerated rapidly so that the molten metal on the flashing surfaces will be extruded before it can solidify in the joint. Motion should continue with sufficient force to upset the metal and weld the two pieces together.

Upset current is sometimes applied as the joint is being upset to maintain temperature by resistance heating. This permits upset of the joint with lower force than would be required without it. Upset current is normally adjusted by electronic heat control on the basis of either experience or welding tests.

ADVANTAGES AND LIMITATIONS

BUTT JOINTS BETWEEN parts with similar cross section can be made by friction welding and upset welding, as well as by flash welding. The major difference between friction welding and upset and flash welding is that the heat for friction welding is developed by rubbing friction between the faying surfaces, rather than from electrical resistance. Upset welding is similar to flash welding except that no flashing action occurs.

Listed below are some important advantages of flash welding:

(1) Cross sectioned shapes other than circular can be flash welded: for example, angles, H sections, and rectangles. Rotation of parts is not required.

(2) Parts of similar cross section can be welded with their axes aligned or at an angle to each other, within limits.

(3) The molten metal film on the faying surfaces and its ejection during upset acts to remove impurities from the interface.

(4) Preparation of the faying surfaces is not critical except for large parts that may require a bevel to initiate flashing.

(5) Rings of various cross sections can be welded.

(6) The heat-affected zones of flash welds are much narrower than those of upset welds.

The following are some limitations of the process:

(1) The high single-phase power demand produces unbalance on three-phase primary power lines.

(2) The molten metal particles ejected during flashing present a fire hazard, may injure the operator, and may damage shafts and bearings. The operator should wear face and eye protection, and a barrier or shield should be used to block flying sparks.

(3) Removal of flash and upset metal is generally necessary and may require special equipment.

(4) Alignment of workpieces with small cross sections is sometimes difficult.

(5) The parts to be joined must have almost identical cross sections.

FLASH WELDING APPLICATIONS

Base Metals

MANY FERROUS AND nonferrous alloys can be flash welded. Typical metals are carbon and low alloy steels, stainless steels, aluminum alloys, nickel alloys, and copper alloys. Titanium alloys can be flash welded, but an inert gas shield to displace air from around the joint is necessary to minimize embrittlement.

Dissimilar metals may be flash welded if their upsetting characteristics are similar. Some dissimilarity can be overcome with a difference in the initial extensions between the clamping dies, adjustment of flashing distance, and selection of welding variables. Typical examples are welding of aluminum to copper or a nickel alloy to steel.

Typical Products

THE AUTOMOTIVE INDUSTRY uses wheel rims produced from flash welded rings that are formed from flat cold-rolled steel stock. The electrical industry uses motor and generator frames produced by flash welding plate and bar stock previously rolled into cylindrical form. Cylindrical transformer cases, circular flanges, and seals for power transformer cases are other examples. The aerospace industry uses flash welds in the manufacture of landing gear struts, control assemblies, hollow propeller blades, and rings for jet engines and rocket casings.

The petroleum industry uses oil drilling pipe with fittings attached by flash welding. Several major railroads are using flash welding to join relatively high carbon steel track. In many cases, welding is done in the field using welding machines and portable generating equipment mounted on railroad cars.

Miter joints are sometimes used in the production of rectangular frames for windows, doors, and other architectural trim. These products are commonly made of plain carbon and stainless steels, aluminum alloys, brasses, and bronzes. Usually the service loads are limited, but appearance requirements of the finished joints are stringent.

EQUIPMENT

Typical Machines

A TYPICAL FLASH welding machine consists of six major parts:

(1) The machine bed which has platen ways attached

(2) The platens which are mounted on the ways

(3) Two clamping assemblies, one of which is rigidly attached to each platen to align and hold the parts to be welded

(4) A means for controlling the motion of the movable platen

(5) A welding transformer with adjustable taps

(6) Sequencing controls to initiate part motion and flashing current

Flash welding machines may be manual, semi-automatic, or fully automatic in their operations; however, most of them are either semi-automatic or fully automatic. With manual operation, the operator controls the speed of the platen from the time that flashing is initiated until the upset is completed. In semi-automatic operation, the operator usually initiates flashing manually and then energizes an automatic cycle that completes the weld. In fully automatic operation, the parts are loaded into the machine and the welding cycle is then completed automatically. The platen motion of many small flash welding machines is provided mechanically by a cam that is driven by an electric motor through a speed reducer. Large machines may be hydraulically or pneumatically operated. Equipment for flash welding is discussed in Chapter 19.

Operating personnel should be given instructions on how to operate the machinery in a safe manner. Hands must be kept clear of moving machinery, and contact with electrically charged surfaces must be avoided.

Controls and Auxiliary Equipment

ELECTRICAL CONTROLS ON flash welding machines are integral types designed to sequence the machine, control the welding current, and precisely control the platen position during flashing and upsetting. Silicon controlled rectifier (SCR) contactors are widely used on machines drawing up to 1200 A from the power lines. Ignitron contactors are common on larger machines.

Preheat and postheat cycles are normally controlled with electronic timers and phase-shift heat controls. Timers for these functions may be initiated manually or automatically in proper order during the welding period.

Dies

FLASH WELDING DIES, compared to spot and seam welding electrodes, are not in direct contact with the welding area. Dies may be considered work holding and current conducting clamps. Since the current density in these dies is normally low, relatively hard materials with low electrical conductivity may be used. However, water cooling of the dies may be necessary in high production to avoid overheating.

There are no standardized designs for these dies since they must fit the contour of the parts to be welded. The size of the dies depends largely upon the geometry of the parts to be welded and the mechanical rigidity needed to maintain proper alignment of parts during upsetting. The dies are usually mechanically fastened to the welding machine platens.

Electrode contact area should be as large as practical to avoid local die burns. The contact surfaces may be incorporated in small inserts attached to larger dies for low cost replacement and convenient detachment for redressing. A facing insert of RWMA[1] Group B material which is brazed to the die is frequently used for maximum wear resistance.

If the parts are backed up so that the clamping dies do not need to carry the upset force, clamping pressures need only be sufficient to provide good electrical contact. If the work cannot be backed up, it may be necessary to use serrated clamp inserts. In this case, the inserts are usually made of hardened tool steel.

Flash welding dies tend to wear but do not mushroom. As wear takes place, the contact area may decrease and cause local hot spots (die burns). The dies should be kept clean. Flash and dirt will tend to embed in the dies and cause hot spots and die burns. All bolts, nuts, and other die-holding devices should be tight. Additional information on flash welding dies and materials is given in Chapter 19.

Fixtures and Backups

THE FUNCTIONS OF fixtures for flash welding are (1) to rapidly and accurately locate two or more parts relative to each other, (2) to hold them in proper location while they are being welded, and (3) to permit easy release of the welded assembly. A fixture is either fastened to the machine or built into it. Parts are loaded directly into the fixture and welded.

Resistance welding processes are very rapid compared to other methods of joining. If maximum production is to be attained, fixtures must be easily loaded and unloaded. The following factors should be considered when designing a fixture:

(1) Quick-acting clamps, toggles, and other similar devices should be employed. Sometimes ejector pins are used to facilitate removal of the finished assembly.

(2) The fixture must be designed so that welding current is not shunted through any locating devices. This may require insulation of pins and locating strips.

(3) Nonmagnetic materials are usually preferred, because any magnetic material located in the throat of the machine will increase the electrical impedance and limit the maximum current which the machine can deliver.

(4) The operator should be able to load and unload the parts safely. This may require the use of swivel devices or slides, so that the fixture can be moved out of the machine. A guard should swing in place to prevent the operator from reaching between the platens. The guard can also act as the flash shield.

(5) A fixture must provide for movement of the parts as they are being clamped in the dies.

(6) All bearings, pins, slides, etc., should be protected from spatter and flash.

Backups are needed if the clamping dies cannot prevent slippage of the parts when the upsetting force is applied. Slippage usually occurs when the section of the part in the die is too short for effective clamping, or the part is unable to withstand sufficient clamping force without damage.

A backup often consists of a steel bracket that can be bolted in various positions to the platen. Brackets can have either fixed or adjustable stops against the parts.

WELDING PROCEDURES

EVERY WELDING OPERATION involves numerous variables that affect the quality of the resulting weld. For this reason, a welding procedure should be developed that prescribes the settings for the welding variables to ensure consistent weld quality. Flash welding involves dimensional, electrical, force, and time variables. The dimensional variables are shown in Figures 18.2 A and B and 18.3. The paths of the movable platen and the faying surfaces during flashing and upsetting are also shown in Figure 18.3. The current, force, and time variables are shown in Figure 18.4. Most operations do not involve all of the variables shown. A simple flash welding cycle involves flashing at one voltage setting followed by upset.

Joint Design

THREE COMMON TYPES of welds made by flash welding are shown in Figure 18.5. Several basic design rules for flash welding are as follows:

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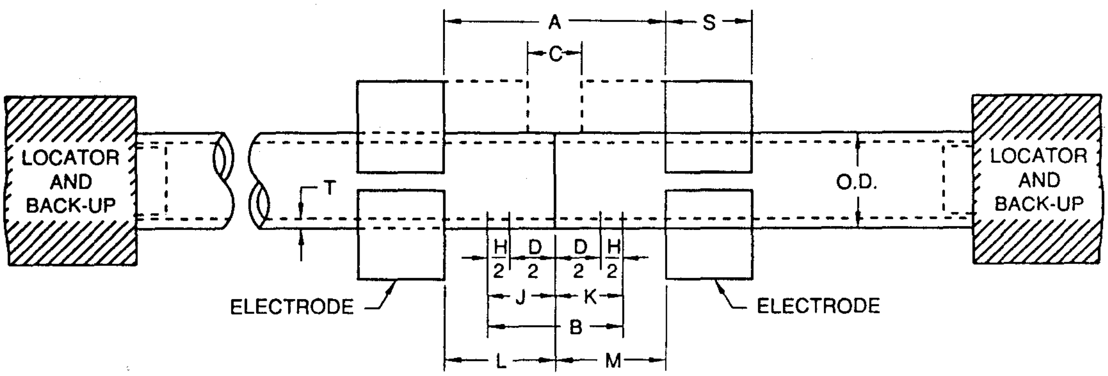
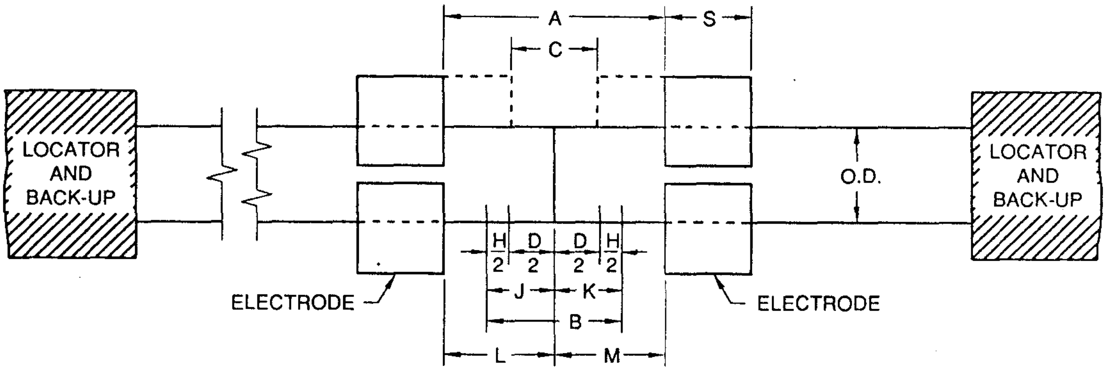
[1] Resistance Welder Manufacturers Association



T = TUBE WALL OR SHEET THICKNESS
A = INITIAL DIE OPENING
B = MATERIAL LOST
C = FINAL DIE OPENING
D = TOTAL FLASH-OFF
H = TOTAL UPSET
J = K = MATERIAL LOST PER PIECE
L = M = INITIAL EXTENSION PER PIECE
O.D. = OUTSIDE DIA. OF TUBING
S = MINIMUM NECESSARY LENGTH OF ELECTRODE CONTACT

Figure 18.2A–Flash Welding of Tubing and Flat Sheets (See Table 18.5 for Recommended Data)



O.D. = OUTSIDE DIA. OF ROUNDS OR MINIMUM DIMENSION OF OTHER SECTIONS
A = INITIAL DIE OPENING
B = MATERIAL LOST
C = FINAL DIE OPENING
D = TOTAL FLASH-OFF
H = TOTAL UPSET
J = K = MATERIAL LOST PER PIECE
L = M = INITIAL EXTENSION PER PIECE
S = MINIMUM NECESSARY LENGTH OF ELECTRODE CONTACT

Figure 18.2B–Flash Welding of Solid Round, Hex, Square and Rectangular Bars (See Table 18.6 for Recommended Data)

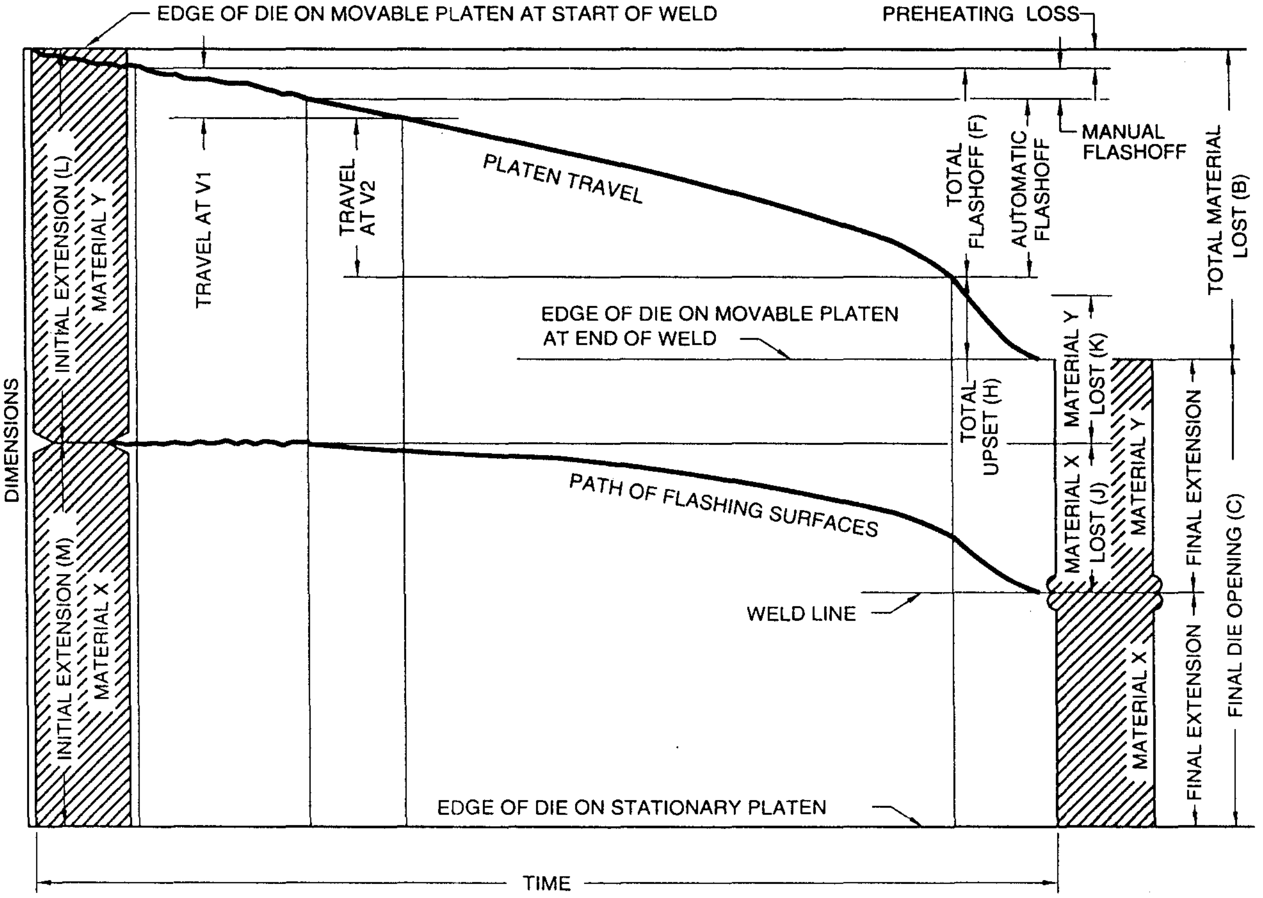


Figure 18.3–Flash Welding Dimensional Variables and Motions

(1) The design should provide for an even heat balance in the parts so that the ends to be welded will have nearly equal compressive strengths at the end of the flashing time.

(2) The metal lost during flashing (flash loss) and upset must be included in the initial length when designing the part. With miter joints, the angle between the two members must be taken into account in the design.

(3) The parts must be designed so that they can be suitably clamped and held in accurate alignment during flashing and upset, with the joint perpendicular to the upset force direction.

(4) The end preparation should be designed so that the flash material can escape from the joint, and that flashing starts at the center or the central area of the parts.

In general, the two parts to be welded should have the same cross section at the joint. Bosses may have to be machined, forged, or extruded on parts to meet this requirement.

In the flash welding of extruded or rolled shapes with different thicknesses within the cross-section, the temperature distribution during flashing will vary with section thickness. This tendency can often be counteracted by proper design of the clamping dies, provided the ratio of the thicknesses does not exceed about 4 to 1.

The recommended maximum joint lengths for several thicknesses of steel sheet are given in Table 18.1. The maximum diameters for steel tubing of various wall thicknesses are listed in Table 18.2. The limits can be exceeded in some cases using special procedures and equipment.

When flash welding rings, there is a ratio of circumference to cross-sectional area below which shunting of current becomes a problem. That power loss can be high. The minimum ratio will depend upon the electrical resistivity of the metal to be welded. With metals of high resistivity, such as stainless steel, the ratio can be lower than with low resistivity metals, such as aluminum.

When heavy sections are welded, it is often advisable to bevel the end of one part to facilitate the start of flashing.

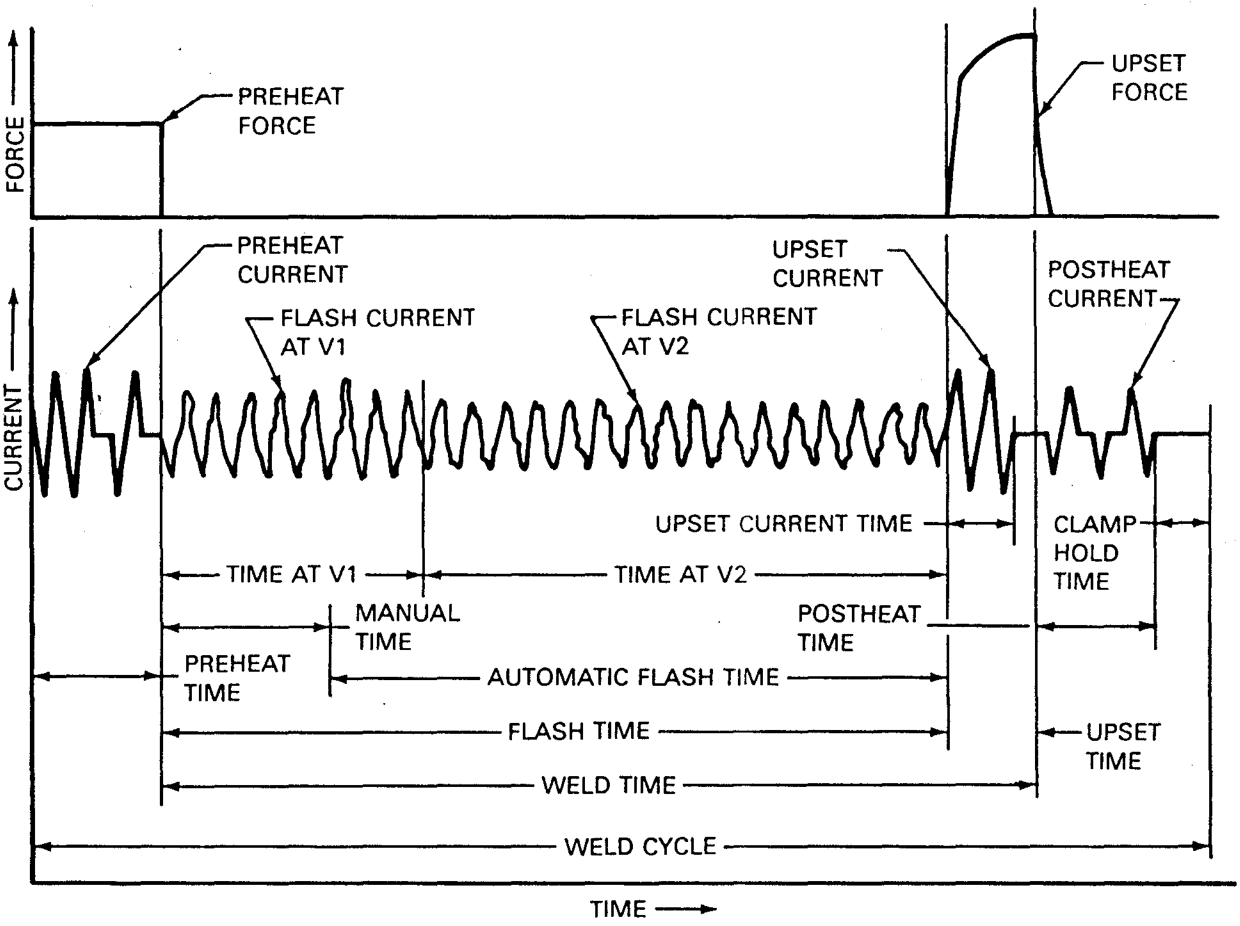
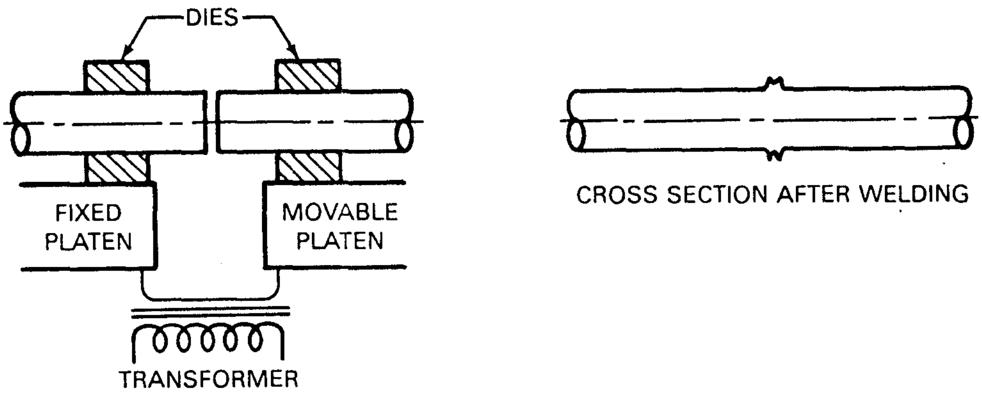


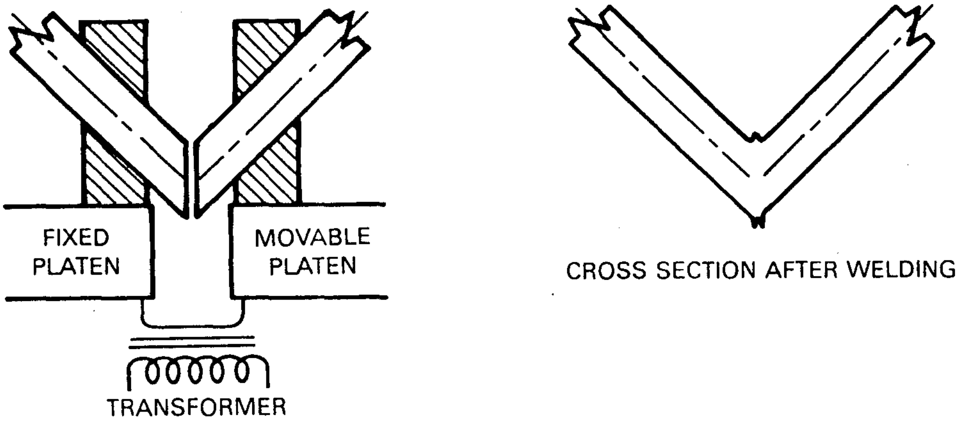
Figure 18.4–Flash Welding Current, Force, and Time Variables

Table 18.1
Recommended Maximum Joint Lengths of Flat Steel Sheet for Flash Welding

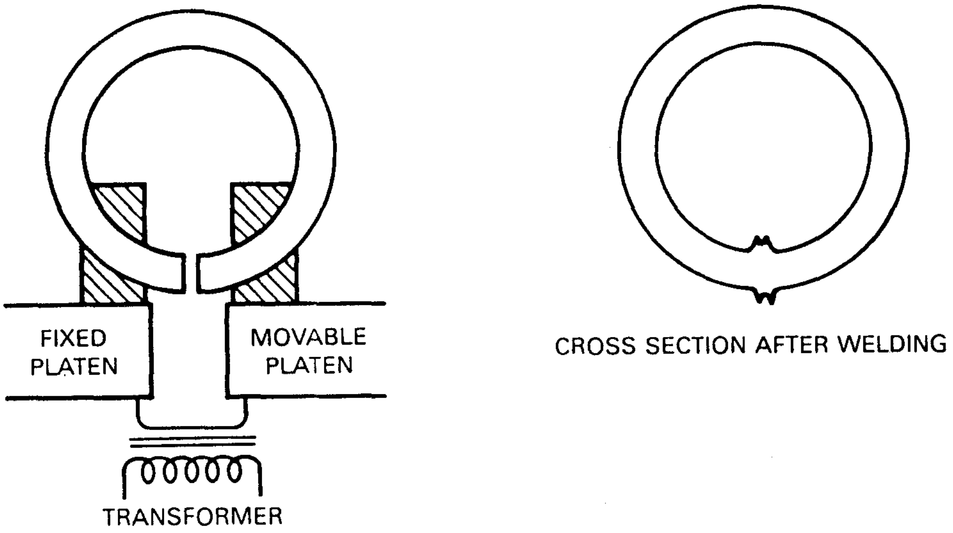
Sheet Thickness,		Max. Joint Length,		Sheet Thickness,		Max. Joint Length,	
in.	mm	in.	mm	in.	mm	in.	mm
0.010	.25	1.00	25	0.060	1.5	25.00	635
0.020	.50	5.00	125	0.080	2.0	35.00	890
0.030	.75	10.00	250	0.100	2.5	45.00	1145
0.040	1.0	15.00	375	0.125	3.2	57.00	1450
0.050	1.3	20.00	500	0.187	4.8	88.00	2235



(A) AXIALLY ALIGNED WELD



(B) MITER WELD



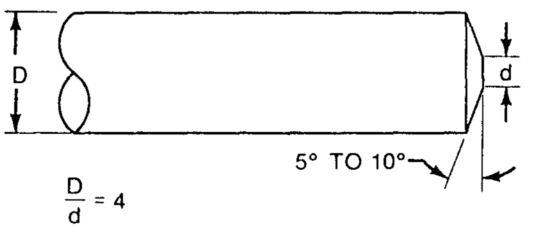
(C) RING WELD

Figure 18.5–Common Types of Flash Welds

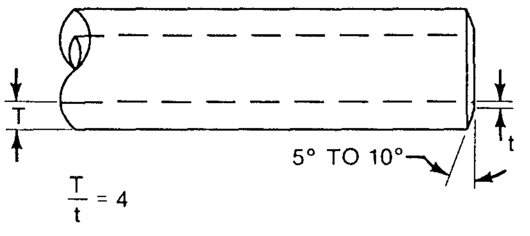
Such beveling may eliminate the necessity for preheating or initially flashing at a voltage higher than normal. Suggested dimensions for beveling plate, rod, and tubing are shown in Figure 18.6.

Heat Balance

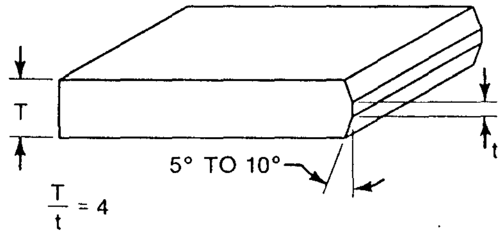
IN AXIALLY ALIGNED joints, when the two parts to be welded are of the same alloy and cross section, the heat generated in each of the parts during the weld cycle will be the same, provided the physical arrangement for welding is uniform. Flash loss and upset loss will also be equal in each part. In general, the heat balance between two parts of the same alloy will be adequate if their respective cross-sectional areas do not differ by more than normal manufacturing tolerances.



(A) RODS AND BARS OF 0.25 in. AND LARGER



(B) TUBING OF 0.188 in. WALL AND LARGER



(C) FLAT PLATE OF 0.188 in. AND THICKER

NOTE: BEVEL ONLY ONE PIECE WHEN D IS 0.25 in. OR LARGER AND T IS 0.188 in. OR GREATER.

Figure 18.6–End Preparation for One Part to Facilitate the Flashing of Large Sections

When flash welding two dissimilar metals, the metal loss during flashing may differ for each metal. Such behavior can be attributed to differences in electrical and thermal conductivities or melting temperatures, or both. To compensate for this, the extension from the clamping die of the more rapidly consumed part should be greater than that of the other part. In the case of aluminum and copper, the extension of the aluminum part should be twice that of the copper part.

Flash welding of nonaligned sections (miter joints) may produce a joint with varying properties across it because of heat unbalance across the joint. Since the faying surfaces are not perpendicular to their respective part lengths, the volume of metal decreases across the joint to a minimum at the apex. Consequently, flashing and upset at the apex may vary significantly from that which occurs across the remainder of the joint.

Miter joints between round or square bars should have a minimum included angle of 150 degrees. At smaller angles, the weld area at the apex will be poor quality because of the lack of adequate backup metal. Satisfactory miter joints may be made between thin rectangular sections in the same plane with an included angle as small as 90 degrees, provided the width of the stock is greater than 20 times its thickness. If service loading produces a tensile stress at the apex, the outside corner should be trimmed to remove the poor quality joint area.

Surface Preparation

SURFACE PREPARATION FOR flash welding is of minor importance and in most cases none is required. Clamping surfaces usually require no special preparation unless excessive scale, rust, grease, or paint is present. The abutting surfaces should be reasonably clean to accomplish electrical contact. Once flashing starts, dirt or other foreign matter will not seriously interfere with the completion of the weld.

Initial Die Opening

THE INITIAL DIE opening is the sum of the initial extensions of the two parts, as shown in Figures 18.2 (A) and (B) and 18.3. The initial extension for each part must provide for metal loss during flashing (flash loss) and upset, as well as some undisturbed metal between the upset metal and the clamping die. Initial extensions for both parts are determined from available welding data or from welding tests. The initial die opening should not be too large, otherwise nonuniform upset and joint misalignment may occur.

Alignment

IT IS IMPORTANT that the parts to be welded are properly aligned in the welding machine so that flashing on the faying surfaces is uniform. If the parts are misaligned, flashing will occur only across opposing areas and heating will not

Table 18.2
Recommended Maximum Diameters of Steel Tubing for Flash Welding

Wall Thicknesses,		Max. Tubing Diameter,		Wall Thicknesses,		Max. Tubing Diameter,	
in.	mm	in.	mm	in.	mm	in.	mm
0.020	0.5	0.50	13.0	0.125	3.2	4.00	102
0.030	0.8	0.75	19.0	0.187	4.7	6.00	152
0.050	1.3	1.25	32.0	0.250	6.4	9.00	230
0.062	1.6	1.50	38.0				
0.080	2.0	2.00	51.0				
0.100	2.5	3.00	76.0				

be uniform when upset, thus the parts will tend to slip past each other, as illustrated in Figure 18.7. Alignment of parts should be given careful consideration in designing of the machine, the parts to be welded, and the tooling for welding them. This is especially true when the ratio of the width to thickness of sections is large.

Material Loss

THE FINAL LENGTH of the welded assembly will be less than the sum of the lengths of the original workpieces because of flash and upset losses. These losses must be established for each assembly and then added to the workpiece length so that the welded assembly will meet design requirements. Changes in welding procedures may require modification of workpiece lengths.

Gas Shielding

IN SOME APPLICATIONS, displacement of air from the joint area by an inert or reducing gas shield may improve joint quality by minimizing contamination by oxygen, nitrogen, or both. However, gas shielding cannot compensate for improper welding procedures, and it should only be used when required by the application.

Argon or helium is particularly effective when flash welding reactive metals, such as titanium. At high temperatures, these metals are embrittled when they are exposed to air. Dry nitrogen may be effective with stainless and heat-resisting steels.

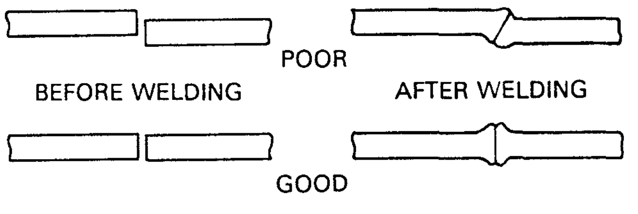


Figure 18.7–Effect of Poor Alignment on Joint Geometry

The value of a protective atmosphere depends upon the effectiveness of the shield design. The flash loss material may deposit on the gas shielding apparatus and interfere with its operation. Provisions for platen movement must be provided in the design.

If gas cylinders are used to provide the gas shielding, they should be protected from damage by plant traffic. Cylinder storage racks should have securing devices. If the gas shield is provided by a piping system, the piping should be properly labeled.

Preheating

DURING PREHEATING, THE parts are brought into contact under light pressure and then the welding transformer is energized. The resistance heating effect of high density current flow heats the metal between the dies. The temperature distribution across the joint during preheating approximates a sinusoidal waveform with the peak temperature point at the interface.

Three useful functions may be served by a preheating operation:

(1) It raises the temperature of the parts which, in turn, makes flashing easier to start and maintain.

(2) It produces a temperature distribution with a flatter gradient which persists throughout the flashing operations. This, in turn, distributes the upset over a longer length than is the case when no preheat is employed.

(3) It may extend the capacity of a machine and permit the joining of larger cross sections than would be otherwise possible. However, there is one possible drawback to preheating. Since preheating is often a manual operation, even when the machine is capable of flash welding automatically, the reproducibility of the preheating operation is largely a function of operator skill.

Welding

MOST COMMERCIAL FLASH welding machines are operated automatically. The welding schedule is established for the particular operations by a series of test welds that are evaluated for quality. The machine is then set up to reproduce the qualified welding schedule for the particular application.

The operator may load and unload the machine and observe the welding cycle for consistency of operation. In some applications, automatic feed and ejection devices may be incorporated on the machine.

Postheating

STEELS WITH EXTREMELY high alloy or carbon content may crack if the weld is cooled too rapidly. In some cases, this condition may be avoided by preheating large parts, which will decrease the subsequent cooling rate. Postheating the joint in the welding machine by resistance heating or by immediately placing the weldment in a furnace operating at the desired temperature may prevent cracking when preheating is ineffective.

A postheat cycle may be incorporated in a flash welding machine using an electronic timer and phase-shift heat control. The postheat timer can be initiated at the end of upset or after a time delay. The desired temperature can be attained by adjustment of the heat control. However, heat will be transferred from the weldment to the clamping dies during the postheat. This must be considered in designing the die and in material selection, and water cooling may be necessary.

Flash Removal

IT IS FREQUENTLY necessary to remove the flash material from the welded joint. In some cases, this is done only for the sake of appearance. A joint is somewhat stronger in tension if the flash is not removed, because of the larger cross section provided by upset material. However, the notch effect at the weld line may then cause a reduction of fatigue strength. The notched portion of the upset material should be removed, but the balance may be left in place when the design of parts indicates that reinforcement is beneficial.

It is generally easier to remove the flash immediately after welding while the metal is still hot. This can be done by a number of methods, including machining, grinding, high-speed wheels, die trimming, oxy-fuel gas cutting, high-speed sanding, and pinch-off type clamping dies. With some alloy steels, flash removal with cutting tools is often difficult because of their hardness. In these cases, either grinding or oxyfuel gas cutting is usually employed.

With soft metals such as aluminum and copper, the flash may be almost sheared off using pinch-off dies. These dies have sharp tapered faces which cut almost through the metal as upsetting takes place. The final die opening is small. The partially sheared flash is then easily removed by other means. The joint can then be smoothed by filing or grinding.

PROCESS VARIABLES

Flashing Voltage

FLASHING VOLTAGE IS determined by the welding transformer tap setting. It should be selected to be as low as possible consistent with good flashing action. Electronic phase-shift heat control is not an effective means for reducing the flash voltage. The secondary voltage wave form produced by this means is incompatible with good flashing action.

Changes in flashing voltage should be made only by changing the tap setting of the transformer. One system for providing two voltage ranges uses two primary contactors, each of which is connected to separate transformer taps. One contactor is energized to provide a high secondary voltage (V_1 in Figures 18.3 and 18.4) during the initial stages of flashing. The high voltage assists in starting the flashing action. The other contactor is energized after a predetermined time in the flashing operation to provide a normal secondary voltage (V_2 in Figures 18.3 and 18.4). The first contactor is de-energized at the same time. The best flashing action is achieved with this arrangement.

Flashing Time

FLASHING IS CARRIED out over a time interval to obtain the required flash loss of metal. The time required will be related to the secondary voltage and the rate of metal loss as flashing progresses. Since a flashing pattern is generally parabolic, the variables are interrelated. In any case, smooth flashing action for some minimum flashing distance during some time interval is necessary to produce a sound, strong weld.

Upset

IN THE PRODUCTION of a satisfactory flash weld, the flash and upset variables must be considered together since they are interrelated. The upset variables include the following:

(1) Flashing voltage cutoff
(2) Upset rate
(3) Upset distance
(4) Upset current magnitude and duration

Flashing Voltage Cutoff

FLASHING VOLTAGE SHOULD be terminated at the moment that upset of the weld commences. Adjustments should be made during actual welding tests to ensure that voltage termination does not take place before the faying surfaces make full contact.

Upset Rate

UPSET IS INITIATED by increasing the acceleration of the parts to bring the faying surfaces together quickly. The molten metal and oxides present on the surfaces are forced out of the joint as this occurs. The hot weld zone is upset. The upset rate must be sufficient to expel the molten metal before it solidifies and to produce the optimum upset while the metal has adequate plasticity.

The welding machine must apply a force to the movable platen to properly accelerate the part and overcome the resistance of the parts to plastic deformation. The force required depends upon the cross-sectional area of the joint, the yield strength of the hot metal to be welded, and the mass of the movable platen. Table 18.3 gives the approximate minimum upset pressures for flash welding typical alloys. These values may be used for a first approximation in determining the welding machine size required to flash weld a particular joint area on one of these alloys.

Upset Distance

THE MAGNITUDE OF the upset distance must be sufficient to accomplish two actions:

(1) The oxides and molten metal must be expelled from the faying surfaces.

(2) The two faying surfaces must be brought into intimate metal-to-metal contact over the entire cross section.

The amount of upset required to obtain a sound flash weld depends upon the metal and the section thickness. If the flashing conditions produce relatively smooth flashed surfaces, smaller upset distances than needed for roughly flashed surfaces will be satisfactory for most metals. Some heat-resistant alloys may require upset distances as large as 1 to 1.25 times the section thickness. Satisfactory welds are made in aluminum with upset distances about 50 percent greater than those employed with steels of similar thicknesses. Typical flash welding dimensions including upset distances and material losses are shown in Tables 18.5 and 18.6. These data are for low and medium strength forging steels.

Table 18.3
Upsetting Pressures for Various Classes of Alloys

Strength Classification	Examples	Upset Pressure ksi	MPa
Low forging	SAE 1020, 1112, 1315 and those steels commonly designated as high strength low alloy	10	69
Medium forging	SAE 1045, 1065, 1335, 3135, 4130, 4140, 8620, 8630	15	103
High forging	SAE 4340, 4640, 300M, tool steel, 12% Cr and 18-8 stainless steel, titanium, aluminum	25	172
Extra high forging	Materials exhibiting extra high compressive strength at elevated temperature such as A286, 19-9 DL, nickel- and cobalt-based alloys	35	241

Upset Current

AS DISCUSSED UNDER postheating above, in some cases the weld zone may tend to cool too rapidly after flashing is terminated. This may result in inadequate upset or cold cracking of the upset metal. The joint temperature can be maintained during upset by resistance heating with current supplied by the welding transformer. The current magnitude is commonly controlled electronically.

Normally, upset current would be terminated at the end of upset. If the flash is to be mechanically trimmed immediately after welding, upset current may be maintained for an additional period to achieve the desired temperature for trimming.

WELD QUALITY

Effect of Welding Variables

WELD QUALITY IS significantly affected by the specific welding variables selected for the application. Table 18.4 indicates the effects of several variables on quality when they are excessive or insufficient in magnitude. Each variable is considered individually, although more than one can produce the same result. Commmon defects found in flash welds are discussed below.

Base Metal Structure

METALLURGICAL DISCONTINUITIES THAT often originate from conditions present in the base metal can usually be minimized by specifying necessary qualities in the materials selected. The inherent fibrous structure of wrought mill products may cause anisotropic mechanical behavior. An out-turned fibrous structure at the weld line often results in some decrease in mechanical properties as compared to the base metal, particularly in ductility.

The decrease in ductility caused by flash welding is normally insignificant except in two cases:

(1) The base material may be extremely nonhomogeneous. Examples are severely banded steels, alloys with excessive stringer type inclusions, and mill products with seams and cold shuts produced during the fabrication process.

(2) The upset distance may be excessive.

Table 18.4
Effect of Variables on Flash and Upset Weld Quality

	Voltage	Rate	Time	Current	Distance or Force
Excessive	Deep craters are formed that cause voids and oxide inclusions in the weld; cast metal in weld.	Tendency to freeze.	Metal too plastic to upset properly.	Molten material entrapped in upset; excessive deformation.	Tendency to upset too much plastic metal; flow lines bent perpendicular to base metal.
Insufficient	Tendency to freeze; metal not plastic enough for proper upset.	Intermittent flashing, which makes it difficult to develop sufficient heat in the metal for proper upset.	Not plastic enough for proper upset; cracks in upset.	Longitudinal cracking through weld area; inclusions and voids not properly forced out of the weld.	Failure to force molten metal and oxides from the weld; voids.

When the upset distance is excessive, the fibrous structure may be completely reoriented transverse to the original structure.

Oxides

ANOTHER SOURCE OF metallurgical discontinuities is the entrapment of oxides at the weld interface. Such defects are rare since proper upset should expel any oxides formed during the flashing operation.

Flat Spots

FLAT SPOTS ARE metallurgical discontinuities that are usually limited to ferrous alloys. Their exact cause is not certain. They appear on a fractured surface through the weld interface in the form of smooth, irregularly shaped areas.

There is excellent correlation between the location of flat spots and localized regions of carbon segregation in steels. In many cases, the cooling rates associated with flash welds are rapid enough to produce brittle, high carbon martensite at areas on the flashing interface where the carbon content happens to be greater than the nominal composition of the alloy. Microhardness tests and metallographic examination have confirmed the presence of high carbon martensite in the region surrounding a "flat spot" in almost every case, even in plain carbon steels. Furthermore, steels with banded microstructures appeared significantly more susceptible to this type of defect than unbanded steels.

Die Burns

BURNS ARE DISCONTINUITIES produced by local overheating of the base metal at the interface between the clamping die and the part surface. They can usually be avoided by keeping the parts clean and mating them properly with the dies.

Voids

VOIDS ARE USUALLY the result of either insufficient upset or excessive flashing voltage. Deep craters produced on the faying surfaces by excessive flashing voltage may not be completely eliminated during upset. Such discontinuities are usually discovered when the welding procedure is being qualified. They are readily avoided by decreasing the flashing voltage or increasing the upset distance. Figures 18.8 (A) and (B) show the appearance of flash welds with satisfactory and unsatisfactory upset.

Cracking

THE TYPE OF discontinuity known as a crack may be internal or external. It may be related to the metallurgical characteristics of the metal. Alloys that exhibit low ductility over some elevated temperature range may be susceptible to internal hot cracking. Such alloys, known as "hot-short" alloys, are somewhat difficult to flash weld, but usually can be successfully welded with the proper conditions.

Cold cracking may occur in hardenable steels. It can usually be eliminated by welding with conditions that moderate the weld cooling rate, coupled with post-welding heat treatment as soon as possible after welding.

Insufficient heating prior to or during upset is the usual cause of cracking in the external upset metal, as shown in Figure 18.8 (C). This can be eliminated by resistance heating during upset.

Mechanical Discontinuities

MECHANICAL DISCONTINUITIES INCLUDE misalignment of the faying surfaces prior to welding, and nonuniform upset during welding. These discontinuities are easily detected by visual inspection. Misalignment of the parts is corrected by adjustment of the clamping dies and fixtures. Nonuniform upset may be caused by part misalignment, insufficient clamping force, or excessive die opening at the start of upset. The latter can be corrected by decreasing the initial die opening and then adjusting the welding schedule, if necessary.

Table 18.5
Data for Flash Welding of Tubing and Flat Sheets* (See Fig. 18.2A for Assembly of Parts)

Thickness in.	Initial Die Opening in.	Material Lost in.	Final Die Opening in.	Total Flash Loss in.	Total Upset in.	Material Loss Per Piece in.	Initial Extension Per Piece in.	Flash Time Seconds	O.D. in.	Minimum Length of Electrode Contact	
										Within Backup	Without Backup
0.010	0.110	0.060	0.050	0.040	0.020	0.030	0.055	1.00	0.250	0.375	1.00
0.020	0.215	0.115	0.100	0.080	0.035	0.058	0.108	1.50	0.312	0.375	1.00
0.030	0.325	0.175	0.150	0.125	0.050	0.088	0.163	2.00	0.375	0.375	1.50
0.040	0.430	0.230	0.200	0.165	0.085	0.115	0.215	2.50	0.500	0.375	1.75
0.050	0.530	0.280	0.250	0.205	0.075	0.140	0.265	3.25	0.750	0.500	2.00
0.060	0.620	0.330	0.290	0.240	0.090	0.165	0.310	4.00	1.000	0.750	2.50
0.070	0.715	0.385	0.330	0.280	0.105	0.193	0.358	5.00	1.50	1.000	3.00
0.080	0.805	0.435	0.370	0.315	0.120	0.218	0.403	6.00	2.00	1.250	**
0.090	0.885	0.475	0.410	0.345	0.130	0.238	0.443	7.00	2.50	1.750	**
0.100	0.970	0.520	0.450	0.375	0.145	0.260	0.485	8.00	3.00	2.000	**
0.110	1.060	0.570	0.490	0.410	0.160	0.285	0.530	9.00	3.50	2.250	**
0.120	1.140	0.610	0.530	0.440	0.170	0.305	0.570	10.0	4.00	2.500	**
0.130	1.225	0.650	0.575	0.470	0.180	0.325	0.613	11.0	4.50	2.750	**
0.140	1.320	0.700	0.620	0.510	0.190	0.350	0.660	12.0	5.00	2.750	**
0.150	1.390	0.730	0.660	0.530	0.200	0.365	0.695	13.0	5.50	3.000	**
0.160	1.470	0.770	0.700	0.560	0.210	0.385	0.735	14.0	6.00	3.250	**
0.170	1.540	0.800	0.740	0.580	0.220	0.400	0.770	15.0	6.50	3.500	**
0.180	1.620	0.840	0.780	0.610	0.230	0.420	0.810	16.0	7.00	3.750	**
0.190	1.690	0.870	0.820	0.630	0.240	0.435	0.845	17.0	7.50	4.000	**
0.200	1.760	0.900	0.860	0.650	0.250	0.450	0.880	18.0	8.00	4.250	**
0.250	2.010	1.010	1.000	0.730	0.280	0.505	1.005	24.0	8.50	4.500	**
0.300	2.245	1.120	1.125	0.810	0.310	0.560	1.123	30.0	9.00	4.750	**
0.350	2.460	1.210	1.250	0.880	0.330	0.605	1.230	36.0	9.50	5.000	**
0.400	2.640	1.290	1.350	0.930	0.360	0.645	1.320	42.0			
0.450	2.780	1.350	1.430	0.970	0.380	0.675	1.390	48.0			
0.500	2.910	1.410	1.500	1.020	0.390	0.705	1.455	54.0			
0.550	3.040	1.465	1.575	1.055	0.410	0.733	1.520	60.0			
0.600	3.135	1.505	1.630	1.085	0.420	0.753	1.568	66.0			
0.650	3.245	1.555	1.690	1.125	0.430	0.778	1.623	73.0			
0.700	3.360	1.610	1.750	1.160	0.450	0.805	1.680	80.0			
0.800	3.525	1.675	1.850	1.210	0.465	0.838	1.763	92.0			
0.900	3.660	1.730	1.930	1.250	0.480	0.865	1.830	104.0			
1.000	3.800	1.800	2.000	1.300	0.500	0.900	1.900	116.0			

Notes:

* Data based on welding without preheat, and for two pieces of same welding characteristics, using constant acceleration of flash rate.

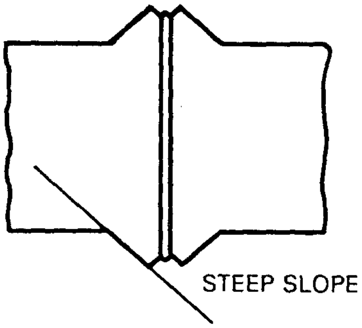
** Not recommended without use of backup.

TESTING AND INSPECTION

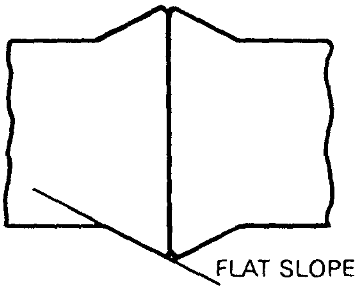
NONDESTRUCTIVE EVALUATION OF flash welded joints is complicated by several factors including the flash, the variation in thickness for bars, and other factors. Fortunately, one of the major advantages of flash welding is that it can be highly mechanized and automated. Therefore, a consistent quality level is readily maintained after satisfactory welding conditions are established. The fact that no filler metal is employed means that the strength of the weld is primarily a function of the base metal composition and properties. Consequently, properly made flash welds should exhibit satisfactory mechanical properties.

In commercial practice, both destructive and nondestructive tests are employed to ensure maintenance of the desired quality level in critical flash welded products. The process control procedure usually includes the following:

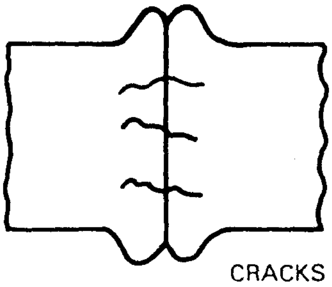
(1) Material certification
(2) Qualification of welding procedure
(3) Visual inspection of the product
(4) Destructive testing of random samples



(A) SATISFACTORY HEAT AND UPSET



(B) INSUFFICIENT HEAT OR UPSET OR BOTH



(C) CRACKS DUE TO INSUFFICIENT HEAT

Figure 18.8–Visual Indications of Flash Weld Quality

When the product is used in a critical application, the above procedure is supplemented by other tests such as magnetic particle and dye penetrant examination. When the welded joint is subsequently machined, routine measurement of the hardness of the weld area may also be specified. In addition, specifications may require proof testing of flash welded products.

Material Certification

SINCE MATERIAL DEFECTS may cause flash weld discontinuities, each lot of raw material should be carefully inspected upon delivery to ensure that it meets specifications. Certified chemical analysis, mechanical property tests, macroetch examination, and magnetic particle inspection may be applicable.

Procedure Qualification

EACH NEW COMBINATION of material and section size to be flash welded normally requires qualification of a new welding procedure. This usually involves welding a number of test specimens that duplicate the material, section size, welding procedure, and heat treatment to be used in producing the product. All of these specimens are visually inspected for cracks, die burns, misalignment, and other discontinuities. Where required, weld hardnesses are measured. To verify weld strength, a tensile specimen should be machined from a test weld using the entire welded cross section where possible. The test results should be compared to the base metal properties and design requirements.

All pertinent welding conditions used in producing the qualification test should be recorded. The production run is then made using the qualified welding procedure.

Nondestructive Inspection

EACH COMPLETED WELD in the production run should be visually examined for evidences of cracks, die burns, misalignment, or other external weld defects. Where specified, magnetic particle or fluorescent penetrant inspection is performed on random samples to assist in detecting flaws not visible to the unaided eye. In critical applications, random radiographic examination may also be specified.

Destructive Testing

DEPENDING UPON THE size of the production run, a specified number of randomly chosen parts may be selected for destructive testing of the welds. The results of these destructive tests must all meet the same criteria specified in the welding procedure qualification test. Additional tests are required if any fail. A report of the results of all destructive tests is then prepared to certify the maintenance of the required average quality level for the lot.

Bend Tests. Notched bend tests may be used to force a fracture to occur along the weld interface for visual examination. A bend test may be useful as a qualitative means for establishing a welding schedule. However, such tests are not generally used for specification purposes.

Tension Tests. Where strength testing is required, the tension test specimen should be machined to include the entire welded cross-section of the flash weld, as applied for Procedure Qualification above.

WELDING OF STEEL

TYPICAL DATA FOR the flash welding of steel tubing and flat sheets are given in Table 18.5. For welding solid round, hexagonal, square, and rectangular steel bars, data are given in Table 18.6. Both tables are applicable to steels of low and medium forging strength. They give the recommended dimensions for setting up a flash welding machine to weld the various sections. Total flashing time is based on welding without preheating.

When setting up a schedule, the dimensional variables and flashing time are selected from the tables. The welding machine is adjusted to the lowest secondary voltage at which steady and consistent flashing can be obtained. The secondary voltages available are dependent upon the electrical design of the welding transformer.

The upsetting force used for a particular application depends upon the alloy and the cross-sectional area of the joint. The selection of equipment for steels should be based on the values of recommended upset pressures given in Table 18.3. Such values are based on welding without preheat.

Table 18.6
Data for Flash Welding of Solid Round, Hex, Square and Rectangular Bars* (See Fig. 18.2(B) for Assembly of Parts)

Thickness in.	Initial Die Opening in.	Material Lost in.	Final Die Opening in.	Total Flash Loss in.	Total Upset in.	Material Loss Per Piece in.	Initial Extension Per Piece in.	Flash Time Seconds	O.D. in.	Minimum Length of Electrode Contact	
										Within Backup	Without Backup
0.050	0.100	0.050	0.050	0.040	0.010	0.025	0.050	1.00	0.250	0.375	1.00
0.100	0.182	0.082	0.100	0.062	0.020	0.041	0.091	1.50	0.312	0.375	1.00
0.150	0.270	0.120	0.150	0.090	0.030	0.060	0.135	2.00	0.375	0.375	1.50
0.200	0.350	0.150	0.200	0.110	0.040	0.075	0.175	2.50	0.500	0.375	1.75
0.250	0.430	0.180	0.250	0.130	0.050	0.090	0.215	3.25	0.750	0.500	2.00
0.300	0.510	0.210	0.300	0.150	0.060	0.105	0.255	4.00	1.000	0.750	2.50
0.350	0.600	0.250	0.350	0.180	0.070	0.125	0.300	5.00	1.50	1.000	3.00
0.400	0.685	0.285	0.400	0.205	0.080	0.143	0.343	6.00	2.00	1.250	**
0.450	0.770	0.320	0.450	0.230	0.090	0.160	0.385	7.00	2.50	1.750	**
0.500	0.850	0.350	0.500	0.250	0.100	0.175	0.425	8.00	3.00	2.000	**
0.550	0.940	0.390	0.550	0.280	0.110	0.195	0.470	9.00	3.50	2.250	**
0.600	1.025	0.425	0.600	0.305	0.120	0.213	0.513	10.0	4.00	2.500	**
0.650	1.100	0.450	0.650	0.325	0.125	0.225	0.550	11.0	4.50	2.750	**
0.700	1.180	0.480	0.700	0.350	0.130	0.240	0.590	12.0	5.00	2.750	**
0.750	1.260	0.510	0.750	0.375	0.135	0.255	0.630	13.0	5.50	3.000	**
0.800	1.340	0.540	0.800	0.400	0.140	0.270	0.670	14.0	6.00	3.250	**
0.850	1.420	0.570	0.850	0.425	0.145	0.285	0.710	15.0	6.50	3.500	**
0.900	1.500	0.600	0.900	0.450	0.150	0.300	0.750	16.0	7.00	3.750	**
0.950	1.580	0.630	0.950	0.475	0.155	0.315	0.790	17.0	7.50	4.000	**
1.000	1.660	0.660	1.000	0.500	0.160	0.330	0.830	18.0	8.00	4.250	**
1.050	1.740	0.690	1.050	0.525	0.165	0.345	0.870	20.0	8.50	4.500	**
1.100	1.820	0.720	1.100	0.550	0.170	0.360	0.910	22.0	9.00	4.750	**
1.150	1.900	0.750	1.150	0.575	0.175	0.375	0.950	24.0	9.50	5.000	**
1.200	1.980	0.780	1.200	0.600	0.180	0.390	0.990	27.0			
1.250	2.060	0.810	1.250	0.625	0.185	0.405	1.030	30.0			
1.300	2.140	0.840	1.300	0.650	0.190	0.420	1.070	33.0			
1.400	2.300	0.900	1.400	0.700	0.200	0.450	1.150	36.0			
1.500	2.460	0.960	1.500	0.750	0.210	0.480	1.230	42.0			
1.600	2.620	1.020	1.600	0.800	0.220	0.510	1.310	49.0			
1.700	2.780	1.080	1.700	0.850	0.230	0.540	1.390	57.0			
1.800	2.940	1.140	1.800	0.900	0.240	0.570	1.470	66.0			
1.900	3.100	1.200	1.900	0.950	0.250	0.600	1.550	77.0			
2.000	3.260	1.260	2.000	1.000	0.260	0.630	1.630	92.0			

Notes:

* Data based on welding without preheat, and for two pieces of same welding characteristics, using constant acceleration of flash rate.

** Not recommended without use of backup.

UPSET WELDING

DEFINITION

UPSET WELDING (UW) is a resistance welding process that produces coalescence over the entire area of faying surfaces, or progressively along a butt joint, by the heat obtained from the resistance to the flow of welding current through the area where those surfaces are in contact. Pressure is used to complete the weld.

PRINCIPLES OF OPERATION

WITH THIS PROCESS, welding is essentially done in the solid state. The metal at the joint is resistance heated to a temperature where recrystallization can rapidly take place across the faying surfaces. A force is applied to the joint to bring the faying surfaces into intimate contact and then upset the metal. Upset hastens recrystallization at the interface and, at the same time, some metal is forced outward from this location. This tends to purge the joint of oxidized metal.

PROCESS VARIATIONS

UPSET WELDING HAS two variations:

(1) Joining two sections of the same cross section end-to-end (butt joint)
(2) Continuous welding of butt joint seams in roll-formed products such as pipe and tubing.

The first variation can also be accomplished by flash welding and friction welding. The second variation is also done with high frequency welding.

BUTT JOINTS

Metals Welded

A WIDE VARIETY of metals in the form of wire, bar, strip, and tubing can be joined end-to-end by upset welding. These include:

(1) Carbon steels
(2) Stainless steels
(3) Aluminum alloys
(4) Brass
(5) Copper
(6) Nickel alloys
(7) Electrical resistance alloys

Sequence of Operations

THE ESSENTIAL OPERATIONAL steps to produce an upset welded butt joint are as follows:

(1) Load the machine with the parts aligned end-to-end
(2) Clamp the parts securely
(3) Apply a welding force
(4) Initiate the welding current
(5) Apply an upset force
(6) Cut off the welding current
(7) Release the upset force
(8) Unclamp the weldment
(9) Return the movable platen and unload the weldment

The general arrangement for upset welding is shown in Figure 18.9. One clamping die is stationary and the other is movable to accomplish upset. Upset force is applied through the moveable clamping die or a mechanical backup, or both.

Joint Preparation

FOR UNIFORM HEATING, the faying surfaces should be flat, comparatively smooth, and perpendicular to the direction of the upsetting force. Prior to welding, they should be cleaned to remove any dirt, oil, oxidation, or other materials that will impede welding.

The contact resistance between the faying surfaces is a function of the smoothness and cleanliness of the surfaces and the contact pressure. This resistance varies inversely with the contact pressure, provided the other factors are constant. As the temperature at the joint increases, the

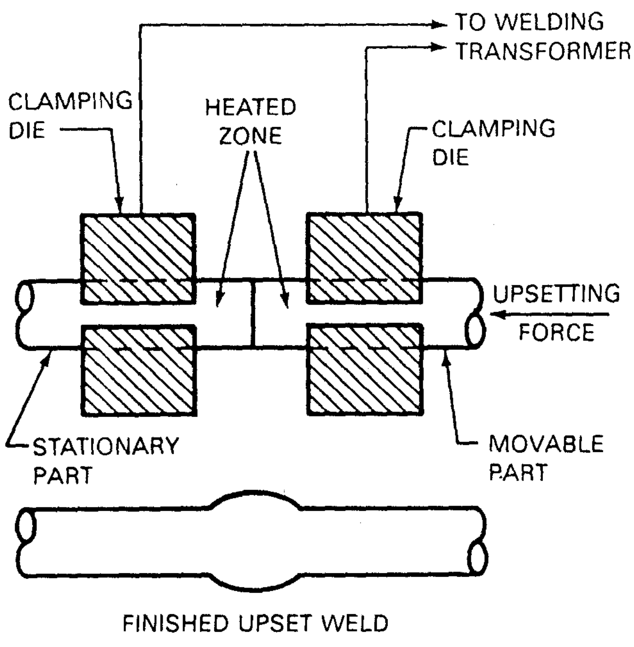


Figure 18.9–General Arrangement for Upset Welding of Bars, Rods, and Pipes

contact resistance changes, but it finally becomes zero when the weld is formed. Upset welding differs from flash welding in that no flashing takes place at any time during the welding cycle.

Generally, force and current are maintained throughout the entire welding cycle. The force is kept low at first to promote high initial contact resistance between the two parts. It is increased to a higher value to upset the joint when the welding temperature is reached. After the prescribed upset is accomplished, the welding current is turned off and the force is removed.

Equipment

EQUIPMENT FOR UPSET welding is generally designed to weld a particular family of alloys, such as steels, within a size range based on cross-sectional area. The mechanical capacity and electrical characteristics of the machine are matched to that application. Special designs may be required for certain aluminum alloys to provide close control of upset force.

Electric current for heating is provided by a resistance welding transformer. It converts line power to low voltage, high current power. No-load secondary voltages range from about 0.4 to 8 V. Secondary current is controlled by a transformer tap switch or by electronic phase shift.

Basically, an upset welding machine has two platens, one of which is stationary and the other movable. The clamping dies are mounted on these platens. The clamps operate either in straight line motion or through an arc about an axis, depending upon the application. Force for upset butt welding is produced generally by a mechanical, pneumatic, or hydraulic system.

Heat Balance

THE UPSET PROCESS is generally used to join together two pieces of the same alloy and same cross-sectional geometry. In this case, heat balance should be uniform across the joint. If the parts to be welded are similar in composition and cross section but of unequal mass, the part of larger mass should project from the clamping die somewhat farther than the other part. With dissimilar metals, the one with higher electrical conductivity should extend farther from the clamp than the other. When upset welding large parts that do not make good contact with each other, it is sometimes advantageous to interrupt the welding current periodically to allow the heat to distribute evenly into the parts.

Applications

UPSET WELDING IS used in wire mills and in the manufacture of products made from wire. In wire mill applications, the process is used to join wire coils to each other to facilitate continuous processing. The process also is used to fabricate a wide variety of products from bar, strip, and tubing. Typical examples of mill forms and products that have been upset welded are shown in Figure 18.10. Wire and rod from 0.05 to 1.25-in. (1.27 to 31.75 mm) diameter can be upset welded.

Weld Quality

BUTT JOINTS CAN be made that have about the same properties as the unwelded base metal. With proper procedures, welds made in wires are difficult to locate after they have passed through a subsequent drawing process. In many instances, the welds are then considered part of the continuous wire.

Upset welds may be evaluated by tension testing. The tensile properties are compared to those of the base metal. Metallographic and dye penetrant inspection techniques are also used.

A common method for evaluating a butt weld in wire is a bend test. A welded sample is clamped in a vise with the weld interface located one wire diameter from the vise jaws. The sample then is bent back and forth until it breaks in two. If the fracture is through the weld interface and shows complete fusion, or if it occurs outside the weld, the weld quality is considered satisfactory.

CONTINUOUS UPSET BUTT WELDING

General Description

IN THE MANUFACTURE of continuously welded pipe or tubing by upset welding, coiled strip is fed into a set of forming rolls. These rolls progressively form the strip into cylindrical shape. The edges to be joined approach each other at an angle and culminate in a longitudinal vee at the point of welding. A wheel electrode contacts each edge of the tube a short distance from the apex of the vee. Current from the power source travels from one electrode along the adjacent edge to the apex, where welding is taking place, and then back along the other edge to the second electrode. The edges are resistance-heated by this current to welding temperature. The hot edges are then upset together by a set of pinch rolls to consummate a weld.

Equipment

FIGURE 18.11 SHOWS a typical tube mill that uses upset welding to join the longitudinal seam. Figure 18.11 (A) shows the steel strip entering the strip guide assembly and the first stages of the forming section. The heat regulator, located behind the forming section, can be adjusted either manually or by phase-shift heat control. Figure 18.11 (B) shows a rotary type oil-cooled welding transformer. This welding equipment includes (1) a dressing tool assembly for dressing the welding electrodes without removing them from the welding machine, and (2) a scarfing tool assembly that removes the upset metal after welding. In the third step, the welded tube enters the straightening and sizing section, shown in Figure 18.11 (C). Following this, the tubing is cut to the desired length.

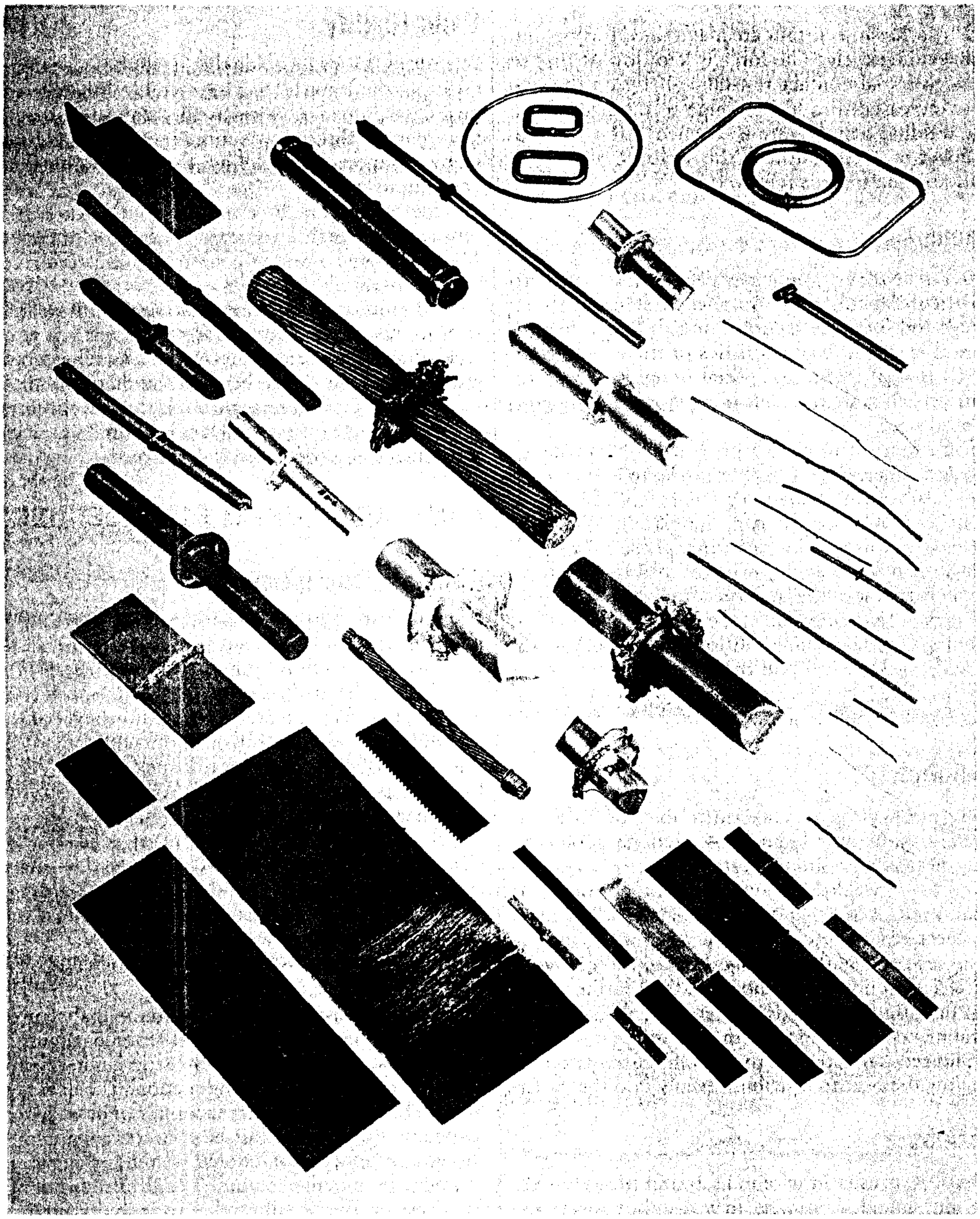
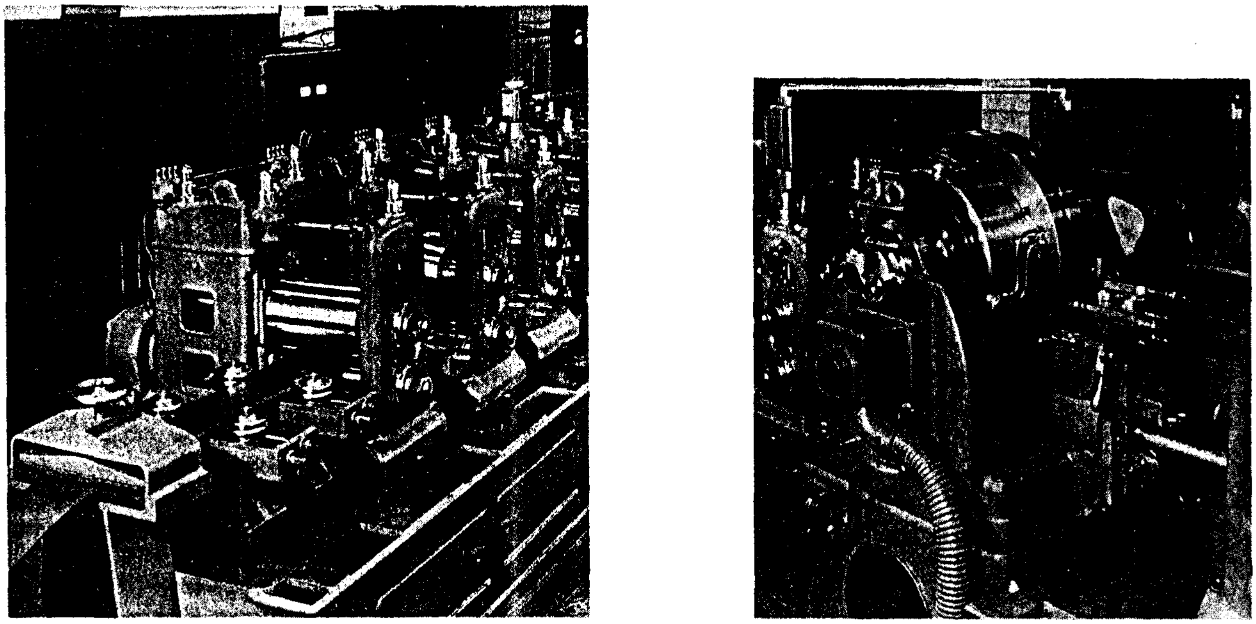
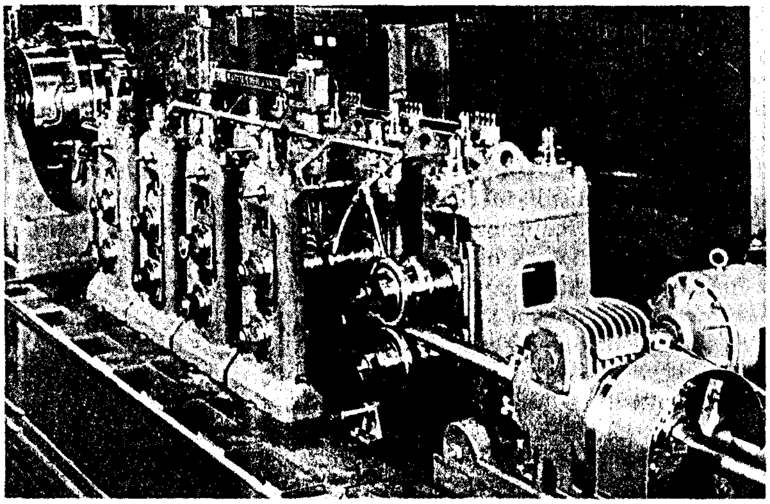


Figure 18.10–Typical Mill Forms and Products Joined by Upset Welding



(A) STRIP GUIDE ASSEMBLY AND FIRST STAGES OF THE FORMING SECTION

(B) ROTARY TYPE OIL-COOLED WELDING TRANSFORMER



(C) STRAIGHTENING AND SIZING SECTION

Figure 18.11–Typical Tube Mill Using Welding for Joining the Longitudinal Seam

Welding can be done using either ac or dc power. Alternating current machines may be operated on either 60 Hz single-phase power or on power of higher frequency produced by a single-phase alternator. Direct current machines are powered by a three phase transformer-rectifier unit.

Welding Procedures

AS THE FORMED tube passes through the zone between the electrodes and the pinch rolls, there is a variation in pressure across the joint. If no heat were generated along the edges, this pressure would be maximum at the center of the squeeze rolls. However, since heat is generated in the metal ahead of the squeeze roll center line, the metal gradually becomes plastic and the point of initial edge contact is slightly ahead of the squeeze roll axes. The point of maximum upset pressure is somewhat ahead of the squeeze roll centerline.

The current across the seam is distributed in inverse proportion to the resistance between the two electrodes. This resistance, for the most part, is the contact resistance between the edges to be welded. Pressure is effective in reducing this contact resistance. As the temperature of the joint increases, the electrical resistance will increase and the pressure will decrease. A very sharp thermal gradient caused by the resistance heating at the peaks of the ac cycle produces a "stitch effect". The stitch is normally of circular cross section, lying centrally in the weld area and parallel to the line of initial closure of the seam edges. It is the hottest portion of the weld. The stitch area is molten while the area between stitches is at a lower temperature. The patches of molten metal are relatively free to flow under the influence of the motor forces (current and magnetic flux) acting on them. Consequently, they are ejected from the stitch area. If the welding heat is excessive, too much metal is ejected and pinhole leaks may result. With too little heat, the individual stitches will not overlap sufficiently, resulting in an interrupted weld.

The longitudinal spacing of the stitches must have some limit. The spacing is a function of the power frequency and the travel speed of the tube being welded. With 60 Hz power, the speed of welding should be limited to approximately 90 ft/min (0.45 m/sec). To weld tubing at higher speeds than this requires welding power of higher frequency. Typical welding speeds using various sizes of 180 Hz power sources for steel tubing of several wall thicknesses are shown in Table 18.7.

It is desirable to close the outside corners of the edges first as the formed tube moves through the machine so that the stitches will be inclined forward. This condition is known as an inverted vee. The advantages of using an inverted vee are twofold: (1) the angle deviation from the vertical reduces the forces tending to expel any molten metal in the joint, and (2) the major portion of the solid upset metal is extruded to the outside where it is easily removed. The tubing is normally formed so that the included angle of the vee is about 5 to 7 degrees.

Table 18.7
Typical Seam Welding Speeds for Steel Tubing Using 180Hz Power Sources

Wall Thickness, in.	Speed, ft/min.			
	125kVA	200kVA	300kVA	500kVA
0.050	150	200	--	--
0.065	110	140	200	--
0.083	72	105	145	--
0.095	--	85	115	--
0.109	--	66	90	--
0.125	--	50	70	140
0.134	--	--	60	125
0.156	--	--	--	85

Surface Burns

AS IN SPOT and seam welding, the current that provides the welding heat must enter the stock through electrode contacts. The resistance of these contacts must be kept to a minimum to avoid resistance heating sufficient to result in surface burns on the tube. Burns are actually surface portions of the tube that are heated to their fusion or melting point. They tend to stick to or embed themselves in the face of the wheel electrode. If large steel particles become embedded in the electrode face, the contact resistance will increase and cause more severe burning. This action continues to build up with each revolution of the electrode. To stop burning, the operation must be interrupted to clean or replace the electrode.

To eliminate burns, the area of contact and the pressure between the electrode and the tube must be adequate. As a rule of thumb, each electrode should have sufficient contact area so that the current density will be less than 50 000 A/in.^{2} (32 A/m^2). The relative shapes of the formed tube and the electrode should ensure that the maximum contact pressure occurs next to the seam.

Without the aid of some backup support, electrode contact pressure is limited by the ability of the tube to support the forces being applied. The maximum permissible pressure in the welding throat is a function of the yield strength of the metal and the ratio of tube diameter to wall thickness (D/t ratio). In extreme cases where the D/t ratio is high, a backup mandrel must be used to prevent distortion of the tube wall and misalignment of the joint.

INSPECTION AND TESTING

UPSET WELDS CAN be inspected and tested in the same manner as flash welds. In general, the quality requirements for upset welds are not so stringent as those specified for flash welds. The process normally cannot produce welds with the consistency available with flash welding.

PERCUSSION WELDING

DEFINITION AND GENERAL DESCRIPTION

PERCUSSION WELDING IS a joining process that produces coalescence with an arc resulting from a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the eletrical discharge.

In general, "percussion welding" is the term used in the electronics industry for joining wires, contacts, leads, and similar items to a flat surface. On the other hand, if the item is a metal stud that is welded to a structure for attachment purposes, it is called *capacitor discharge stud welding*[2].

In application of the process, the two parts are initially separated by a small projection on one part, or one part is moved toward the other. At the proper time, an arc is initiated between them. This arc heats the faying surfaces of both parts to welding temperature. Then, an impact force drives the parts together to produce a welded joint. There are basically two variations of the percussion process: capacitor discharge and magnetic force.

Although the steps may differ in certain applications because of process variations, the essential sequence of events in making a percussion weld is as follows:

(1) Load and clamp the parts into the machine.
(2) Apply a low force on the parts or release the driving system.
(3) Establish an arc between the faying surfaces (1) with high voltage to ionize the gas between the parts or (2) with high current to melt and vaporize a projection on one part.
(4) Move the parts together percussively with an applied force to extinguish the arc and consummate a weld.
(5) Turn off the current.
(6) Release the force.
(7) Unclamp the welded assembly.
(8) Unload the machine.

Percussion welding is similar to capacitor discharge stud welding. The differences between the two processes lie in the applications and the type of power source. Percussion welding may be used to join equal cross sections of wires, rods, and tubes. Welding current is supplied by a capacitor storage bank in these applications.

The process may also be used to weld wires or contacts to large flat areas with power from a capacitor bank or a transformer.

PRINCIPLES OF OPERATION

WELDING HEAT IS generated by a high current arc between the two parts to be joined. The current density is very high, and this melts a thin layer of metal on the faying surfaces in a few milliseconds. Then the molten surfaces are brought together in a percussive manner to complete the weld.

There are two process variations that differ in the type of power supply, method of arc initiation, and work drive motion.

Capacitor Discharge Percussion Welding

WITH THE CAPACITOR discharge method, power is furnished by a capacitor storage bank. The arc is initiated by the voltage across the terminals of the capacitor bank (charging voltage) or a superimposed high voltage pulse. Motion may be imparted to the movable part by mechanical or pneumatic means.

Magnetic Force Percussion Welding

FOR MAGNETIC FORCE welding, power is supplied by a welding transformer. The arc is initiated by vaporizing a small projection on one part with high current from the transformer. The vaporized metal provides an arc path. The percussive force is applied to the joint by an electromagnet that is synchronized with the welding current. Magnetic force percussion welds are made in less than one half cycle of 60 Hz. Consequently, the timing between the initiation of the arc and the application of magnetic force is critical.

ADVANTAGES OF PERCUSSION WELDING

THE EXTREME BREVITY of the arc in both versions of percussion welding limits melting to a very thin layer on the faying surfaces. Consequently, there is very little upset or flash on the periphery of the welded joint (but enough to remove impurities from the joint). Heat-treated or cold-worked metals can be welded without annealing them.

Filler metal is not used and there is no cast metal at the weld interface. A percussion welded joint usually possesses higher strength and conductivity than does a brazed joint. Unlike brazing, no special flux or atmosphere is required.

A particular advantage of the capacitor discharge method is that the capacitor charging rate is easily controlled and low compared to the discharge rate. The line power factor is better than with a single-phase ac machine. Both these factors give good operating efficiency and low power line demand.

Percussion welding can tolerate a slight amount of contamination on the faying surfaces because expulsion of the thin molten layer tends to carry any contaminants out of the joint.

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[2] See Chapter 9, Stud Welding.

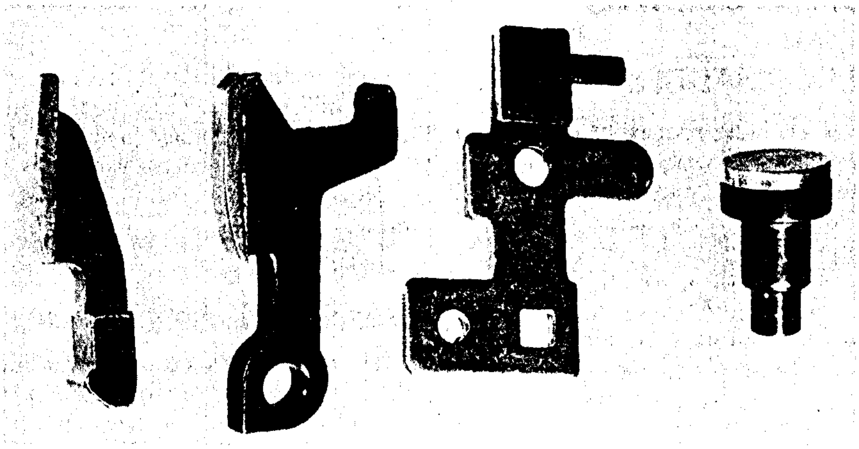

Figure 18.12–Typical Electrical Contacts Joined by Magnetic Force Percussion Welding

LIMITATIONS

THE PERCUSSION WELDING process is limited to butt joints between two like sections and to flat pads or contacts joined to flat surfaces. In addition, the total area that can be joined is limited since control of an arc path between two large surfaces is difficult.

Joints between two like sections can usually be accomplished more economically by other processes. Percussion welding is usually confined to the joining of dissimilar metals not normally considered weldable by other processes, and to the production of joints where avoidance of upset is imperative.

Another limitation of this process is that two separate pieces must be joined. It cannot be used to weld a ring from one piece.

APPLICATIONS

Weldable Metals

THE MAGNETIC FORCE method is primarily used for joining electrical contacts to contactor arms. Combinations include copper to copper, silver-tungsten to copper, silver oxide to copper, and silver-cadmium oxide to brass. Areas from 0.040 to 1.27 in^2. (26 to 820 mm^2) are being welded in production. Some metal loss occurs at the weld interface, and in most instances some flash must be removed from the periphery of the weld. Figure 18.12 shows several contact designs welded by this process. Figure 18.13 shows a section through a typical weld.

The capacitor discharge method is usually employed to produce the following types of joints:

(1) Butt joints between wires or rods
(2) Lead wire ends to flat conductors or terminals
(3) Contacts to relay arms

The wire is usually made of copper and may be solid or stranded, bare or tinned. The rods are usually copper, brass, or nickel-silver. Other alloys such as steel, alumel, chromel, aluminum, and tantalum may be welded to themselves or to other materials. The method is also applicable to reactive, refractory, and dissimilar metal welds, because the short weld time limits contamination of the reactive metals and the formation of low-strength intermetallic zones in the joints.

Industrial Uses

COMPANIES USING PERCUSSION welding are mainly those in the electrical contact or component field. Large contact assemblies for relays and contactors are usually made in magnetic force percussion welding machines. Such machines can be automated for high production.

Figure 18.13–Photomacrograph of a Section Through a Silver Contact (Top) Welded to a Brass Terminal (Bottom)

Hand held capacitor discharge equipment may be used to weld wires to pins. This is particularly applicable to aerospace equipment that is subject to shock and vibration. The process is also used to weld electronic components to terminals.

EFFECT ON METALS WELDED

Heat Effects

A PERCUSSION WELD is made in an extremely short time. It may take milliseconds when using magnetic force welding. Because of this short time, the heat-affected zones of percussion welds are shallow, usually less than 0.010 in. (0.25 mm). There is little oxidation of mating surfaces and a minimum of alloying between dissimilar metals. Since the heat-affected depth is so small, heat-treated metals may be welded without softening them. The heat input is so concentrated and of such short duration that heat-sensitive components near the weld area are not affected by the welding cycle.

Heat balance between parts is usually not a factor of concern. Since percussion welding is essentially a dc process, polarity of the two parts involved may be important in some cases, as in arc welding.

Metal Loss

THE METAL LOSS that occurs during a percussion weld is not as great as in arc stud welding. The loss varies with the area of the weld and the type of welding machine. Metal loss can generally be ignored for parts to be joined by capacitor discharge percussion welding. However, it should be considered in magnetic force percussion welding.

Flash

FLASH IS THE metal that is expelled at high velocity from the weld interface during a percussion weld. It can damage adjacent tooling and may affect accuracy of assembly. Any flash attached to the weld joint should be removed so that it will not cause a problem in service.

MAGNETIC FORCE PERCUSSION WELDING

Welding Machines

MAGNETIC FORCE MACHINES use a low voltage power supply (20 to 35 volts from a transformer), a projection type arc starter, and an electromagnetic system to produce the weld force. A unit generally consists of a modified press type resistance welding machine with specially designed transformer, controls, and tooling. Figure 18.14 shows a typical machine used to weld the type of part shown in Figure 18.12. An air cylinder provides the initial force to bring the parts together.

Magnetic force percussion welding machines usually have an independent power source for the electromagnet so that the force magnitude and time of application can be varied with respect to the initiation of welding current. This is accomplished by using two separate transformers, one for welding power and one for the electromagnet power. The acceleration of the force member can be controlled by adjusting the magnitude of the electromagnet current, thereby providing a duration control for arc time.

Since welding is done during 1/2 cycle of 60 Hz, current is unidirectional. In some cases, the polarity of the two parts may have some effect on weld quality. In general, the same conditions that prevail in dc arc welding are also in effect in percussion welding with respect to polarity. The current is always passing through the transformer in the same direction and the core can become partially saturated. Consequently, the electrical controls should provide a low amplitude 1/2-cycle pulse in the opposite direction to deflux the transformer and electromagnet. This can be done during the loading time.

Joint Design

FOR WELDING TWO flat surfaces together, a projection similar to that for resistance welding must be formed on one piece as shown in Figure 18.15. Its diameter and height must be developed for each application. The diameter must be large enough to support the initial force applied to the parts but too small to carry the welding current. The height determines the gap between the faying surfaces and, thus, the initial arc voltage. When large area contacts are welded, two projections may be required.

The surfaces to be joined must be flat and parallel during welding so that arcing will occur over the entire area. Areas that are not melted will probably not weld when impacted together.

Voltage And Current

IT IS NECESSARY to establish and maintain the desired magnitude of voltage and current for the required weld area. These are determined by the projection desired, the capacity of the welding transformer, and the impedance of the secondary circuit. The transformer should have low impedance with secondary voltages higher than those commonly used in resistance welding.

Arc Time

ARC TIME CAN be considered as the time beginning with the explosion of the projection and ending when the two parts come together and the arc is extinguished. The timing between the initiation of the arc and the application of magnetic force is very critical.

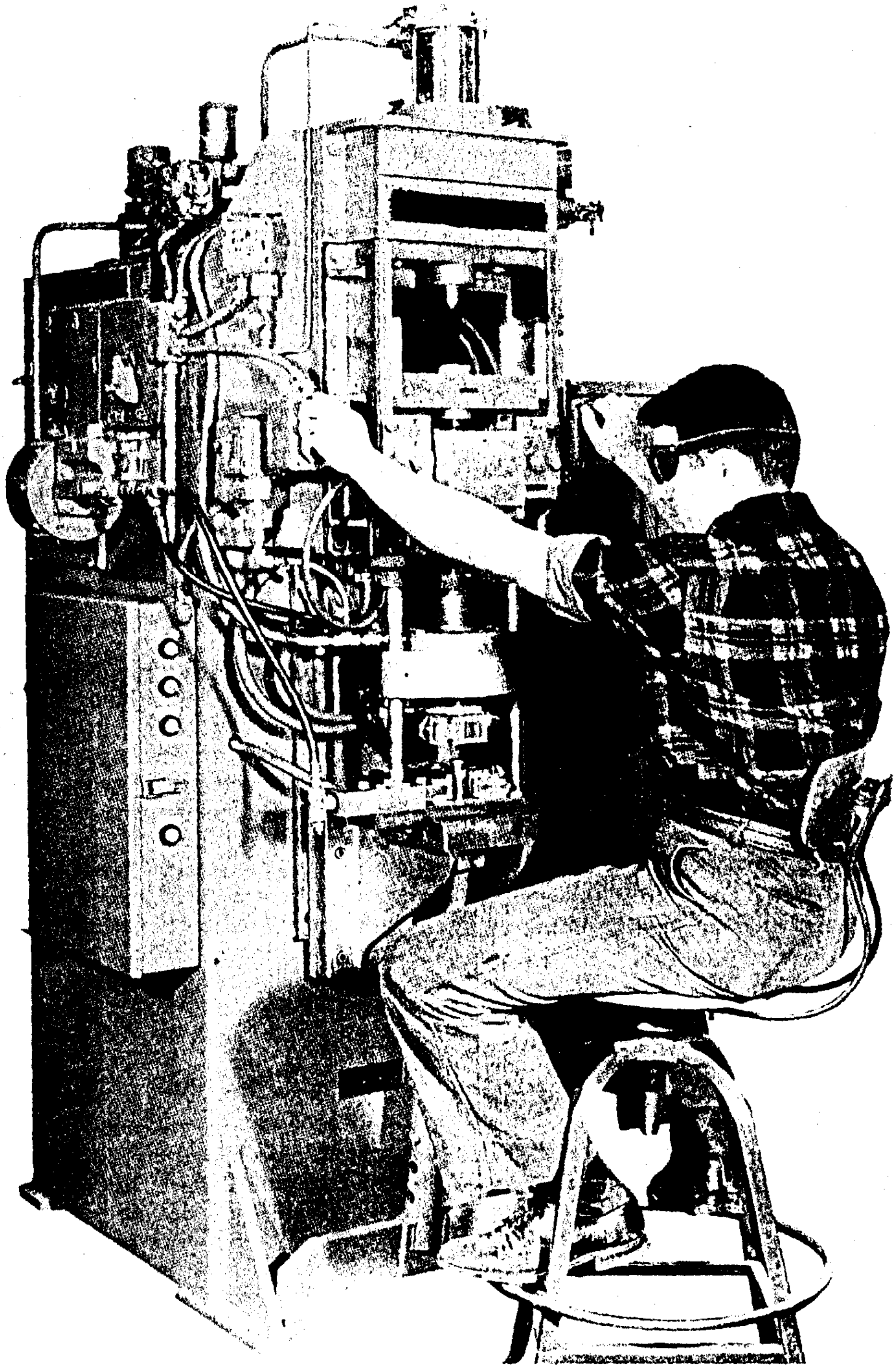

Figure 18.14–Magnetic Force Percussion Welding Machine

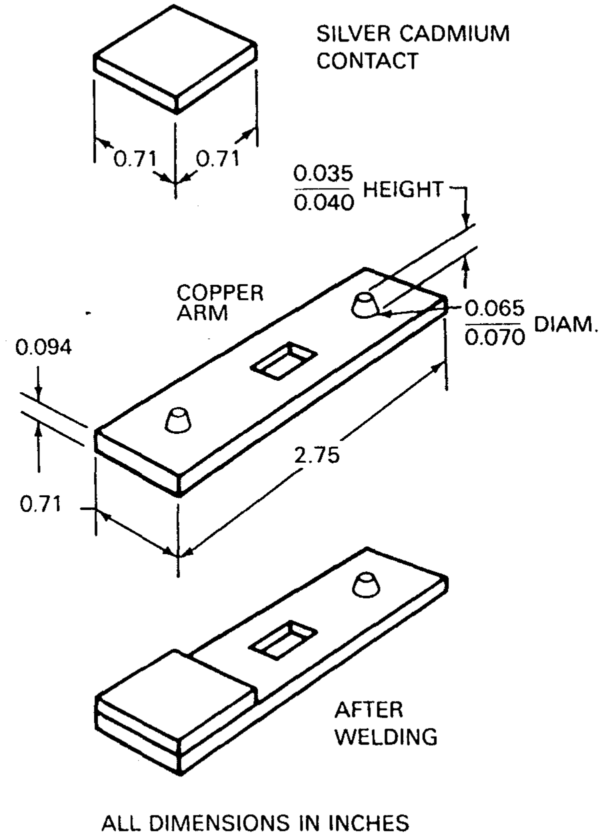

Figure 18.15–Typical Design of a Magnetic Force Percussion Welded Contact Assembly

The arc time is a function of:

(1) Magnitude of magnetic force

(2) Timing of the magnetic force with relation to welding current

(3) Inertia or mass of the moving parts in the force system

(4) Height of the projection

(5) Magnitude of the welding current and the diameter of the projection

Acceleration of the movable head is directly proportional to the magnetic force applied and inversely proportional to the mass. The acceleration of the movable head with the two transformer system can be controlled by adjusting the magnitude of the force current, which thereby provides a duration control for arc time, within limits.

CAPACITOR DISCHARGE PERCUSSION WELDING

Two types of machines are presently used. One uses a high voltage, low capacitance system. Charging voltages range from 1 to 3 kV. With this system, wire end preparation is not critical since the applied potential is sufficient to ionize the air in the gap and start the arc.

The other system uses a low voltage, high capacitance energy source. This has the advantages of a safe working voltage (about 50V), a simple power supply, and low weld spatter. In some designs, the high voltage power is discharged through a transformer of low voltage output.

A low voltage system requires 600V arc starting circuit and special wire end preparation. Once the air gap is ionized with the 600V (low amperage) circuit, the arc is sustained by the 50V circuit. The arc initiation circuit does no appreciable melting.

One type of low voltage machine consists of a hand held gun and a portable power supply. The gun is designed to weld wires to terminals by holding a small flat or square terminal in one set of stationary jaws and the wire to be welded in a set of movable jaws. When the gun is triggered, springs move the wire toward the terminal at a high velocity. A feather edge on the end of the wire greatly improves arc starting. The arc is initiated at the point of contact of the wire and terminal. The welding current melts the feather edge on the wire faster than the wire is moving toward the, terminal. The arc spreads over the wire area and melts a layer about 0.002 to 0.003-in. (0.050 to 0.076 mm) thick in each part. The arc is extinguished after about 150 to 600 microseconds as the two parts come in contact.

Another version of a portable, low voltage welding machine employs a high frequency pulse to initiate the arc. This feature eliminates the need for a special shape on the wire end. The machine uses an electromechanical actuator to accelerate the wire and to provide the necessary forging force. One version of this machine is shown in Figure 18.16.

Low voltage semiautomatic and automatic machines are used to weld assemblies similar to the one shown in Figure 18.17. Component leads are usually tinned annealed copper. Terminals may be brass, tinned brass, or nickel-silver alloys. Wires and leads of 0.006 to 0.102-in. (0.2 to 2.6 mm) diameter can be welded to terminals and plates of various thicknesses above 0.006 in. (0.2 mm) thick.

Controls for capacitor discharge equipment usually include those for welding voltage, capacitance, and high frequency voltage when it is used. Control of the motion mechanism is also provided.

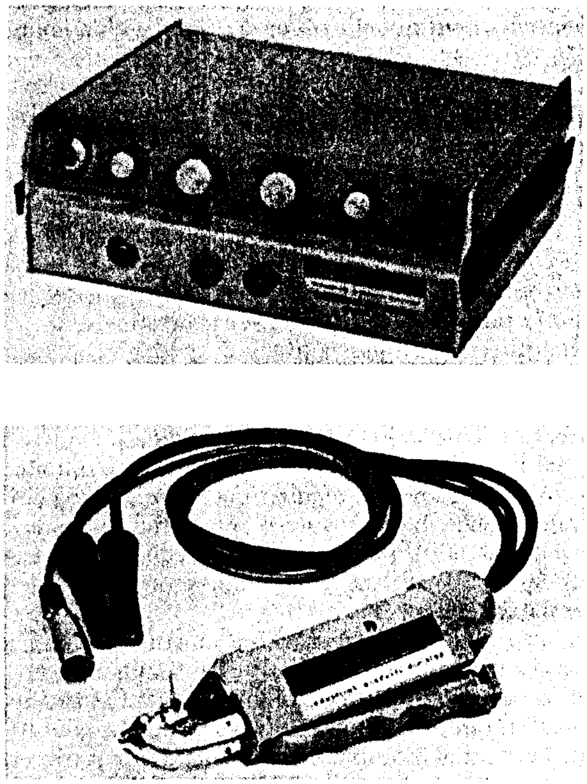

Figure 18.16—A Portable Capacitor Discharge Percussion Welding Power Supply and Hand-Held Gun

WELD QUALITY

THE QUALITY OF percussion welds can be determined by metallographic examination and mechanical tests. Metallographic examination will show the weld interface and the widths of the heat-affected zones. In the case of dissimilar metals, it may reveal the degree of alloying at the interface. Microhardness tests on a metallographic section may indicate the effect of welding on the base metal.

Welded joints may be tested in tension, bending, or shear, depending upon the joint design. The effect of vibration may be important in some applications. The test method should be designed to qualify the welding procedures and weld joint properties for the intended applications.

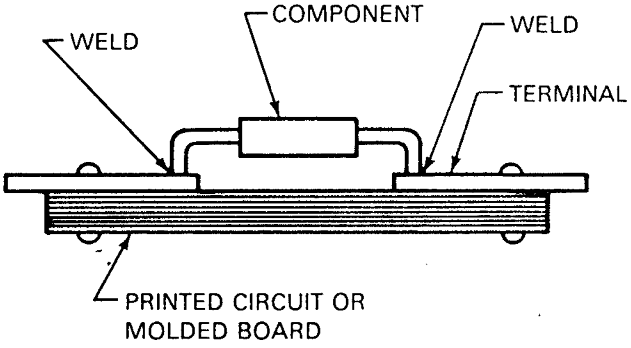

Figure 18.17—A Typical Percussion Welded Electronic Assembly

SAFETY

MECHANICAL

THE WELDING MACHINE should be equipped with appropriate safety devices to prevent injury to the operator's hand or other parts of the body. Initiating devices, such as push buttons or foot switches, should be arranged and guarded to prevent them from being actuated inadvertently.

Machine guards, fixtures, or operating controls should prevent the hands of the operator from entering between the work-holding clamps or the parts to be welded. Dual hand controls, latches, presence-sensing devices, or any similar device may be employed to prevent operation in an unsafe manner.

ELECTRICAL

ALL DOORS AND access panels on machines and controls should be kept locked or interlocked to prevent access by unauthorized personnel. When the equipment utilizes capacitors for energy storage, the interlocks should interrupt the power and discharge all the capacitors through a suitable resistive load when the panel door is open. A manually operated switch or other positive device should also be provided in addition to the mechanical interlock or contacts. Use of this device will assure complete discharge of the capacitors.

A lock out procedure should be followed prior to working with the electrical or hydraulic systems.

SAFETY CONSIDERATIONS FOR PERSONNEL

FLASH GUARDS OF suitable fire resistant material should be provided to protect the operator from sparks and avoid fires. In addition, personal eye protection with suitable shaded lenses should be worn by the operator.

When the welding operations produce high noise levels, operating personnel should be provided with ear protection.

Metal fumes produced during welding operations should be removed by local ventilating systems.

Additional information on safe practices for welding may be found in the American National Standard Z49.1, Safety in Welding and Cutting (latest edition), available from the American Welding Society.

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CHAPTER 19

RESISTANCE WELDING EQUIPMENT

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CHAPTER 19

RESISTANCE WELDING EQUIPMENT

INTRODUCTION

THE SELECTION OF resistance welding equipment is usually determined by the joint design, construction materials, quality requirements, production schedules, and economic considerations. Standard resistance welding machines are designed to meet the requirements of Bulletin No. 16, Resistance Welders Manufacturers Association (RWMA). These machines are capable of welding a wide variety of alloys and component sizes. Specially designed, complex resistance welding equipment may be necessary to meet the economic requirements of mass production or the quality requirements of military specifications.

A resistance welding machine has three principal elements:

(1) An electrical circuit consisting of a welding transformer and a secondary circuit with electrodes that conduct the current to the work

(2) A mechanical system consisting of a machine frame and associated mechanisms to hold the work and apply the welding force

(3) The control equipment to initiate and time the duration of current; it also may control the current magnitude as well as the sequence and the time of other parts of the welding cycle

With respect to electrical operation, resistance welding machines are classified in two basic groups: direct energy and stored energy. Machines in both groups may be designed to operate on either single-phase or three-phase power.

Most resistance welding machines are the single-phase direct energy type. This is the type of machine most commonly used because it is the simplest and least expensive in initial cost, installation, and maintenance. The mechanical systems and secondary circuit designs are essentially the same for all types of welding machines, but transformer designs and control systems can differ considerably.

A single-phase welding machine has a larger volt-ampere (kVA) demand than a three-phase machine of equivalent rating. The demand of a single-phase machine causes unbalance on a three-phase power line. Also, its power factor is relatively low because of the inherent inductive reactance in the welding circuit of the machine. Single phase demand may not be a problem if the welding machine is a small part of the total line load or a number of single-phase welding machines are connected to balance the load on the three phases of the power line.

A three-phase direct energy machine draws power from all three phases of the power line. The inductive reactance of the welding circuit is low because direct current is used for welding. Consequently, the required secondary circuit voltage for a given welding current is reduced; thus the kVA demand of a three-phase machine is lower than that of an equivalent (equal current) single-phase machine. This is a definite advantage where a large capacity machine is needed and power line capacity is limited.

The principle of a stored energy machine is to accumulate and to store electrical energy and then to discharge it to make the weld. The energy is normally stored in a capacitor bank. Single-phase power is generally used for small bench model stored energy machines. The power demand is low because storage time is relatively long in comparison to the weld time.

SPOT AND PROJECTION WELDING MACHINES

ROCKER ARM TYPE

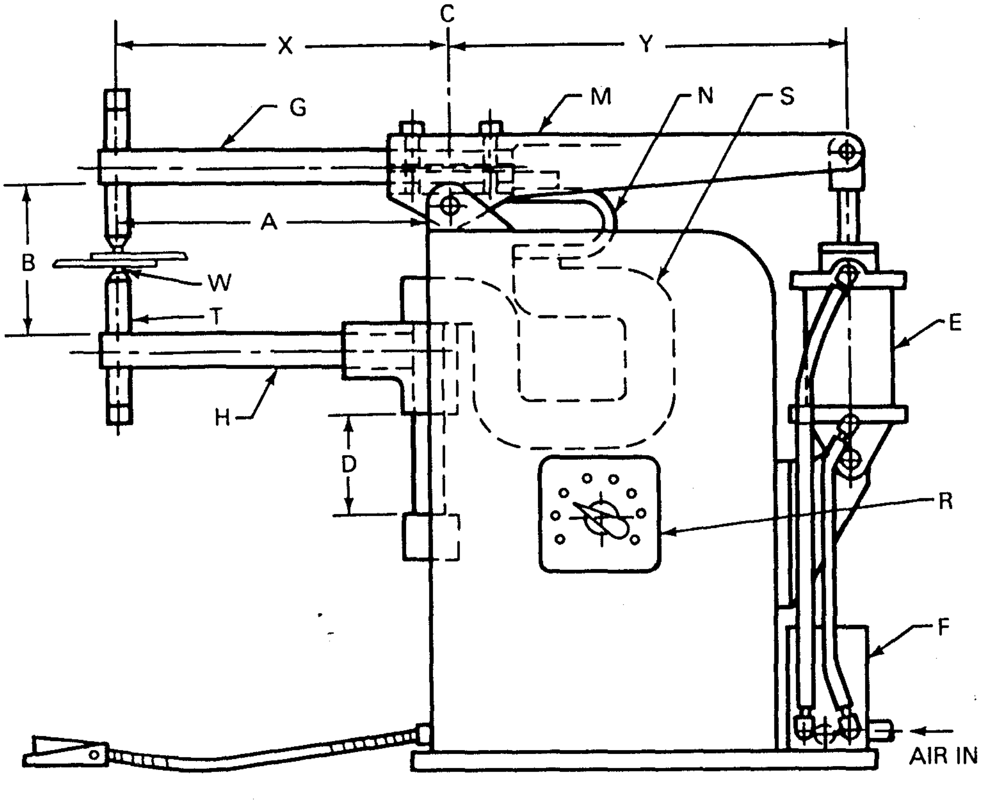
THE SIMPLEST AND most commonly used spot welding machine is the rocker arm design, so called because of the rocker movement of the upper horn. A horn is essentially an arm or extension of an arm of a resistance welding machine which transmits the electrode force and, in most cases, the welding current. This type of machine is readily adaptable for the spot welding of most weldable metals. Three methods of operation are available: (1) air, (2) foot, and (3) motor.

Air-operated machines, such as the one in Figure 19.1, are the most popular. With air operation, the welding cycle is generally controlled automatically with a combination control unit. These machines can operate rapidly and are easily set up for welding.

Foot-operated machines are best suited for miscellaneous sheet metal fabrication, particularly for short production runs where consistent weld quality is not required.

Motor-operated machines are normally used where compressed air is not readily available.

Standard rocker arm machines are generally available with throat depths of 12 to 36 inches and transformer capacities of 5 to 100 kVA. The general construction of these machines is the same with all three types of operation.



A — THROAT DEPTH
B — HORN SPACING
C — CENTERLINE OF ROCKER ARM
D — LOWER ARM ADJUSTMENT
E — AIR CYCLINDER
F — AIR VALVE
G — UPPER HORN
H — LOWER HORN
M — ROCKER ARM
N — SECONDARY FLEXIBLE CONDUCTOR
R — CURRENT REGULATOR (TAP SWITCH)
S — TRANSFORMER SECONDARY
T — ELECTRODE HOLDER
W — ELECTRODE

Figure 19.1–Air-Operated Rocker Arm Spot Welding Machine

Electrode Position

THE TRAVEL PATH of the upper electrode is an arc about the fulcrum of the upper arm. The electrodes must be positioned so that both are in the plane of the horn axes. Also, the two horns should be parallel when the electrodes are in contact with the work. Even with parallel horns, electrode skidding can occur if the electrode holders or horns are not sufficiently rigid. Skidding can be reduced by changing to more rigid electrode holders, adjusting the position of the electrodes, or providing support to the lower horn. Because of the radial motion of the electrode, these machines are not recommended for projection welding.

Mechanical Design

THE MACHINE FRAME houses the transformer and tap switch and supports the mechanical and electrical components.

For air-operated machines, the stroke of the air cylinder must be proportioned to the required electrode spacing. Its diameter must be proportioned to the required electrode and lever arm ratio Y/X, as shown in Figure 19.1. For a given cylinder diameter, the available welding force will decrease as the throat depth is increased, maintaining the original fulcrum point. Electrode spacing can be set by adjusting the position of the electrodes in the horns. In most cases, however, it is desirable to use a double-acting air cylinder with adjustable stroke.

The force exerted by a piston is equal to the product of its surface area and the air pressure applied to that area. Most industrial air systems are operated at 80 psi (550 kPa) minimum, and cylinder size is generally determined on this basis.

Electrode force is the product of the piston force and the lever arm ratio Y/X. Consequently, it is in direct proportion to the air pressure as controlled by a pressure regulator. Air pressures below 20 psi (140 kPa) should not be used because of possible erratic and inconsistent behavior of the air cylinder.

With foot and motor operated machines, the air cylinder is replaced by a stiff spring. The spring is compressed by a foot operated lever arm or a motor-driven cam as it exerts a force on the end of the rocker arm. The amount of force is determined by the stiffness of the spring and the compression distance.

PRESS TYPE

PRESS TYPE MACHINES are recommended for all projection welding operations and many spot welding applications. With this type of machine, the movable welding head travels in a straight line in guide bearings or ways. These bearings must be of sufficient proportions to withstand any eccentric loading on the welding head.

Standard press type welding machines, as defined by the RWMA, are available with capacities of 5 to 500 kVA and throat depths up to 54 inches (Figure 19.2). Nonstandard units, such as magnetic force and bench types, are widely used for the manufacture of radios, instruments, electrical components, and jewelry.

Press type machines are classified according to their use and method of force application. They may be designed for spot welding, projection welding, or both. Force may be applied by air, hydraulic, or electromagnetic systems, or manually when used with small bench units.

A few general guidelines for the selection of a machine of this type are as follows:

(1) Hydraulic operation is not normally used on machines rated below 200 kVA because of the higher cost as compared to air operation. It is also not recommended for use with projection welding because of its slower "follow-up" characteristic compared to that of air. The follow-up of a welding machine is the ability of the force mechanism to react to the dynamic changes that occur during a weld and to maintain the proper clamping pressure.

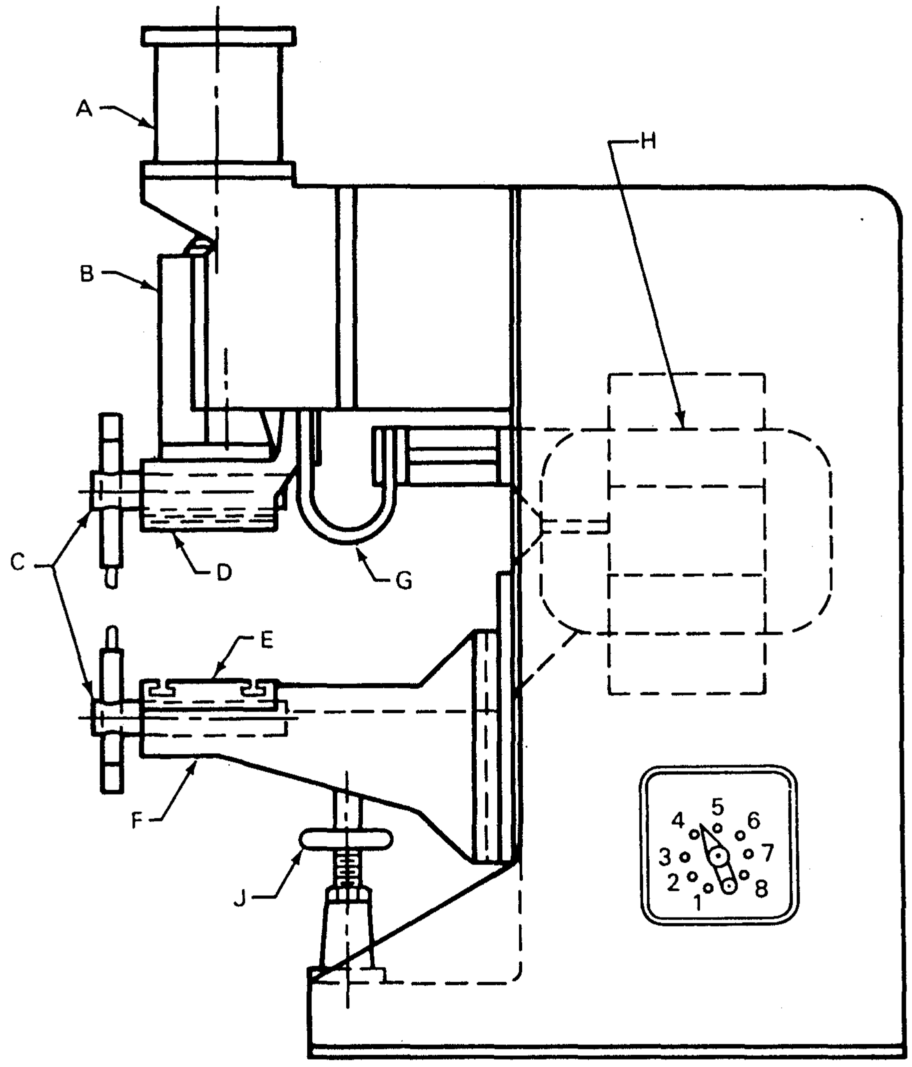
(2) Air operation may be used on all sizes of machines. When high forces are required, however, air cylinders and valves will be quite large, operation will be slow, and air consumption will be high. When all factors are taken into consideration, most machines of 300 kVA and under are air operated, and machines of 500 kVA and above are hydraulically operated. In between, they may be operated by either method.

Frequently a high KVA rating system may be supplied to meet a high duty cycle requirement and not a high KVA demand. These machines can be equipped for air operation.

Fast electrode follow-up is particularly important when spot welding or projection welding relatively thin sections, particularly those of aluminum and other nonferrous metals. Air operation provides much faster follow-up than does hydraulic operation because of the compressibility of air. With hydraulic operation, follow-up must occur by liquid motion and is therefore determined by the capacity of the pump. A pre-charged air accumulator, commonly referred to as a surge tank, is sometimes used with the system to further improve the air operated follow-up system.

Fast follow-up on large machines (even air operated machines) is often achieved with the use of a spring system mounted below the guiding arrangement for the ram. This spring system allows the upper electrode to follow-up the weld independent of the inertia of the ram. Also, bellows-type air systems are used in conjunction with precision timers and dumping valves that allow the ram to follow-up independent of the friction and air limitations of the air cylinder. While the bellows system is costly, it has the advantage of using the precision guidance of the ram system, and this is especially important when welding multiple projections.

When welding precious or dissimilar metals, the synchronization of heat and pressure must be precise and con-



A — AIR OR HYDRAULIC CYLINDER
B — RAM
C — SPOT WELDING ATTACHMENT
D — UPPER PLATEN
E — LOWER PLATEN
F — KNEE
G — FLEXIBLE CONDUCTOR
H — TRANSFORMER SECONDARY
J — KNEE SUPPORT

Figure 19.2–Press Type Combination Spot and Projection Welding Machine

sistent. One answer is to use an electromagnetic force system assisted by a smaller air cylinder. This combination provides a workable system for precisely controlling the exact time when force is applied to the work.

The magnetic force builds up in synchronization with the weld current. This force, combined with the initial clamping force, assures that when maximum heating occurs there will be proper follow-up of the welder head. As the current decays towards zero, the magnetic force also decreases and in the end, the weld is held by the clamping force. The magnetic force builds to a peak on both the positive and negative half cycles of current.

GENERAL CONSTRUCTION

STANDARD PRESS TYPE welding machines are designed and built on the *unit principle* for economy in manufacture. The same frame size is used with two or three transformers of different kVA ratings and with a range of throat depths. A typical press type welding machine is shown in Figure 19.2.

Projection welding machines have platens on which dies, fixtures, and other tooling are mounted. In most cases, the platens are a direct part of the secondary circuit. The platens have flat surfaces and usually have standard T-slots on which to bolt attachments.

Machines designed for spot welding are equipped with horns and electrode holders. A combination unit will have both platens and horns. Such a machine will have one throat depth as a projection welding machine and a greater throat depth as a spot welding machine. The platens, the ram, and the force cylinder are all on the same center line. The distance from this center line to the face of the secondary plate is the depth of the projection welding throat. On standard machines with horns, the spot welding electrodes are located six inches or more from the face. This is true whether or not platens are used.

On projection and combination machines, the lower platen is mounted to, or may be a part of, a knee which can be adjusted vertically. The knee may be made of copper, bronze, steel, or cast iron.

MECHANICAL DESIGN

Air Operated Machines

THESE MACHINES ARE usually the direct acting type where the electrode force is exerted by the air cylinder through the ram. Four general types of double-acting air cylinders are employed. These are illustrated in Figure 19.3. In all cases, air for the pressure stroke enters at port A and exhausts at port B. For the return stroke, the air enters at Port B and exhausts at port A.

Figure 19.3A shows a fixed-stroke cylinder with stroke adjustment. The stroke adjuster K limits the travel of piston P and the electrode opening.

An adjustable-stroke cylinder with a dummy piston is shown in Figure 19.3B. The dummy piston R is attached to the adjusting screw K which positions this piston. Chamber L is connected to port A through the hollow adjusting screw. The stroke of the force piston P is adjusted by the position of the dummy piston R above it. This cylinder design responds faster than a fixed-stroke cylinder because the volume L above piston P can be made smaller than that of a fixed-stroke cylinder of the same size.

The adjustable-stroke cylinder can be modified to provide a retraction feature. This feature can accommodate additional electrode opening for loading and unloading the machine, or for electrode maintenance. See Figure 19.3C. With the adjustable-retractable stroke cylinder, a third port C is connected to chamber H above the dummy piston R. If air is admitted to chamber H at a pressure slightly higher than the operating pressure in chamber L, piston R will move down to a position determined by the adjustable stop X. This determines the UP position for piston P and the electrode opening for welding. When the air from chamber H is exhausted to atmosphere, piston P will lift piston R with it until stop X contacts the cylinder head. This will increase the electrode opening for loading and unloading the machine. Readmission of air to chamber H will return pistons P and R to welding position when the pressure in chamber H is slightly higher than that in chamber M. Flow control valves or cushions are usually used to control the operating speed of an air cylinder.

Figure 19.3D shows a diaphragm type cylinder. In this design, separate cylinders are used to retract the entire cylinder and ram to allow work piece loading. The deflection of the diaphragm by the pressure differential on either side of it provides the electrode movement. This system responds very rapidly due to its inherent low friction and inertia, providing fast follow-up of the electrodes as the weld nugget is formed. Dual electrode force is easily attained by alternately pressurizing and depressurizing chamber B while chamber A is held at a constant pressure.

Hydraulic Machines

WITH THESE MACHINES, a hydraulic cylinder is used in place of an air cylinder. The designs for hydraulic cylinders are similar to those for air-operated cylinders. Refer to Figure 19.3. Hydraulic cylinders are generally smaller in diameter than air cylinders because higher pressures can be developed with a liquid system.

In the simplest type of hydraulic system, a constant speed motor drives a constant pressure, constant delivery pump. The output pressure of the pump is controlled by an adjustable relief valve. Liquid delivery is controlled with a four-way valve of design similar to that employed in an air system. Auxiliary devices include a sump, a filter, a heat exchanger, a gauge, and sometimes an accumulator.

Portable Type

A TYPICAL PORTABLE spot welding machine consists of four basic components:

(1) A portable welding gun or tool
(2) A welding transformer and, in some cases, a rectifier
(3) An electrical contactor and sequence timer
(4) A cable and hose unit to carry power and cooling water between the transformer and welding gun

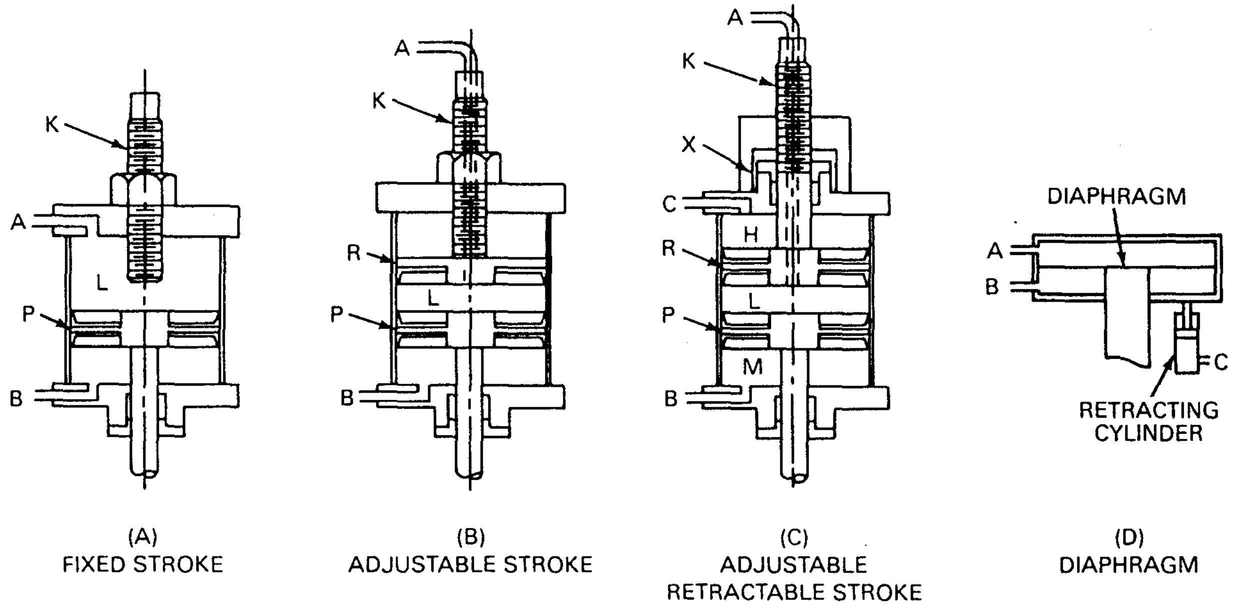


Figure 19.3–Typical Air Cylinder Designs for Air-Operated Press Type Welding Machines

A typical portable welding gun consists of a frame, an air or hydraulic actuating cylinder, hand grips, and an initiating switch. The unit may be suspended from an adjustable balancing unit.

There are two basic types of air or hydraulically operated guns. One is the scissor type which is analogous to a rocker arm spot welding machine. The other is a "C" type, so-called because of its shape. This type has action similar to a press type spot welding machine.

The design of a gun is influenced by the electrode force required. To minimize the size and weight of a gun, a hydraulic cylinder is commonly used to provide forces greater than 750 pounds. However, air cylinders supplying up to 1500 pounds are sometimes used for simplicity of equipment.

Transformers for portable guns should produce open-circuit secondary voltages that are two to four times greater than those of transformers for stationary machines. The higher voltages are needed because of the cable added between the transformer and the gun. The introduction of this cable into the secondary circuit has three fundamental effects:

(1) It increases the total impedance on an ac or frequency converter control. Therefore, considerably higher secondary voltage is required in a gun welder to produce a given secondary current than is required on a stationary type welder.

(2) It increases the resistance component of the impedance so that the power factor is much higher than in a stationary type welder. On a dc machine, the increased resistance lowers the available current unless voltage is proportionately increased.

(3) It minimizes the effect of the impedance in the weld pieces upon both the current output of the welder and the power factor of the load. For power calculations, maximum welding amperes, kVA demand, and power factor may be assumed to be the same as their short circuit values.

Another type of gun currently in use is called a transgun. Transguns have transformers mounted directly to a self-equalizing force system and offer several advantages. They are significantly more compact than the transformer described previously. They also have power factors that can exceed 85 percent. The work, however, is the primary resistance component of the secondary circuit and must be taken into account when rated short circuit currents are used to size the transformer.

An air-hydraulic booster is a piston device for transforming air pressure into high hydraulic pressure. The pressure increase is proportional to the ratio of the area of the hydraulic piston to the area of the pneumatic piston. The booster provides the necessary hydraulic pressure to the gun cylinder.

A combination control is required to operate a portable gun unit. It consists of a primary contactor and a sequence timer. If an electronic tube contactor is used, the control is usually mounted separately, but as close to the transformer as possible. If the contactor is a solid state device, the compactness of this unit permits mounting the control directly on the transformer.

MULTIPLE SPOT WELDING TYPE

A MULTIPLE SPOT welding machine is a special purpose unit designed to weld a specific assembly. This type of machine should be considered when the production requirements and the number of spot or projection welds on an assembly are so large that welding with a single point machine is uneconomical. The principal advantages of these machines are:

(1) A number of welds can be made at the same time.

(2) Part dimensions and weld locations can be reasonably consistent.

(3) The equipment can be very reliable and easy to maintain.

Welding Station Design

MULTIPLE SPOT WELDING machines have a number of transformers, usually of dual secondary design. Figure 19.4 shows typical standardized components that are used in designing a wide range of multiple spot welding machines. Force is applied directly to the electrode through a holder by an air or hydraulic cylinder.

To make welds on close centers, the cylinder diameter must be small. This can be accomplished with tandem or triple pistons on the same shaft. A 2 in. (51 mm) diameter triple piston cylinder can develop 500 pounds of force (2224 N) at 60 psi (414 KPa). This force is adequate for spot welding two 0.030 in. (0.76 mm) thicknesses of cold rolled steel. Closer spot weld spacing may be obtained by using hydraulic cylinders of smaller diameter. Another

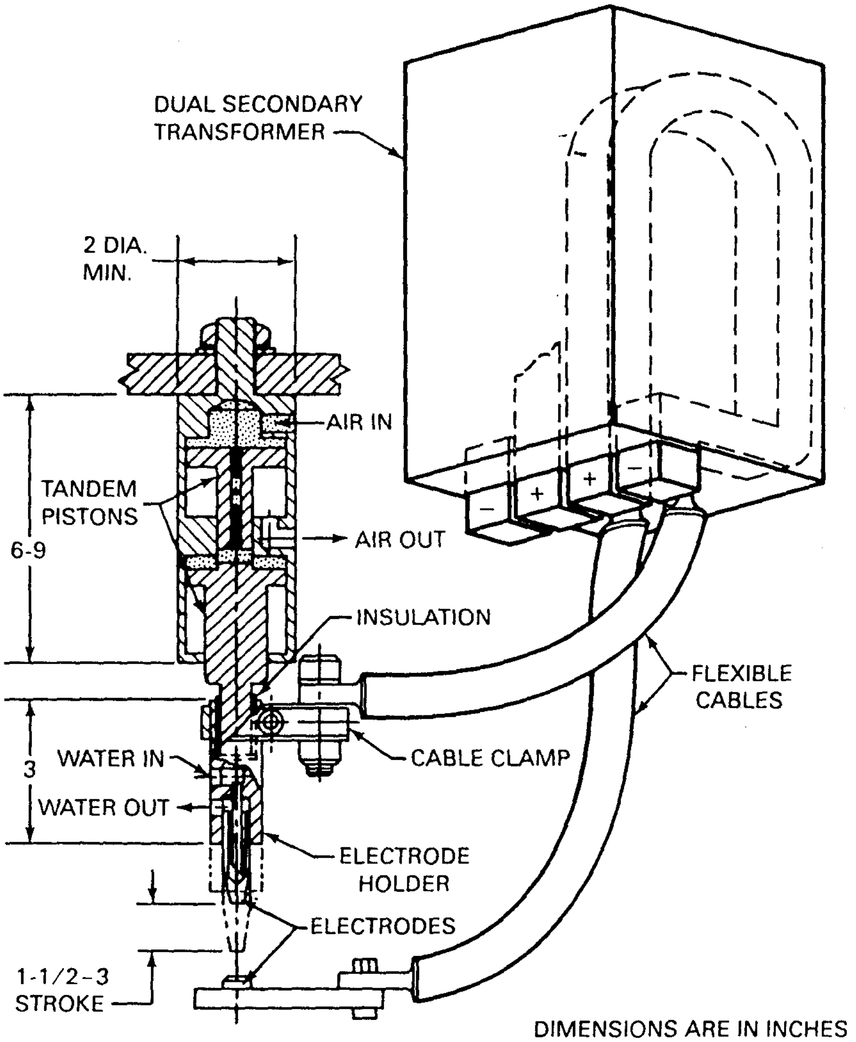


Figure 19.4–Basic Components of a Multiple Spot Welding System

method, generally of last resort, is to use offset electrodes. This does, however, induce eccentric loading on the cylinder. When this type of electrode is used, the stroke of the cylinder should be kept to a minimum. The combination cylinder and electrode holder assemblies are commonly referred to as welding guns.

A welding transformer with two insulated secondaries can power two separate welding circuits, though there can be no individual current control of each circuit. There can also be significant variance in the output of each secondary, even when great care is taken to provide duplicate secondary loops. When critical welding must be accomplished, it is recommended that separate transformers be used for each circuit.

The dual-secondary type of transformer is noted for its compact design and narrow width. If desired, only one of the dual secondaries need be used at one time. For higher secondary voltage, the two secondaries can be connected in series to feed one secondary circuit. To increase the welding current available to a single circuit, the secondaries can be connected in parallel. Welding guns and transformer units of this type can be designed to spot weld two sheets of cold rolled carbon steel up to 0.125 in. (3.2 mm) thick.

For most applications, the lower electrode is a piece of solid copper alloy with one or more electrode alloy inserts that contact the part to be welded. It is normally water cooled to remove heat. The inserts generally are designed with large contact areas to resist wear. Pointed electrodes are not normally used against the "show" side of the work to avoid marking.

Self-equalizing gun designs are often used where standard electrodes are needed on both sides of the weld to obtain good heat balance, or where variations in parts will not permit consistent contact with a large, solid lower electrode. The same basic welding gun is used for these designs but it is mounted on a special "C" frame similar to that for a portable spot welding gun. The entire assembly can move as electrode force is applied at the weld locations.

Machine Designs

MULTIPLE TRANSFORMER MACHINES are used extensively in the manufacture of formed sheet metal products. Because of their broad usage and requirements, many designs of multiple transformer machines are available. The machines may be designed as welding stations in large, high production, automated assembly lines, or they may be used independently. Independent machines may be loaded and unloaded either manually or automatically. They are commonly interfaced with robots for both welding and material handling purposes.

In many instances, a single weld control can be used to initiate all of the weld sequences. In such a case, up to six separate primary contactors are signaled in series fashion; i.e., each is fired after the previous one has completed its full weld sequence. This type of firing sequence is referred to as cascade firing. Some of these controls also have the ability to serve as PLCs (Programmable Logic Control) but are generally limited to small applications.

There are several advantages to using this type of weld control. The primary advantage is the economic saving of purchasing a single control. Also, a single unit control aids in machine maintenance and trouble shooting. There is, however, the disadvantage of lost cycle time waiting for completion of each weld.

In designing the machine for a particular weldment, a number of factors must be considered. These include:

(1) Shape, size, and complexity of the part
(2) Consistency of the parts being joined
(3) Part composition and thickness
(4) Required weld appearance
(5) Production rate requirements
(6) Available equipment (presses, frames, and dial tables)
(7) Changeover time for different assemblies
(8) Economic factors including initial cost, labor to operate, and maintenance.

ROLL SPOT AND SEAM WELDING MACHINES

A ROLL SPOT or seam welding machine is similar in principle to a spot welding machine, except that wheel-shaped electrodes are substituted for the electrode tips used in spot welding. Both roll spot and seam welding can be performed on the same type of machine.

The essential elements of a standard seam welding machine are as follows:

(1) A main frame that houses the welding transformer and tap switch
(2) A welding head consisting of an air cylinder, a ram, and an upper electrode mounting and drive mechanism
(3) The lower electrode mounting and drive mechanism, if used
(4) The secondary circuit connections
(5) Electronic controls and contactor
(6) Wheel electrodes
(7) Wheel bearings — current carrying type

The main frame, tap switch, ram, and air cylinder are essentially the same as those of a standard press type spot or projection welding machine. The transformer is normally heavier duty, due to the continuous nature of seam welding versus spot welding. Hydraulic cylinders are seldom used on seam welding machines because the electrode force requirements are not usually high.

To provide for electrode wear, either an adjustable connection is used between the ram and the piston rod or an adjustable-stroke air cylinder is employed. In addition, the position of the lower electrode and its mounting arrangement are sometimes adjustable. This adjustment is used to position the work at a proper height for convenient operation.

Most seam welding of thin gages is done using continuous drive systems. With thick gages, intermittent drive systems must be used to maintain electrode force on the weld nugget as it solidifies. The thickness range that can be welded with each drive system will depend upon the metal being joined.

The majority of continuous drive mechanisms use a constant speed, ac electric motor with a variable speed drive. The speed range depends upon the drive design and the electrode diameter. Good flexibility may also be obtained with a constant torque, variable speed dc drive.

TYPES

THERE ARE THREE general types of seam welding machines:

(1) Circular, where the axis of rotation of each electrode is perpendicular to the front of the machine; this type is used for long seams in flat work and for circumferential welds, such as welding the heads into containers; such a machine is shown in Figure 19.5

(2) Longitudinal, where the axes of rotation of the electrodes are parallel to the front of the machine; this type is used for such applications as the welding of side seams in cylindrical containers and short seams in flat work

(3) Universal, where the electrodes may be set in either the circular or longitudinal position; this is accomplished with a swivel type upper head in which the electrode and its bearing can be rotated 90 degrees about a vertical axis; two interchangeable lower arms are used, one for circular operation and the other for longitudinal operation

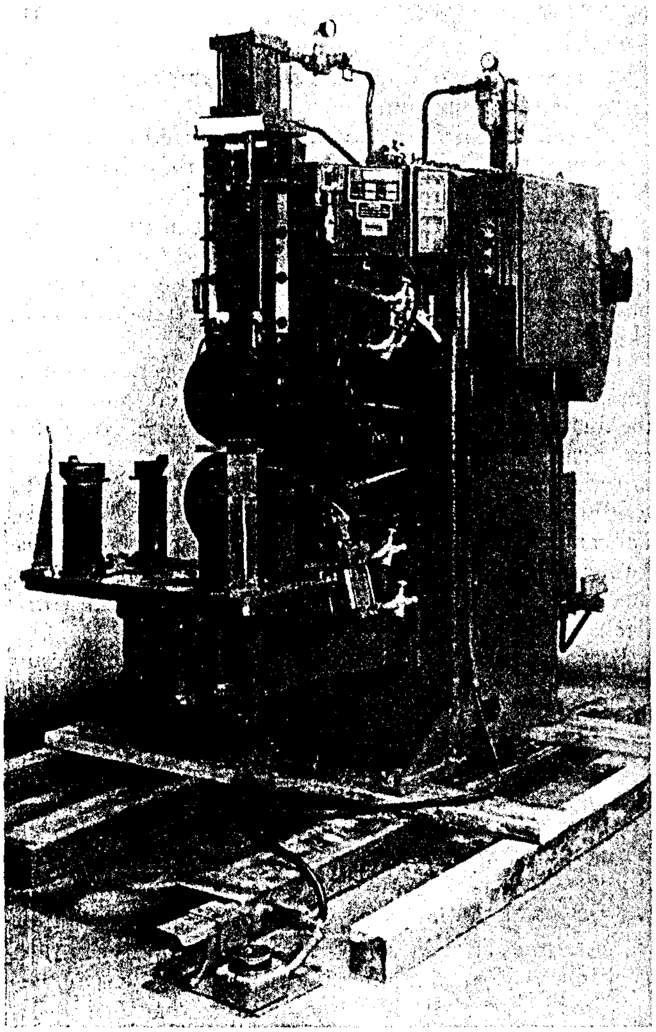


Figure 19.5–A Standard Circular Seam Welding Machine with a Special Fixture

ELECTRODE DRIVE MECHANISMS

Knurl or Friction Roller

THE KNURL OR friction roller drive has either the upper or the lower electrode, or both, driven by a friction wheel on the periphery of the electrode. When these friction rolls have knurled teeth, they are known as knurls or knurl drives. Knurl or friction roller drive will maintain a constant welding speed as the electrode diameter decreases from wear.

A knurl drive is commonly used on machines for seam welding galvanized steel, terne plate, scaly stock, or other materials where the electrodes are likely to pick up surface material from the parts being welded. The knurl drive wheel tends to break up the material on the electrode face. Where the nature of the work permits, both electrodes should be knurl-driven to provide a more positive drive and lessen the possibility of skidding.

A knurl drive may also function to control the shape of the contact face of the wheel electrode. This can be accomplished by using knurlers designed with a radius in the wheel contact area, or by using a flat knurler designed with side cutters that constantly trim the wheel contact face to a specific width.

Gear Drive

WITH THIS METHOD, the electrode shaft is driven by a gear train powered by a variable speed drive. Only one electrode should be driven to avoid skidding. Otherwise, a differential gear box is necessary. This type of drive is generally less desirable than a knurl drive because the welding speed decreases as the electrode wears. This can be overcome by gradually increasing the drive speed.

The most important applications for a gear-driven machine are the welding of aluminum and magnesium and the fabrication of small diameter containers. Standard seam welding machines are designed with some minimum distance between electrode centers for each machine size. If one of the electrodes must be small to fit inside a container, the other must be correspondingly larger to maintain the required center distance. If the ratio of the two electrode diameters exceeds about 2 to 1, the smaller electrode should be driven and the large one should idle to minimize electrode skidding.

SPECIAL PURPOSE MACHINES

SPECIAL PURPOSE MACHINES are available for specific applications. Such machines can be generally grouped as traveling electrode type, traveling fixture type, and portable seam welding machines.

Traveling Electrode Type

WITH THIS TYPE of machine, the seam to be welded is clamped or otherwise positioned on a fixed mandrel or shoe of some type and the ram and wheel electrode are moved along the seam. The mandrel or shoe is the lower electrode. The ram and electrode are moved by an air or hydraulic cylinder or by a motor-driven screw. Sometimes two upper electrodes operating in series are used side by side or in tandem. Figure 19.6 shows a typical traveling electrode machine.

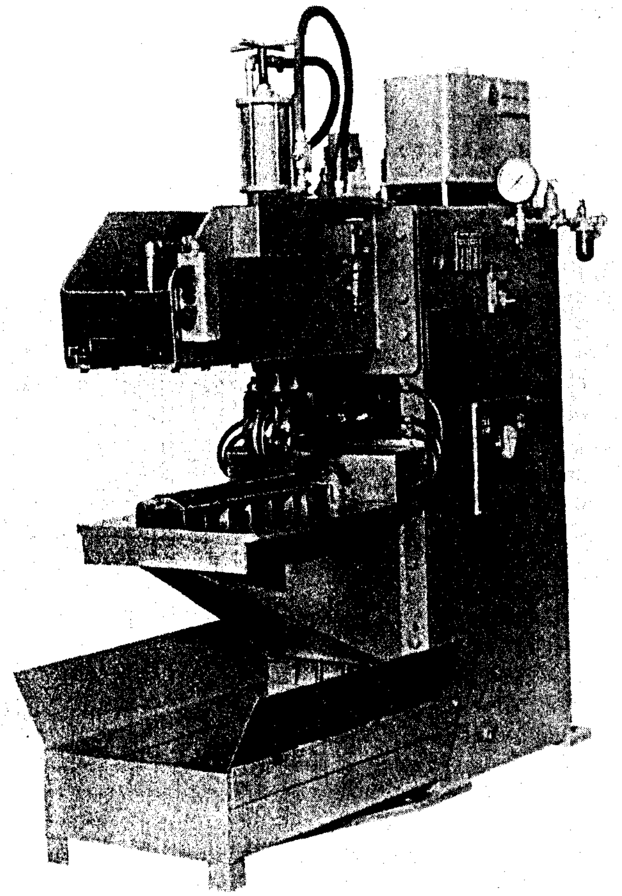


Figure 19.6–Traveling Electrode Seam Welding Machine

Traveling Fixture Type

IN THE TRAVELING fixture type, the upper electrode remains in a fixed position. The fixture and work are moved under the electrode by a suitable driving system. Multiple electrodes can also be used to advantage with this type of machine, such as the one shown in Figure 19.7.

Portable Type

PORTABLE SEAM WELDING guns may be used for work that is too large and bulky to be fed through a standard machine. The gun consists of a pair of motor-driven wheel electrodes and bearings, together with an air cylinder and associated mechanism for applying the electrode force. Welding current is supplied in the same manner as for portable spot welding. A variable speed dc drive may be used where a wide range of welding speeds is desirable. The motor and speed reducer are mounted directly on the welding gun frame.

COOLING

ONE REQUIREMENT IN seam welding is the proper cooling of the machine, the electrodes, the current-carrying bearings, and other components of the secondary circuit. Temperature rise in these components causes an increase in electrical resistance in the secondary circuit. This results in lower welding current. Therefore, proper cooling is necessary to maintain control of the resistance and current in the secondary circuit. Cooling the work is also important in most applications to minimize warpage from the local heating. Water jets spraying on both the work and the welding electrodes are usually satisfactory. Welding under water may be done in special cases.

Another method of cooling the weldment is a water mist that removes heat by evaporation. A mist is produced by mixing air and water in proper proportions in a nozzle.

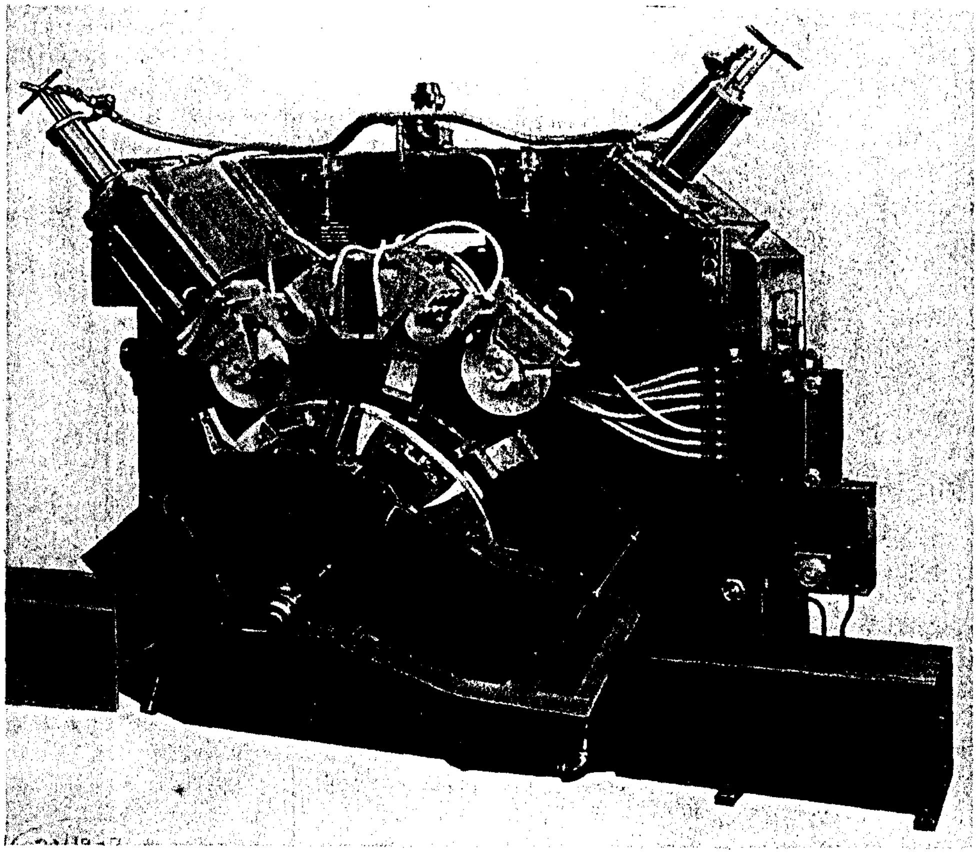


Figure 19.7—Traveling Fixture Seam Welding Machine with Two Electrodes in Tandem

FLASH AND UPSET WELDING MACHINES

FLASH AND UPSET welding machines are similar in construction. The major difference is the motion of the movable platen during welding and the mechanisms used to impart the motion. Flash welding is generally preferred for joining components of equal cross section end-to-end. Upset welding is normally used to weld wire, rod, or bar of small cross section and to continuously join the seam in pipe or tubing. Flash welding machines usually have a much larger capacity than upset welding machines.

FLASH WELDING MACHINES

General Construction

A STANDARD FLASH welding machine consists of a main frame, a stationary platen, a movable platen, clamping mechanisms and fixtures, a transformer, a tap switch, electrical controls, and a flashing and upsetting mechanism. The stationary platen is generally fixed in position, although some designs provide a limited amount of adjustment for electrode and work alignment. The movable platen is mounted on ways on the frame and connected to the flashing and upsetting mechanism. Both platens are usually of cast or fabricated steel, although some small welding machines may have cast bronze, cast iron, or copper platens. The platens are connected to the transformer secondary. Electrodes that hold the parts and conduct the welding current to them are mounted on the platens. The transformer and tap switch are generally located within or immediately behind the frame with short, heavy-duty copper leads to the platens.

The depth of the frame and, consequently, the width of the platens depend upon the size of the parts to be welded as well as the clamping mechanism design. Upsetting force should be aligned as nearly as possible with the geometric center of the parts to minimize machine deflection. Dual flashing and upsetting cylinders or cams are sometimes used with wide platens to provide uniform loading or clearance for long pieces to extend over the mechanism.

Transformer and Controls

A FLASH WELDING transformer is essentially the same as those used for other types of single-phase resistance welding machines. A tap switch in the primary circuit is normally used to adjust flashing voltage. An autotransformer is sometimes used to extend the adjustment range of the secondary voltage. The primary power to the transformer is switched with an electronic contactor. Phase-shift heat control may be initiated with the contactor to provide low power for preheating or postweld heat treating in the machine.

Phase shift heat control should never be used to control the secondary voltage during flashing; only voltage tap selection should be used for adjusting the voltage during flashing. If heat control is used during flashing, there are periods of time when no secondary voltage is present, followed by an instantaneous voltage which can be quite high. The result can be deep cratering and entrapped oxides in the weld zone.

With ignitron contactors, auxiliary load resistors must be connected in parallel with the transformer primary for proper operation of the ignitrons.

Programming of secondary current for preheating prior to flashing and postheating of the completed weld in the machine can be done with appropriate controls.

Flashing and Upsetting Mechanisms

IN THE OPERATION of a flash welding machine, the parts are moved together using a predetermined travel pattern. This movement must be carefully controlled to produce consistently sound welds. After the appropriate flashing time, the pieces are rapidly brought into contact and upset. The upsetting action must be accurately synchronized with the termination of flashing.

The type of mechanism used for flashing and upsetting will depend upon the size of the welding machine and the application requirements. Some mechanisms permit the faying surfaces to be butted together under pressure and then preheated. After the appropriate temperature is reached, the pieces are separated and then the flashing and upsetting sequence is initiated. The movable platen may be actuated with a motor-driven cam or with an air or hydraulic cylinder.

Motor-operated machines use an ac or dc motor with a variable speed drive, which in turn drives a rotary- or wedge-shaped cam. The cam is designed to produce a specific flashing pattern. It may contain an insert block to upset the joint at the end of flashing. The speed of the cam determines the flashing time. The platen may be moved directly by the cam or through a lever system. The motor may operate intermittently for each welding cycle or continuously. With continuous operation, the drive is engaged through a clutch on the output shaft of the speed reducer. The motor speed may be electronically controlled to produce a specific flashing pattern. A typical motor-operated flash welding machine is shown in Figure 19.8.

A motor-driven flashing cam may be used in combination with an air or hydraulic upsetting mechanism, particularly on larger machines. Such a combination provides adjustment of upset speed, distance, and force independently of the flashing pattern. Current is synchronized with the mechanical motion of the platen by limit switches or electronic sequence controls.

Medium and large flash welding machines use hydraulically operated flashing and upsetting mechanisms. These machines are capable of applying high upsetting forces for large sections. They are accurate in operation and are readily set up for a wide range of work requirements. A large hydraulic flash welding machine is shown in Figure 19.9. A servo system is used to control the platen motion for flashing and upsetting. The servo system may be actuated by a pilot cam mechanism, or by an electrical signal generated from the secondary voltage or the primary current. Choice of operating mode depends upon the application. The control may be programmed to include preheating and postheating. An accumulator is generally required to provide an adequate volume of hydraulic fluid from the pumping unit during upsetting.

Electro-hydraulic servo systems are generally of two designs. In one design, the servo valve meters the fluid directly to the hydraulic cylinder for position control. With the other design, the servo valve meters the fluid to a small control cylinder that operates a follower valve on a separate hydraulic system. The first design is simple and straightforward, but the second system has two distinct advantages. First, it has two separate hydraulic circuits for improved valve life. Second, the speed of response is fast, and control of the platen position is accurate.

Clamping Mechanisms and Fixtures

SEVERAL DESIGNS OF clamping mechanisms are available to accommodate different types of parts. These designs may be grouped generally as operating in either the vertical or the horizontal position. In special cases, the mechanisms may be mounted in other positions.

Vertical Clamping. The movement of the electrode may be in a plane perpendicular to the platen ways. The electrode may move either through a slight arc or in a straight line. If operating through an arc, a clamping arm pivots about a trunnion. This design is generally known as the "alligator" type. A machine with this type of clamping arrangement is shown in Figure 19.10. Clamping force may be applied by an air or hydraulic cylinder operating directly

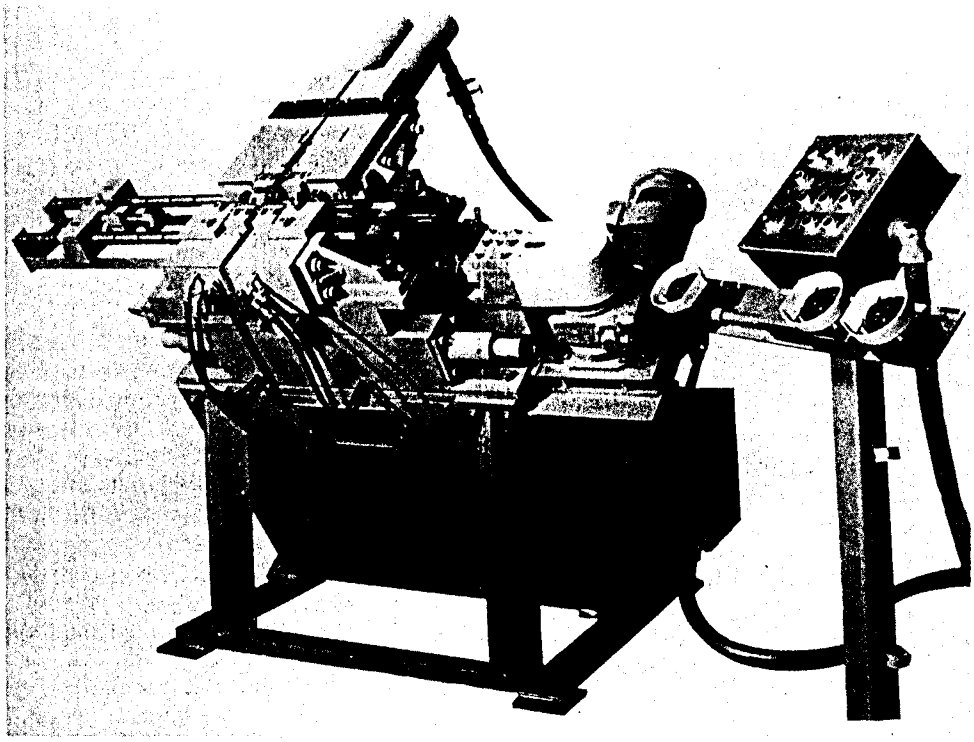


Figure 19.8–Automatic Motor-Operated Flash Welding Machine

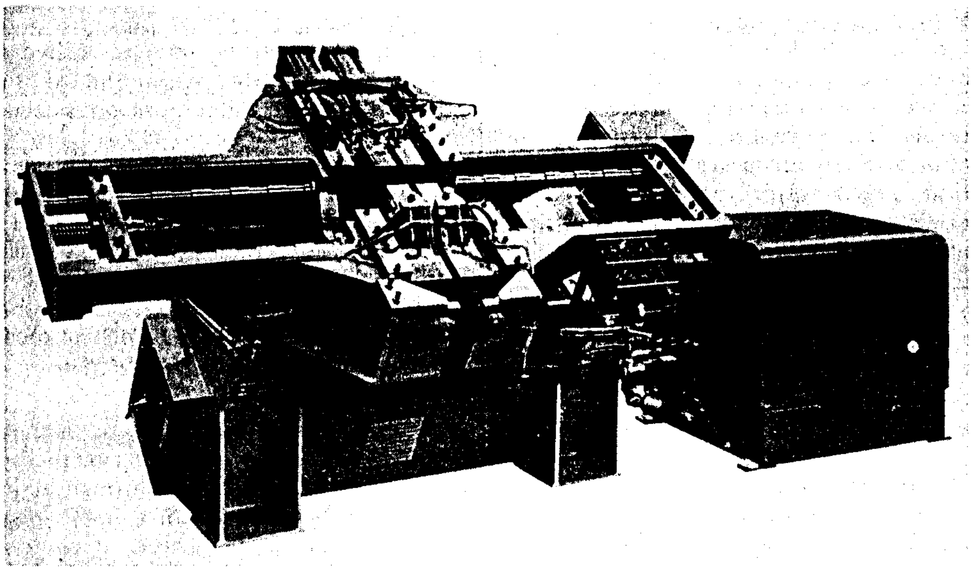


Figure 19.9–Automatic Hydraulically Operated Flash Welding Machine with Horizontal Clamping

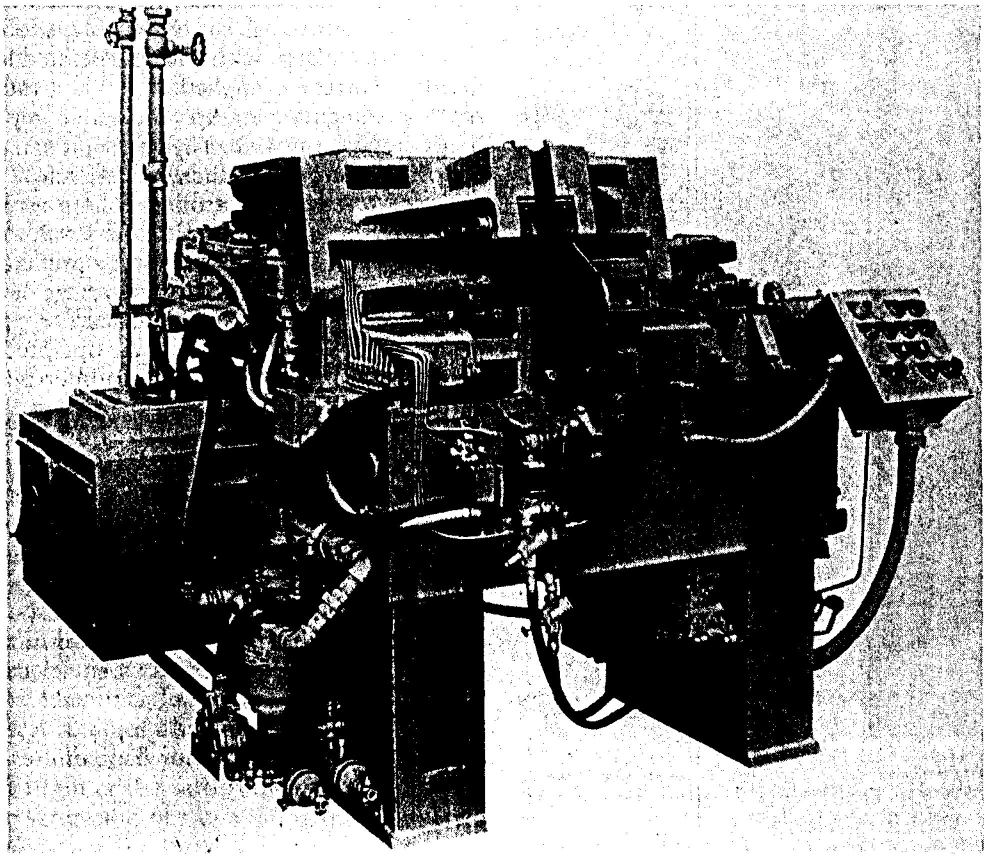


Figure 19.10–An Automatic Flash Welding Machine with Vertical Alligator Type Clamping

or through a leverage or cam-operated mechanism. Vertical clamping is commonly used for bar stock and other compact sections.

Horizontal Clamping. With this design, the motion of the electrodes is parallel to the platen ways and generally in a straight line, as shown in Figure 19.9. The major advantage of this type of clamping mechanism is that the secondary of the welding transformer can be connected to both halves of the electrodes for uniform transfer of welding current into the work. This arrangement is highly desirable for welding parts with large cross sections. Clamping force can be applied with one of the mechanisms described for vertical clamping.

Fixtures. Fixtures may be used to support and align the parts for welding as well as to back up the parts to prevent slippage of the electrodes during upsetting. They are usually adjustable to accommodate the geometry and length of the parts. The design must be sturdy to withstand the upsetting force without deflecting. When the parts can be supported, the clamping force on the electrodes can be limited to that needed to ensure good electrical contact and maintain satisfactory joint alignment.

UPSET WELDING MACHINES

UPSET WELDING MACHINES are quite similar to flash welding machines in principle, except that no flashing mechanism is required. A typical upset welding machine, such as the one in Figure 19.11, consists of a main frame that houses a transformer and tap switch, electrodes to hold the parts and conduct the welding current, and means to upset the joint. A primary contactor is used to control welding current.

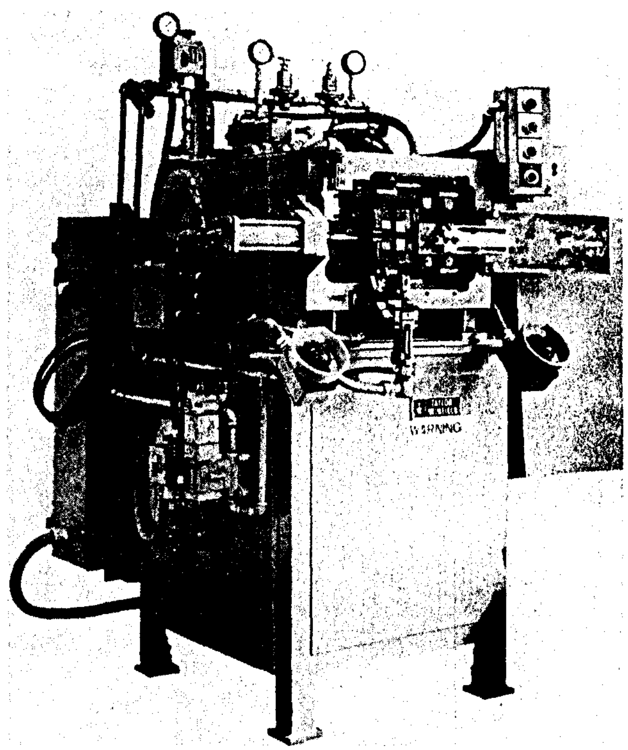


Figure 19.11–An Air-Operated Automatic Upset Welding Machine

The simplest type of upset welding machine is manually operated. In this machine, the pieces to be welded are clamped in position in the electrodes. A force is exerted on the movable platen with a hand-operated leverage system. Welding current is applied, and when the abutting parts reach welding temperature, they are compressed together to accomplish the weld. The current is manually shut off at the proper time during the welding cycle. The work is then removed from the electrodes. A limit switch or a timing device may be used to terminate the welding current automatically after the weld has upset a predetermined length.

Automatic machines may use springs or air cylinders to provide upset force. Either device can provide uniform force consistently. Spring or air-operated machines are particularly adapted for welding nonferrous metals having narrow plastic ranges.

There are three standard sizes of upset welding machines, rated at 2, 5, and 10 kVA. Normal upset forces are 12, 70, and 120 lb, respectively. Larger units are also available.

Upset welding is used extensively for welding of small wires, rods, and tubes in the manufacture of items such as chain links, refrigerator and stove racks, automotive seat frames, and for joining coils of wire for further processing. The upset welding process is often selected for applications where the upset is not objectionable in the context of the design. It is best adapted for joints between parts with relatively small cross section where uniformity of welding current is not a problem.

RESISTANCE WELDING CONTROLS

THE PRINCIPAL FUNCTIONS of resistance welding controls are to (1) provide signals to control machine actions, (2) start and stop the current to the welding transformer, and (3) control the magnitude of the current. There are three general groups of controls: timing and sequencing controls, welding contactors, and auxiliary controls.

TIMING AND SEQUENCE CONTROLS

Sequence Weld Timers

A SEQUENCE WELD timer is a device to control the sequence and duration of the elements of a complete resistance welding cycle. It may also control other mechanical movements of the machine such as driving or indexing mechanisms. Sequence weld timers are used on spot, seam, and projection welding machines.

The four basic steps in any spot, seam, or projection welding cycle are as follows:

(1) Squeeze time
(2) Weld time
(3) Hold time
(4) Off time

Squeeze time is the interval between the initial application of electrode force on the work and the first application of current. Weld time is the duration of welding current with single impulse welding. Hold time is the period during which the electrode force is maintained on the weld after current ceases. Off time is the period during which the electrodes are retracted from the work during repetitive welding. During off time, the work is moved to the next weld location.

A multiple impulse weld timer provides for a number of current pulses with an interval between them. It controls the duration of each pulse, called heat time, as well as the interval between them, or cool time. The sum of the heat and cool times is known as the weld interval.

Timers and combination controls now almost exclusively use synchronous precision phase controls for the welding functions. Non-synchronous controls are obsolete and are now rarely encountered in the workplace.

Single-phase and three-phase resistance welding controls are similar, except for the firing sequence of the electronic switch elements and the techniques of electronic heat control. The timing and control functions are nearly the same, but the terminology used may vary between the two types of equipment.

Synchronous Precision Controls

THIS TYPE OF control uses synchronous precision timers for accurate timing of all periods of current. The timer closes the primary circuit of the welding transformer at precisely the same point (electrical angle) with respect to the ac line voltage. Another distinction of a synchronous precision timer is that accuracy is absolute and equal to the set value. A synchronous precision control always contains an electronic heat control unit.

Control of the exact time when the primary circuit is closed is vital for precise results. This is necessary not only to control the heat obtained, but also because conduction, which does not begin at the same time in each half of a cycle, can cause saturation of the welding transformer.

Classification of Sequence Weld Timers

SEQUENCE WELD TIMERS are classified by the Resistance Welder Manufacturers Association according to the functions they control.

(1) Types 1AS and A1A control the weld time only.

(2) Type 1BS controls heat and cool times for multiple impulse welding operations.

(3) Type A3B covers sequence timers that control squeeze, weld, hold, and off times.

(4) Type A3C is similar to type A3B except that a squeeze delay or initial squeeze time is provided to account for the electrode travel time to contact the work. This type of timer is used for high-speed repetitive welding.

(5) Type A5B, which is also similar to type A3B, is designed for multiple impulse welding applications. This type controls heat, cool, and weld interval times instead of weld time.

(6) Type 7B is a sequence timer used in conjunction with a type 1AS weld timer to control squeeze, weld, hold, and off times.

(7) Type 9B is similar to type 7B except that it is used in conjunction with a type 1BS weld timer.

In the above designations, S indicates a synchronous precision timer, and the prefix A indicates an absolute cycle timer.

Time Mechanisms

SEVERAL TYPES OF timers have been developed to control the duration of various functions during the welding cycle. The availability of inexpensive microprocessors and associated digital circuits has led to their use in most, if not all, of the welding controls now being manufactured. Many older designs used RC (resistor-capacitor) timers for determining intervals.

Digital counters, with or without microprocessor control, provide accurate measurement and control of welding cycles or even parts of cycles (as in heat controls). These counters may be used to time conduction intervals or other actions associated with the welding process.

Some operations, such as postheating of flash or upset welds, are not critical with respect to timing accuracy. Pneumatic or motor-operated timers may be suitable for these applications. Timing ranges may vary from a few seconds to several minutes.

CONTACTORS

A CONTACTOR IS used to close and open the primary power line to the welding transformer. The term *contactor* is actually a misnomer; it is a carry-over from the mechanical (magnetic) contactors which were originally used to control welding transformer conduction in nonsynchronous welding controls. Modern welding controls typically use SCR (silicon controlled rectifier) switch assemblies, made up of a pair of inverse-paralleled devices which act as the switching element or *contactor.* In this arrangement, one SCR conducts during the positive portion of the conduction cycle, and the other during the negative portion. In single-phase equipment, only one set of SCRs is needed in one of the primary lines, as shown in Figure 19.12. With a three-phase frequency converter machine, one set is required in each leg of the transformer for a total of three sets as shown in Figure 19.13.

SCR contactor components are usually assembled in a package resembling a ceramic *hockey puck,* with anode and cathode connections at the faces of the puck and the gate leads exiting through the side of the puck insulator. Water cooled blocks of copper are used on one or on both faces of the pucks, and an insulated tensional bolt and compression springs or washers are used with the copper cooling blocks. SCR switches of this construction are available with continuous current ratings of thousands of amperes and considerably higher current ratings at lower duty cycles. Blocking voltage ratings of 2,500V or more are also available.

Firing of the SCRs is accomplished by applying a current pulse to the gate-cathode junction of the SCR, which is for-

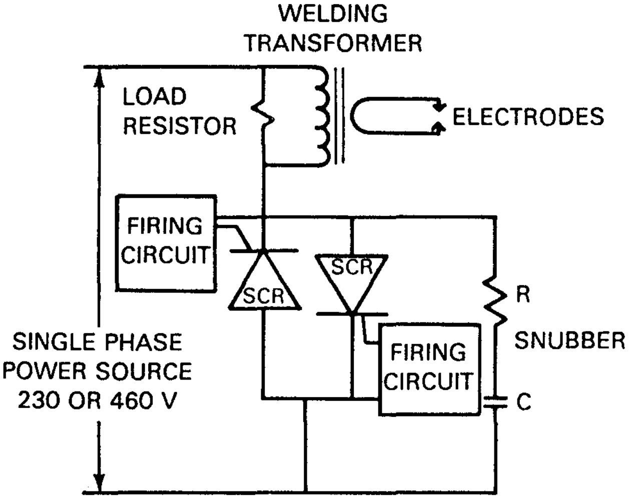


Figure 19.12–Single-Phase Welding Machine with a Pair of SCR Contactors

ward biased at the time that conduction is desired. In single-phase equipment, it is acceptable to fire both SCRs simultaneously, as only the device which is forward biased will conduct. Typically, firing pulses are delivered to the SCRs via pulse transformers which provide voltage isolation for the gating circuitry. The pulses are usually about 1 to 3 amperes in magnitude, with rise times of 1 to 2 microseconds and a total duration of 100 microseconds or less. Because of the low forward voltage drop of an SCR (a few volts), it is possible to control the welding transformer conduction over virtually the entire range of 0 to 100 percent.

SCRs are susceptible to spurious firing by line voltage spikes. They are also susceptible to the rate of rise of the voltage spikes, not just to the spike magnitude. For this reason a series-connected resistor and capacitor (RC) assembly, called a "snubber", is usually connected in parallel with the SCRs. Properly snubbed, SCRs are durable and reliable switches.

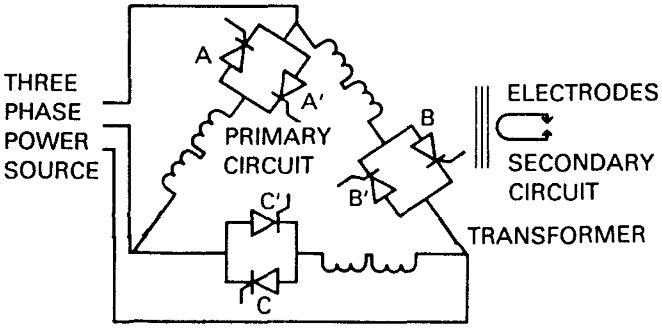


Figure 19.13–Three-Phase Welding Machine with SCR Contactors

Some older control designs use pairs of ignitron tubes triggered either by small SCRs or by thyratron tubes. Although extremely rugged devices, ignitrons have restrictions in mounting orientation because of their internal mercury pools. Also, because of their mercury content, ignitrons pose some personnel hazards. Ignitrons have relatively high holding current levels and forward voltages. As they age, both the minimum holding current levels and forward voltage drops of ignitrons increase. Even when new, ignitrons are not capable of handling the full range of conduction. Typically, their forward voltage drop limits the conduction range available to 20 percent to 100 percent (at 440 or 475V levels).

AUXILIARY CONTROLS

Heat Control

COARSE ADJUSTMENT OF the heat or current output of a welding machine can be accomplished with adjustable taps of the welding transformer. The tap switch changes the ratio of transformer turns for major adjustment of welding current. Precise control is accomplished using electronic heat control.

In electronic heat control circuits, the firing time of the SCRs relative to the start of each half cycle can be delayed to produce the desired heat setting. Referring to Figure 19.14, if the SCR firing pulses are produced 180 degrees out of phase with the ac supply, the SCRs will not conduct and no heat will be produced. As the out-of-phase or delay angle of the firing pulses is decreased, the SCRs begin to fire late in the half cycle and the rms value of the welding transformer primary voltage will be low. As the delay angle is further decreased, the SCRs will fire earlier, and will conduct current for a greater part of the half cycle. The rms current will increase. When the delay angle equals the power factor of the load, 100 percent rms primary current will be conducted to the welding transformer. Figure 19.14 illustrates this concept for welding machines with four different power factors. The higher the power factor (lower angle), the wider the range of heat control.

The reduction in heat or energy varies as the square of the current. Thus, if the rms current can be varied from 100 to 20 percent, the heat will vary from 100 to 4 percent. SCRs allow control of the heat over the entire range from zero to 100 percent, an ability which is not practical with ignitrons.

Automatic heat control is normally the basis of all auxiliary controls that change the welding amperage during a welding sequence. These include current and voltage regulators as well as upslope, downslope, and temper controls.

To minimize variations in welding current, the heat control should be operated as near to full heat as possible. At low settings, a small change of the dial setting can significantly change the rms current. Line voltage disturbances,

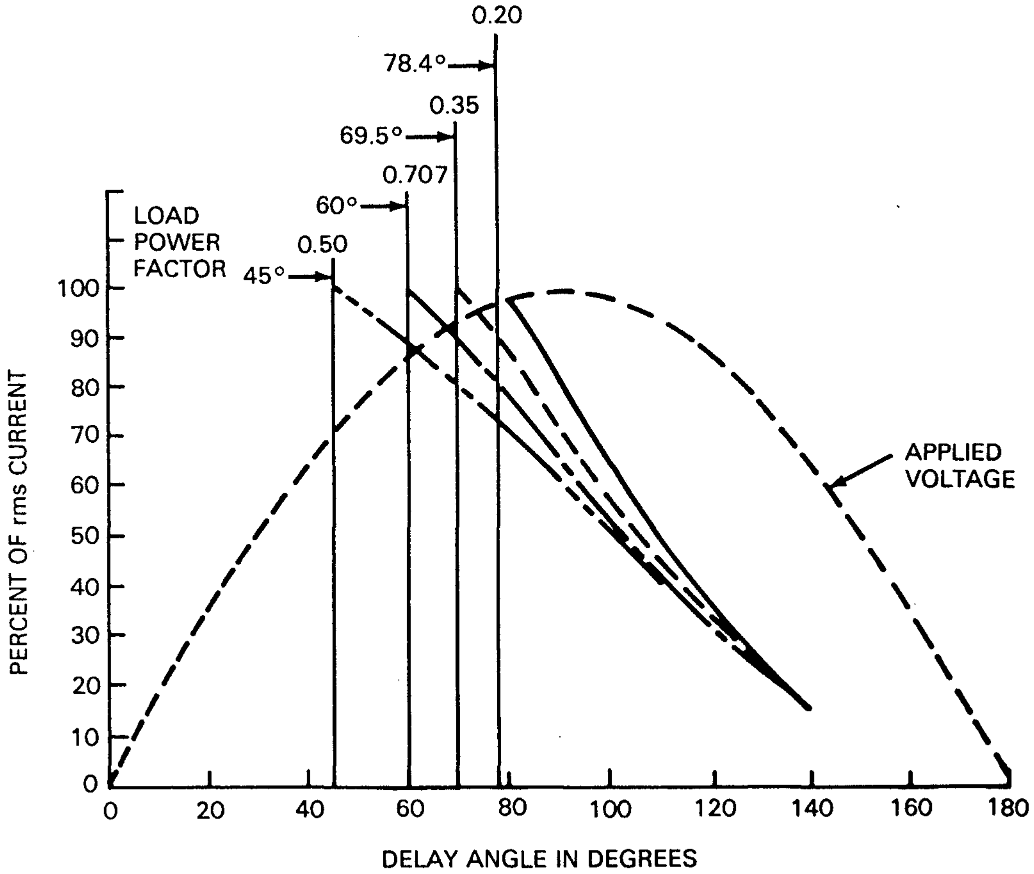


Figure 19.14–The Relationship Between Percent of RMS Current and Firing Delay Angle for Different Power Factors

such as the operation of another welding machine, can sufficiently distort the line voltage wave form to produce such a change. Major changes in welding transformer output should be made by changing the tap switch.

The power demand is always greater when heat control is used to adjust the magnitude of the welding current. In general, the kVA demand with heat control follows a linear relationship with current. For example, if the welding current is adjusted by heat control to 80 percent of its maximum value, the kVA demand will be about 80 percent of its maximum. However if the welding current is reduced to 80 percent of its maximum value by changing the transformer tap switch, the kVA demand will be only about 64 percent of maximum.

Upslope and Downslope Controls

UPSLOPE CONTROL IS used to start the welding current at some low value and control its rate of rise to some maximum value during a period of several cycles. It is frequently used to minimize or prevent the expulsion of molten metal from between the faying surfaces when welding coated steels and some nonferrous metals, particularly aluminum.

Downslope control is used to decrease the welding current from maximum to a lower value called the *postheat current.* The gradual decrease in current reduces the cooling rate of the weld. It may be useful when welding hardenable steels to minimize the cooling rate and the cracking tendency.

Upslope and downslope of welding current are illustrated in Figure 19.15. The accepted nomenclature for the various parts of a welding current cycle are also shown.

Quench and Temper Control

THE QUENCH AND temper control is a device that applies a temper cycle to the completed weld after a quench period during which no current is applied. In each case, the time period is adjustable. Temper current magnitude is normally adjustable with heat control.

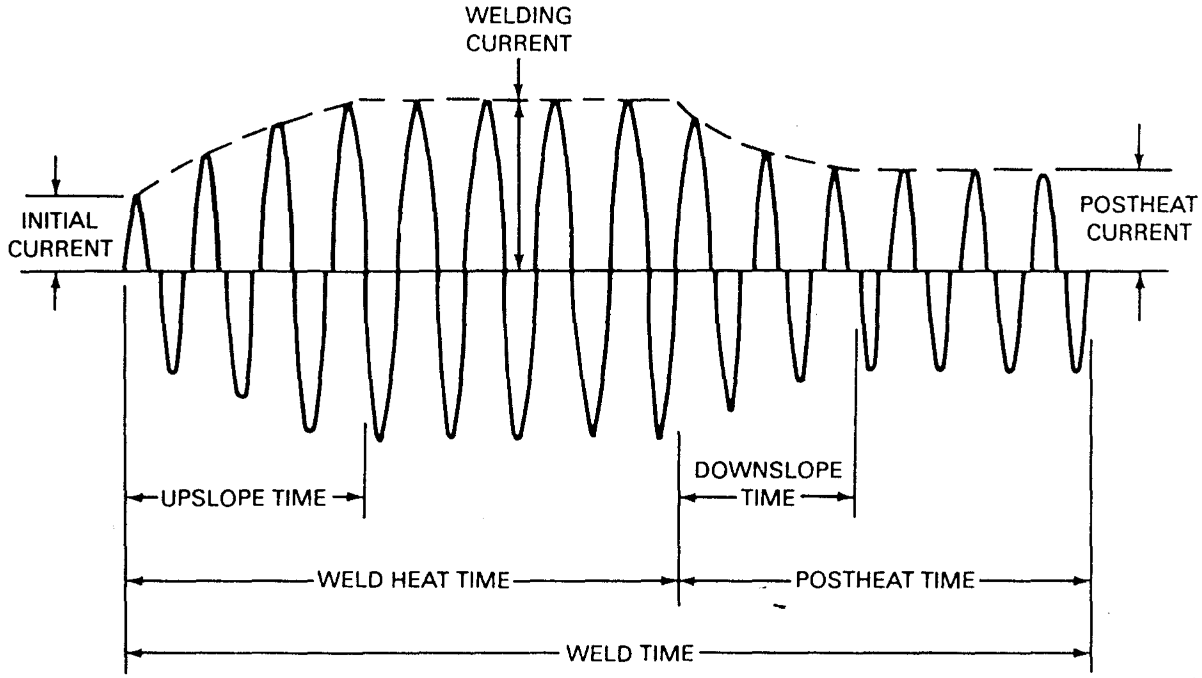


Figure 19.15–Welding Current with Upslope and Downslope Features

Heat control is frequently used when spot welding hardenable steels in thickness ranges from 0.016 to 0.125 in. (0.4 to 3.2 mm). After the weld is made, the weld cools rapidly and martensite is formed. Current pulses are then applied to reheat the weld zone and thus temper the martensite. Although this cycle cannot duplicate furnace heat treatment, it usually will prevent weld cracking.

Forge Delay Control

THIS CONTROL WILL initiate a forging force at a definite time interval after the start of weld time or weld interval. It is used to apply two levels of force to a weld, namely, a welding force and a forging force. Obviously, the welding machine must be designed to perform a dual force function.

Dual force is used when spot welding certain aluminum alloys. The principle is to produce the weld and then apply a high force during cooling to avoid the formation of cracks. It is common to downslope the welding current to retard the cooling rate during the application of forging force.

Electronic Current Regulator

AN ELECTRONIC CURRENT regulator is designed to maintain a constant welding current under changing conditions. This device will make corrections for either line voltage fluctuations or impedance changes caused by insertion of magnetic material into the throat of the welding machine. It first compares the primary current, as measured by a current transformer or other device (feedback signal), to a previously adjusted satisfactory level (command signal); then it varies the phase-shift heat control network to make these signals equal but opposite.

Electronic Voltage Regulator

IF HEAT CONTROLS are not operated too close to their maximum heat settings, many are capable of dynamically adjusting the SCR firing angle to maintain the desired heat level when variations in the AC line voltage (sags and surges) occur. Since heat also varies as the square of voltage (assuming impedance remains constant), a 10 percent drop in line voltage will result in a 19 percent reduction in heat. The welding transformer tap switch should then be set so that the desired weld is obtained at a control heat setting of 81 percent or less, if a 10 percent line sag is to be expected. Reaction time for heat controls employing this compensation feature can be less than one cycle.

Load Distribution Control

A LOAD DISTRIBUTION control is used with resistance welding machines that have two or more transformers. This control distributes the electrical power demand by energizing the welding transformers in sequence on one or more phases. Reconnection is normally provided to energize the transformers simultaneously on two or more phases.

This control generally contains several single-function timers to control mechanical functions, such as squeeze and hold timers, acting over two or more weld periods. In addition, it has a contactor for each transformer. The weld timers are functional but are weld safe; that is, the termination of weld time is not dependent upon conduction of a single electronic device. Accessories such as heat control and upslope control are sometimes added to this type of control.

A less expensive version of this control uses only one ignitron or SCR contactor and a series of magnetic contactors. The ignitron or SCR contactor switches the primary current on and off. The magnetic contactors connect the welding transformers in succession to the contactor circuit during a nonconductive period.

MONITORING AND ADAPTIVE CONTROLS

THERE ARE A number of factors that affect the consistency of resistance spot welds during a production run. These include line voltage variations, electrode deterioration, changes in surface resistance, shunt paths, and variations in the force system. There are several systems available to monitor specific welding variables or actions that occur during the welding cycle. If the monitor detects a fault, it can do one or more of the following:

(1) Turn on an alarm or signal light
(2) Document the information
(3) Reject or identify the faulty part
(4) Interrupt the process until the problem is corrected
(5) Alter time or current for the next weld
(6) Change a variable during the weld cycle to ensure a good weld.

Variables that affect process stability and weld consistency include weld time, welding current, impedance, welding energy, and electrode force. Physical changes that take place in the weld zone are temperature, expansion and contraction, electrical resistance, and, in some cases, metal expulsion.

Monitoring devices can compute either weld energy or impedance by measuring welding voltage, current, resistance, or time. When the computed value falls outside acceptable limits, the unit can notify the operator or automatically adjust one or more of the variables prior to the next weld.

Several systems of adaptive feedback have been developed which are intended to make consistent, acceptable welds. These adaptive feedback systems, whether used singly or in combination, have certain limitations. As examples of these limitations, they may require frequent calibration, work only on single-point welders, or add significantly to machine maintenance. While the systems described below are available, they are not widely used in industry.

In aerospace industries, electrode indentation is a limiting factor for acceptable welds. It has been reported that there is a relationship between electrode indentation and weld strength. Therefore, by controlling electrode indentation, welds of consistent strength with acceptable electrode indentation can be obtained. A welding control based on this principle has been developed.

A relationship between nugget expansion and weld strength has also been established. Instruments have been developed to control nugget expansion. They do this by increasing or decreasing the welding current in real time with reference to a baseline nugget/time expansion curve. The object, of course, is to obtain consistent, acceptable welds. Such a feedback control can compensate for any shunting effect, even in aluminum alloys.

In the automotive industry, portable welding guns are widely used. With a specially designed welding gun, adaptive feedback control can be achieved using the electrode indentation method. However, nugget expansion feedback control is difficult to achieve in a portable gun.

For this reason, the resistance method and the acoustic emission analysis method are used to improve the performance of a portable gun. In the resistance method, a resistance/time curve for a good weld is established. If and when the resistance/time curve of a subsequent weld deviates from this baseline curve, thereby indicating expulsion is imminent, welding current is terminated.

The acoustic method detects metallurgical actions such as melting, expulsion, solidification, phase transformation, and cracking by the acoustic waves they emit, each with a distinguishable wave form and amplitude. By detecting such acoustic waves at the threshold of expulsion, welding current can be terminated to obtain a strong weld.

As an alternative to either taking immediate action (terminating current) or passive monitoring (notifying the operator), some controls are capable of analyzing the data from many welds and detecting trends. Trend analysis allows the control to compensate for a lowering of the weld strength and slow deviations from the desirable weld results by varying process conditions to maintain high quality welds.

ELECTRICAL CHARACTERISTICS

SINGLE-PHASE EQUIPMENT

THE TYPICAL ELECTRICAL system of a single-phase resistance welding machine consists of (1) a transformer, (2) a tap switch, and (3) a secondary circuit including the electrodes.

The welding transformer, in principle, resembles any other iron-core transformer. The primary difference is that its secondary circuit has only one or two turns. Stationary machines usually have single turn secondaries. Portable gun welding transformers may have two turns that can be connected in series or parallel, depending upon the output requirements.

Transformer Rating

RESISTANCE WELDING TRANSFORMERS are normally rated on the basis of temperature rise limitations of the components. The standard rating in kVA is based on the ability of a transformer to produce that power at a 50 percent duty cycle without exceeding design limitations. This means that a transformer can produce its rated power for a total time of 30 seconds during each minute of operation without exceeding temperature limitations, if it is being properly cooled.

Duty cycle is the percentage of time that the transformer is actually "ON" during a one minute integrating period. For 60 Hz power, it can be expressed by the formula:

$$\text{percent duty cycle} = \frac{\text{welds/min x weld time in cycles}}{(60\ \text{cycles/sec})\ (60\ \text{sec/min})} \times 100$$

For example, if a machine is producing 30 welds per minute with a weld time of 12 cycles (60 Hz), its operating duty cycle is:

$$\frac{30 \times 12}{3600} \times 100 = 10\ \text{percent}$$

If a welding transformer is operated at less than 50 percent duty cycle, it can be operated at a power level higher than its thermal rating.

The maximum permissible kVA input for a standard resistance welding transformer at a particular duty cycle can be determined using the following equation:

$$kVA_i = 7.07\ kVA_r/(DC)^{1/2} \qquad (19.1)$$

where

kVA_i = maximum input power

kVA_r = standard power rating at 50 percent duty cycle

DC = operating duty cycle, percent

For example, a welding transformer rated at 100 kVA may be operated at 141 kVA at 25 percent duty cycle without overheating.

Tap Switches

TAP SWITCHES ARE devices for connecting various primary taps on the transformer to the supply lines. They are usually rotary type and designed for flush mounting in an opening in the machine frame, or, in some cases, directly on the transformer. The switches are designed to accommodate the arrangements of the transformer taps. Straight rotary designs are normally used with 4, 6, or 8 tap transformers. To provide a range of secondary voltages, taps are placed at various turns on the primary winding. These taps are connected to the tap switch, and thus the turns ratio of the transformer can be changed to produce different secondary voltages (Figure 19.16). In addition, there may be a series-parallel switch that connects two sections of the primary in series or in parallel. This provides a wider range of secondary voltages.

Most switch handles have locking buttons so that the contacts are centered in each operating position. In addition, some switches have an OFF position which acts as a disconnect. A tap switch should not be operated while the transformer is energized; otherwise, arc-over between points will damage the contact surfaces of the tap switch.

Ac Secondary Circuit

THE GEOMETRY OF the secondary circuit (loop), the size of the conducting components, and the presence of magnetic material in the loop will affect the electrical characteristics of the welding machine. Available welding current and kVA demand will be influenced by the impedance of the secondary circuit.

The electrical impedance of an ac welding machine should be minimized to permit the delivery of the required welding current at minimum kVA demand. The electrical impedance will be smaller when:

(1) The throat area of the welding machine is decreased.

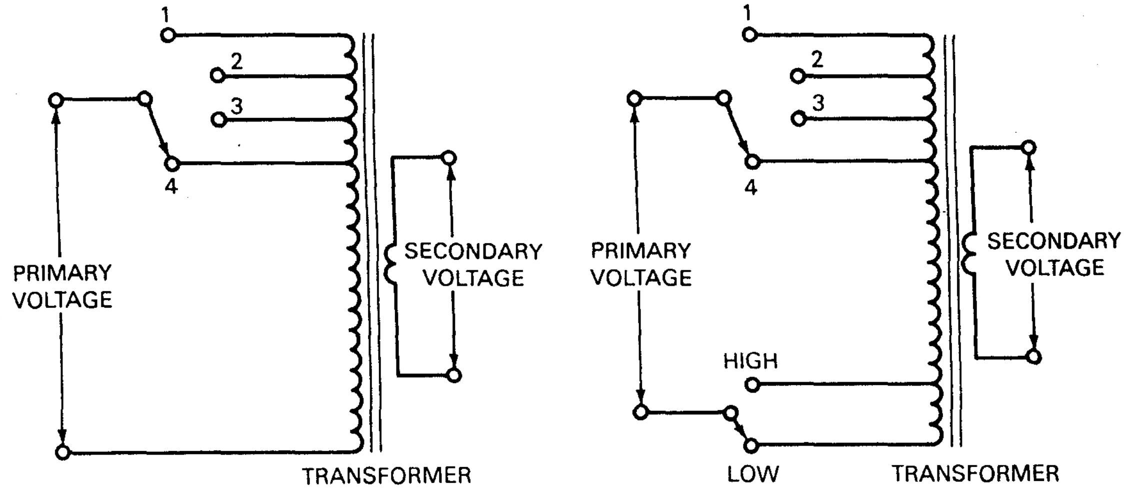
(2) The electrical resistance of the secondary circuit is decreased.

(3) The sizes of the secondary conductors are increased.

(4) The amount of magnetic material in or near the throat of the machine is decreased.

Power Factor Correction

Series Capacitors. Welding machines of good design effectively minimize the impedance of the secondary cir-



STRAIGHT TAPPING

RANGE TAPPING

Figure 19.16–Rotary Tap Switches Used to Provide a Range of Secondary Voltages

cuit. However, the size of the work to be welded and associated fixturing may require a large throat depth or throat height. This requirement may add considerable inductance to the secondary circuit. The increased inductance causes a reactive voltage drop which, in turn, decreases the power factor. To compensate for this, a higher secondary voltage is required and the necessary electrical kVA demand will be increased.

Low power factor and intermittent, high electrical demand are not desirable to the electric utility, which must maintain a stable power supply to other customers. One method of reducing line kVA demand and improving power factor is the use of series capacitors in the primary circuit. A specific amount of capacitance can be connected in series with the transformer of a welding machine to neutralize the inductance of the machine and improve the power factor. This, in turn, will reduce the demand from the power line.

This power factor correction method will increase the voltage applied to the welding machine transformer. High voltage insulation is therefore required. A transformer tap switch is not used because it changes the series resonant condition. The welding current is changed with phase-shift heat control or a tapped autotransformer.

The resistance of the secondary circuit limits the current in any high power factor system. Since the metal being welded has resistance, the welding current may vary significantly with slight changes in metal thickness or cleanliness. This may affect weld consistency and quality, particularly with alloys of high resistance.

Voltages appearing across the welding machine transformer and the series capacitors are higher than the electrical supply voltage. Therefore, special high voltage electrical control panels are normally required. A protective over-voltage device, a discharge resistor, and a contact to ground are generally provided for safe operation and maintenance.

Three-phase welding systems have largely replaced single-phase series capacitor installations. A welding machine with a high power factor is generally less troublesome than a series capacitor installation.

Shunt Capacitors. Shunt capacitors are seldom used with resistance welding equipment. The initial high inrush of current may actually increase the line demand. However, shunt capacitors may be preferred to series capacitors if the welding time is comparatively long, as in non-interrupted resistance seam welding.

Dc Secondary Circuit

ONE METHOD OF decreasing impedance losses in the secondary circuit is to rectify the secondary power to dc. Single-phase dc resistance welding machines have a center-tapped secondary and a full-wave silicon diode rectifier. With this system, the kVA rating of a machine need not be increased much to provide for a larger throat area. For a given size and application, the kVA demand of a dc machine will be significantly lower than that of an ac machine. The reason for this is the high power factor of about

90 percent for dc machines, compared to 25 to 30 percent for ac machines.

Secondary dc power is particularly useful for portable gun welding applications. The impedance loss in the cable connecting the gun and transformer is much lower with dc than with ac. This, in turn, decreases the kVA demand and the required size of the welding transformer. It is also advantageous for spot and seam welding operations, during which the amount of magnetic material in the machine throat increases or decreases as welding proceeds.

DIRECT ENERGY THREE-PHASE EQUIPMENT

Frequency Converter Type

TWO TYPES OF frequency converter systems exist: (1) the classic half-wave system illustrated in Figure 19.13 and (2) the full-wave type which uses three phase input to a rectifier to supply a low frequency converter. Both of these systems perform in a similar fashion, but the full-wave type uses a large core single-phase transformer while the half-wave type uses a large core three-phase transformer.

This type of machine has a specially designed transformer with three primary windings, each of which is connected across one of the three input phases. There is one secondary winding which is interleaved among the primary windings and connected to the secondary conductors.

Referring to Figure 19.13, these transformer primary windings are connected to the power lines by three electronic contactors. Ignitron tubes or SCRs may be used as contactors. A welding control causes contactors A, B, and C to conduct in sequence. With the correct sequence and conduction time, current is passed through the three primary windings in the same direction. This causes unidirectional current in the secondary circuit. Contactors A, B, and C are then shut off at the end of a preselected time. Contactors A', B', and C' are caused to conduct next, with the correct sequence and conduction time, and current will be in the opposite direction through the primary windings and the secondary circuit. This action effectively applies a reversing "dc" voltage to the primary windings.

The maximum duration of unidirectional primary current is governed primarily by the size of the transformer and its saturation characteristics. It is common practice to have two maximum dc pulse lengths. One is a short time of about 5 cycles (60 Hz) for high current applications, and the other is usually 10 cycles with welding current limited to about 50 percent of maximum. Specially designed massive transformers may permit the use of high current for the longer time period.

Figure 19.17 shows a typical current-force diagram for this type of machine. Programming may be provided for other functions, such as preheat current, pre-compression force, and temper current. Single- or multiple-impulse welds may be made.

Dc Rectifier Type

A THREE-PHASE DC rectifier type welding machine is similar to the single-phase type in that each welding transformer powers a rectifier bank. The output of the rectifiers is fed into the welding circuit. Some machines use half-wave rectification, as shown in Figure 19.18(A). In this case, the transformer secondary is wye connected. Other machines,

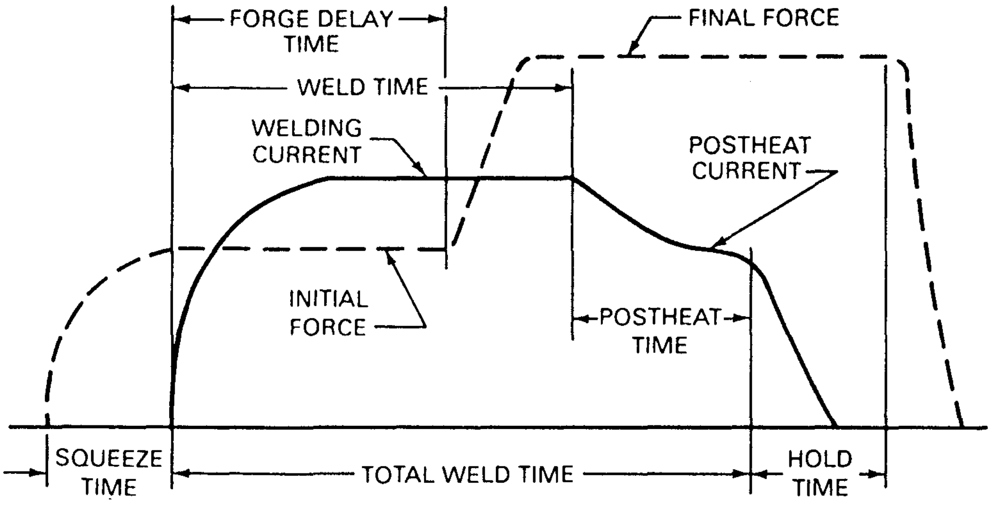
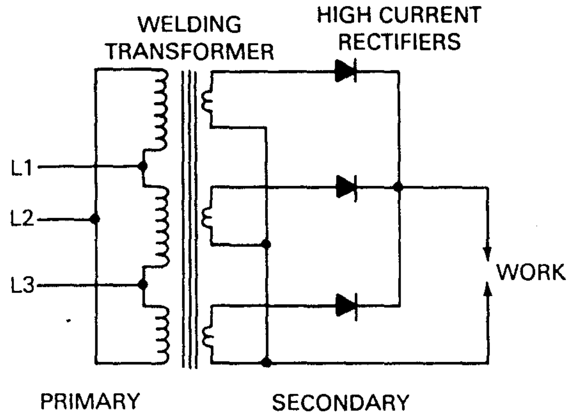
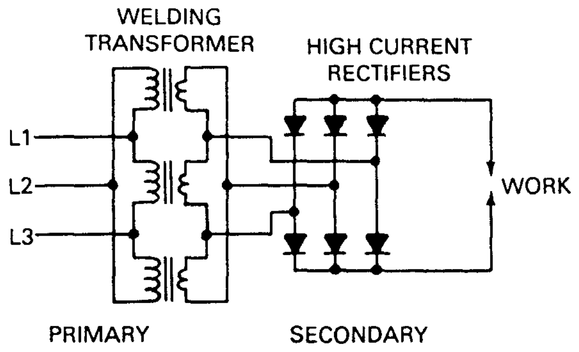


Figure 19.17–Typical Current-Force Diagram for Frequency Converter or DC Rectifier types of Three-Phase Spot Welding Machines



(A) HALF-WAVE RECTIFIER



(B) FULL-WAVE RECTIFIER

Figure 19.18–Electrical Arrangements for Three-Phase DC Rectifier Welding Machines

particularly earlier versions, have full-wave rectification with the transformer secondary connected in delta arrangement, as shown in Fig. 19.18(B).

Welding current is controlled by electronic heat control, sometimes in conjunction with a transformer tap switch. The design of the primary circuit and control varies among equipment manufacturers. The secondary current output of a three-phase machine is much smoother than that of a single-phase machine. In addition, power demand is balanced on the input line.

The three-phase rectifier consists of silicon diodes mounted on water-cooled conductors. The arrangement of conductors and diodes is electrically symmetrical. The impedance of each diode circuit must be similar so that the diodes will share the load (current) equally. The diodes themselves must have similar electrical characteristics. Diodes have long life if properly applied and used. Welding current may be provided continuously as long as the thermal rating of the machine is not exceeded.

A variation of this scheme uses a rectifier in the primary to convert the ac power to dc, and a pulse width modulated power supply to generate a high frequency input to the welding transformer. The output of the welding transformer is then rectified to a smooth low ripple dc for welding. The advantage of this type of circuit is the reduction in size and weight of the welding transformer. This is particularly beneficial when using transguns for robotic welding.

A typical current-force diagram for this type of machine is similar to that of Figure 19.17. In addition, programming may be provided for other functions such as preheating, upslope, downslope, and tempering. Single- or multiple-impulse welds may be made.

STORED ENERGY EQUIPMENT

EQUIPMENT OF THE stored energy type is usually found in small units suitable for bench mounting. They are powered from a single-phase line. Many designs of welding heads or portable tongs that are connected to their power units with cables are available. They are used for a wide variety of applications, including assembly of small electrical components of nonferrous alloys, and the spot welding of foils.

Electrode force may range from a few ounces to several pounds. Calibrated springs are used in a manual force system to apply the electrode force. Stored energy is used to produce the welding current pulse. The welding current amplitude, duration, and wave shape are determined by the electrical characteristics of the power source, including capacitance, reactance, resistance, and capacitor voltage. Welding times are often substantially shorter than one half cycle of 60 Hz.

Figure 19.19 shows a typical foot-operated bench welding machine of the stored energy type, with a maximum electrode force of either 8 or 20 lb., depending upon the spring size. Electrode force is applied by actuating a foot pedal mounted beneath the welding head. A typical power source is rated at 40 watt-seconds, has 600 microfarads of capacitance, and can be adjusted for welding outputs as indicated by the curves in Figure 19.20. Larger machines are available.

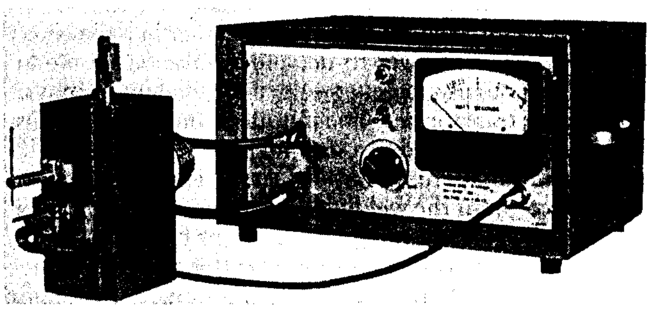


Figure 19.19—A Bench-Mounted Stored Energy Spot Welding Machine

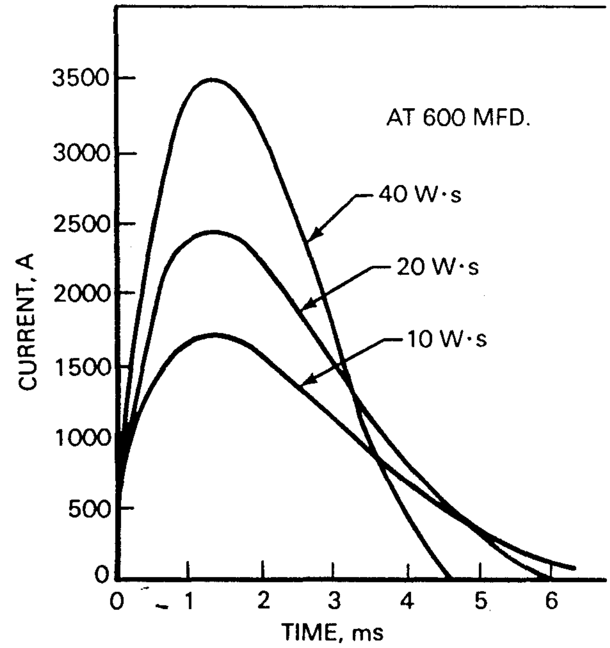


Figure 19.20—Typical Time-Current Wave Forms of a 40 Watt-Second Stored Energy Spot Welding Machine

ELECTRODES AND HOLDERS

THE PERISHABLE TOOLS used in resistance welding are the electrodes, which may be in the form of a wheel, roll, bar, plate, clamp, chuck, or some modification of these. Most spot welding applications use electrode holders or adaptors for mounting the electrodes in the machine.

A welding electrode may perform one or more of the following functions:

(1) Conduct welding current to the parts
(2) Transmit a force to the joint
(3) Fixture or locate the parts in proper alignment
(4) Remove heat from the weld or adjacent part

The electrode design should always provide sufficient mass to transmit the required welding force and current, and provide adequate cooling when needed. High production applications sometimes involve thick sections that require special electrode designs. If it is necessary to compromise the design, that may affect electrode life, weld quality, production rate, or all three. Consequently, selection of the electrode material is very important for good performance.

ELECTRODE MATERIALS

RESISTANCE WELDING ELECTRODE materials are classified by the RWMA.[1] They are divided into three groups: A, copper-base alloys; B, refractory metal compositions, and C, specialty materials. In addition to these materials, there are a number of proprietary alloys available from the various electrode manufacturers. Table 19.1 gives the minimum properties for copper-base alloys to meet the various RWMA classification requirements. The specific alloy compositions are not specified, and they will vary among the manufacturers.

Group A: Copper-Base Alloys

THE COPPER-BASE ALLOYS are divided into five classes. Class 1 alloys are general purpose material for resistance welding

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[1] Standard electrode materials are described in ANSI/RWMA Bulletin No. 16, Resistance Welding Equipment Standards, Resistance Welder Manufacturers Association, Philadelphia, Pennsylvania.

Table 19.1
Minimum Properties for RWMA Electrode Materials

Group A Copper-Base Alloys	Proportional Limit Tension, psi			Hardness, Rockwell B			Conductivity, %[a]			Ultimate Tensile Strength, psi			Elongation, % in 2 in. or 4 diameters		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Rod Diam., In.	**Round Rod Stick (Cold Worked)**														
Up to 1	17,500	35,000	50,000	65	75	90	80	75	45	60,000	65,000	100,000	13	13	9
Over 1 to 2	15,000	30,000	50,000	60	70	90	80	75	45	55,000	59,000	100,000	14	13	9
Over 2 to 3	15,000	25,000	50,000	55	65	90	80	75	45	50,000	55,000	95,000	15	13	9
Thickness, In.	**Square, Rectangular, and Hexagonal Bar Stock (Cold Worked)**														
Up to 1	20,000	35,000	50,000	55	70	90	80	75	45	60,000	65,000	100,000	13	13	9
Over 1	15,000	25,000	50,000	50	65	90	80	75	45	50,000	55,000	100,000	14	13	9
Thickness, In.	**Forgings**														
Up to 1	20,000	22,000[b]	50,000	55	65	90	80	75	45	60,000	55,000	94,000	12	13	9
Over 1 to 2	15,000	21,000[b]	50,000	50	65	90	80	75	45	50,000	55,000	94,000	13	13	9
Over 2	15,000	20,000[b]	50,000	50	65	90	80	75	45	50,000	55,000	94,000	13	13	9
	Castings														
All	--	20,000	45,000	--	55	90	--	70	45	--	45,000	85,000	--	12	5

Group A Copper-Base Alloys	Proportional Limit Tension, psi	Hardness, Rockwell	Conductivity, %[a]	Ultimate Tensile Strength, psi	Elongation, % in 2 in. or 4 Diameters
Class 4 Alloys					
Cast	60,000	33C	18 (Average)	90,000	0.5
Wrought	85,000	33C	20 (Average)	140,000	1.0
Class 5 Alloys, cast					
Type H	16,000	88B	12	70,000	2
Type S	12,000	65B	15	65,000	12
Group B Refractory Metals				**Ultimate Compression Strength, psi**	
Class 10 - Rods, bars, and inserts		72B	45	135,000	
Class 11 - Rods, bars, and inserts		94B	40	160,000	
Class 12 - Rods, bars, and inserts		98B	35	170,000	
Class 13 - Rods, bars, and inserts		69B	30	200,000	
Class 14 - Rods, bars, and inserts		85B	30	---	

a. International Annealed Copper Standard.

b. Hot worked and heat treated but not cold worked.

applications. They may be used for spot and seam welding electrodes where electrical and thermal conductivities are of greater importance than mechanical properties. Other applications are seam welding machine shafts and welding fixtures. This alloy class is recommended for spot and seam welding electrodes for aluminum, brass, bronze, magnesium, and metallic coated steels, because Class 1 alloys have high electrical and thermal conductivity.

Class 1 alloys are not heat treatable. Their strength and hardness are increased by cold working. Therefore, they have no advantage over unalloyed copper for castings, and are rarely used or fabricated in this form.

Class 2 alloys have higher mechanical properties but somewhat lower electrical and thermal conductivities than Class 1 alloys. Class 2 alloys have good resistance to deformation under moderately high pressures, and are the best general purpose alloys. This alloy class is suitable for high production spot and seam welding of clean mild and low alloy steels, stainless steels, low conductivity copper-base alloys, and nickel alloys. These materials comprise the bulk of resistance welding applications.

Class 2 alloys are also suitable for shafts, clamps, fixtures, platens, gun arms, and various other current-carrying structural parts of resistance welding equipment. Class 2 alloys are heat treatable and may be used in both wrought and cast forms. Maximum mechanical properties are developed in wrought form by cold working after heat treatment.

Class 3 alloys are also heat treatable, but have higher mechanical properties and lower electrical conductivity than Class 2 alloys. The chief application for spot or seam welding electrodes made of this alloy is for welding heat resistant alloys that retain high strength properties at elevated temperatures. Welding of these alloys requires high electrode force, which in turn requires a strong Class 3 electrode alloy. Typical heat resistant alloys are some low alloy steels, stainless steels, and nickel-chromium-iron alloys.

Class 3 alloys are especially suitable for many types of electrode clamps and current-carrying structural members of resistance welding machines. Their properties are similar in both the cast and wrought conditions, because they develop most of their mechanical attributes from heat treatment.

Class 4 alloys are age-hardenable types that develop the highest hardness and strength of the Group A copper alloys. Their low conductivity and tendency to be hot-short make them unsuitable for spot or seam welding electrodes. They are generally recommended for components that have relatively large contact area with the part. These include flash and projection welding electrodes and inserts. Other applications are part backup devices, heavy-duty seam welding machine bearings, and other machine components where resistance to wear and high pressure are important.

Class 4 alloys are available in both cast and wrought forms. Because of their high hardness after heat treatment, they are frequently machined in the solution-annealed condition.

Class 5 alloys are available principally in the form of castings with high mechanical strength and moderate electrical conductivity. They are recommended for large flash welding electrodes, backing material for other electrode alloys, and many types of current-carrying structural members of resistance welding machines and fixtures.

Group B: Refractory Metal Compositions

THESE MATERIALS CONTAIN a refractory metal in powder form, usually tungsten or molybdenum. They are made by the powder metallurgy process. Their chief attribute is resistance to deformation in service. They function well for achieving heat balance when two different electrode materials are needed to compensate for a difference in thicknesses or composition of alloys being welded.

Class 10, 11, and 12 compositions are mixtures of copper and tungsten. The hardness, strength, and density increase and the electrical conductivity decreases with increasing tungsten content. They are used as facings or inserts where exceptional wear resistance is required in various projection, flash, and upset welding electrodes. It is difficult to establish guidelines for the application of each grade. The electrode design, welding equipment, opposing electrode material, and workpiece composition and condition are some of the variables that should be considered in each case.

Class 13 and Class 14 are commercially pure tungsten and molybdenum, respectively. They are generally considered to be the only electrode materials that will give good performance when welding nonferrous metals that have high electrical conductivity. The welding of braided copper wire or copper and brass wires to themselves or to various types of terminals are typical uses for Class 13 and 14 materials.

Group C: Other Materials

A NUMBER OF unclassified copper alloys and other materials may be suitable for resistance welding electrodes. Suitability of a particular material for electrodes will depend upon the application. Although most requirements are met by materials meeting RWMA standards, there are cases where other materials will function as well or better. For example, steel may be used for flash welding electrodes for certain aluminum applications.

Dispersion-strengthened copper is an unclassified material that may be used for electrodes. It is high purity copper that contains small amounts of submicroscopic aluminum oxide uniformly distributed in the matrix. The aluminum oxide significantly strengthens the copper matrix and raises the recrystallization temperature of cold worked material. The high recrystallization temperature of wrought material provides excellent resistance to softening and mushrooming of electrodes when the contacting surfaces are heated. This significantly contributes to long electrode life. The mechanical properties and electrical conductivity of dispersion strengthened copper bars meet the requirements for RWMA Group A, Class 1 and 2 alloys, but they are not so classified.

SPOT WELDING ELECTRODES

A SPOT WELDING electrode has four features:

(1) The face
(2) The shank
(3) The end or attachment
(4) Provision for cooling

Face

THE FACE OF the electrode is that portion which contacts the work. Its design is influenced by the composition, thickness, and geometry of the parts to be welded. In turn, the electrode face geometry determines the current and pressure densities in the weld zone. Figure 19.21 shows the standard RWMA electrode face and taper designs. The radius, dome, and flat-faced contours are those most commonly used. The flat-faced electrode is used to minimize surface marking or to maintain heat balance.

The face may be concentric to the axis of the electrode, as in Figures 19.21(A),(B),(C),(E), and (F); eccentric or offset, as in Figure 19.21(D); or at some angle to the axis, as in Figure 19.22. So-called offset electrodes with eccentric faces are used to make a weld near a corner or in other less accessible areas. This is illustrated in Figure 19.23. A facing of Group B material may be brazed to a shank of a Group A alloy to produce composite electrodes for special applications as shown in Figure 19.24.

Shank

THE SHANK OF an electrode must have sufficient cross-sectional area to support the electrode force and carry the welding current. The shank may be straight, as in Figure 19.21, or bent, as in Figure 19.25. The standard shank diameters are shown in Figure 19.21.

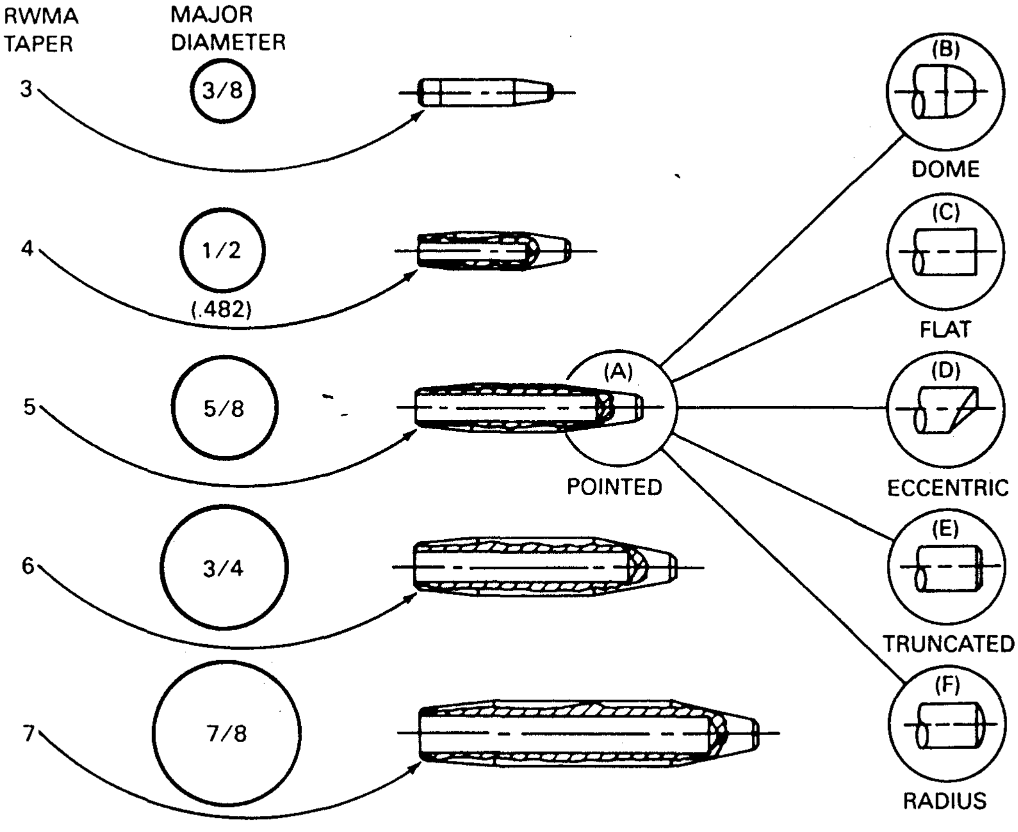

Figure 19.21–Standard RWMA Spot Welding Electrode Face and Taper Designs

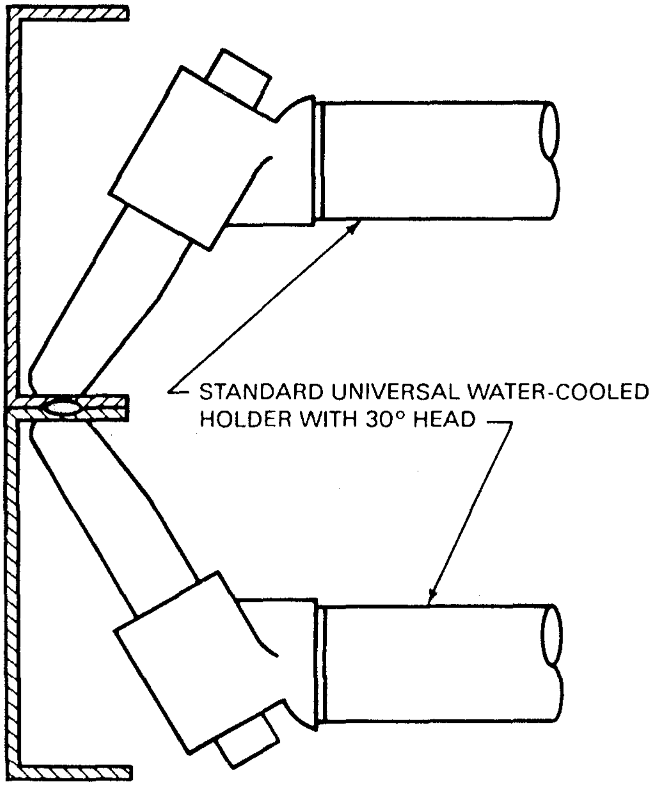

Figure 19.22–Special Spot Welding Electrodes with the Faces Angled at 30 Degrees

Attachment

The method of attaching the shank end to the holder is usually one of three general types: tapered, threaded, or straight-shank.

RWMA tapered attachments use the Jarno taper as the standard. This taper offer the following advantages:

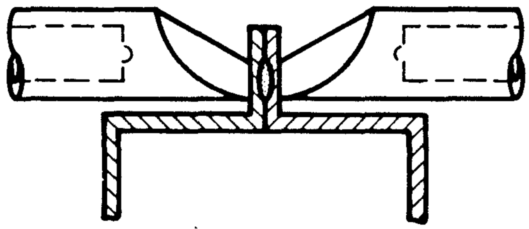

Figure 19.23–An Application of Type D Offset Spot Welding Electrodes

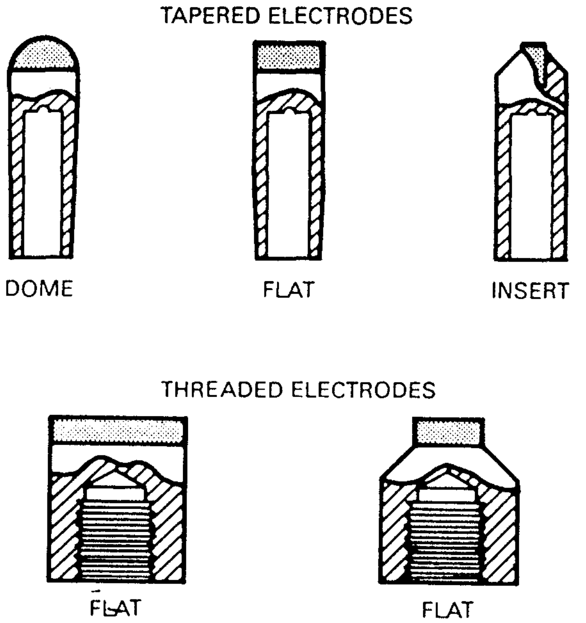

Figure 19.24–Typical Group B Electrode Faces Brazed to Group A Alloy Shanks

(1) The taper number multiplied by 1/8 in. gives the nominal major diameter. For example, RWMA No. 5 taper has 5/8 in. diameter.

(2) The taper numbers progress in sequence from 3 to 7.

(3) The RWMA taper is a uniform 0.600 in./ft for all sizes.

The electrode diameter and taper length increase as the taper number increases. Longer tapers can support higher electrode forces, but there is a maximum force that should be used with each electrode size. Recommended maximum electrode forces for the various sizes are given in Table 19.2.

Threaded attachments are used where high welding forces would make removal of tapered electrodes difficult, or where electrode position is critical. Typical threaded electrodes are shown in Figure 19.26.

Straight-shanked electrodes are used to transmit high welding forces, especially the 3/4 and 7/8 in. diameters. The base of the electrode bears against the holder socket. The water seal is an "O" ring in a recessed groove in the holder. The electrode is mechanically held in-place by a coupling or collar, as shown in Figure 19.27.

Cooling

Wherever practical, spot welding electrodes should have an internal cooling passage extending close to the welding face. This passage should be designed to accom-

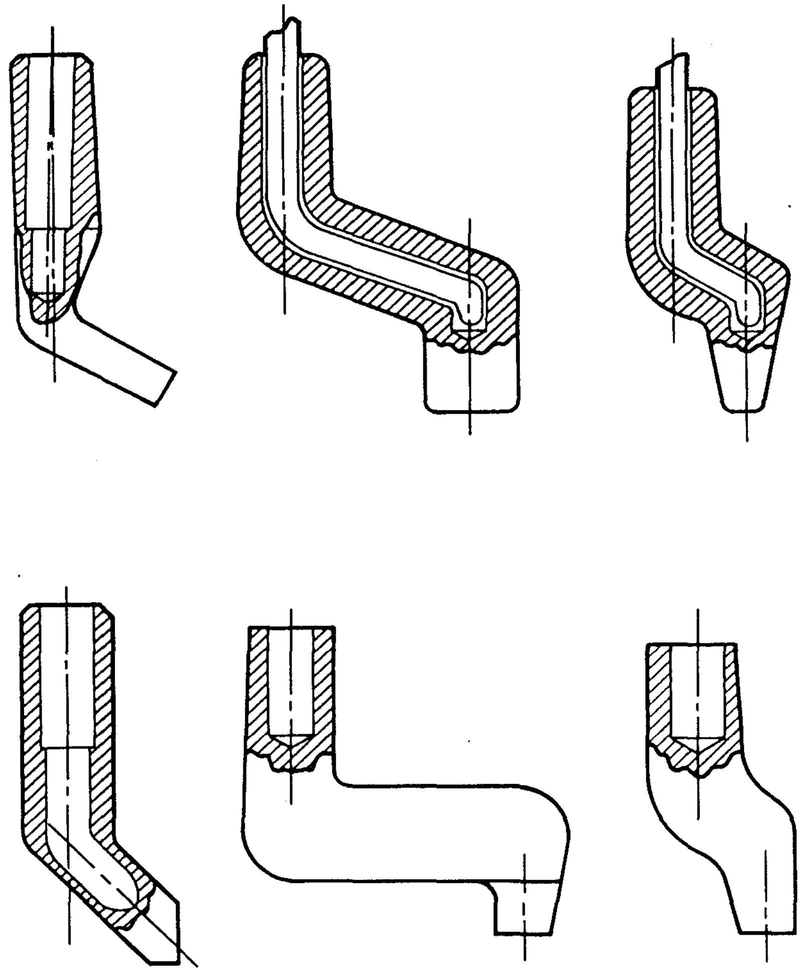

Figure 19.25—Typical Single and Double Bent Spot Welding Electrodes

modate a water inlet tube and to provide for water flow out around the tube. The tube should be positioned to direct the cooling water against the inside of the tip of the electrode. In most cases, the tube is a component of the electrode holder. An exception is the case of bent electrodes. Where internal cooling is not practical, external cooling of the electrodes by immersion, flooding, or attached cooling coils should be considered.

Table 19.2
Recommended Maximum Electrode Force for Standard Spot Welding Electrodes

Taper No.	Shank Diameter in.	Face Diameter In.	Maximum Electrode Force, lb
4	0.482	0.19	800
5	0.625	0.25	1500
6	0.750	0.28	2000
7	0.875	0.31	2400

Two-Piece Electrodes

TWO-PIECE OR CAP-AND-ADAPTOR electrodes are available with both male and female caps, as shown in Figure 19.28. They are available with straight and bent shanks. Use of this electrode design is a matter of economics. Tip maintenance costs may be lower because only the cap needs to be replaced when worn down. On the other hand, the resistance of the cap-to-adaptor interface may contribute to electrode heating and wear. Their use should be evaluated for each application, compared to the one-piece design.

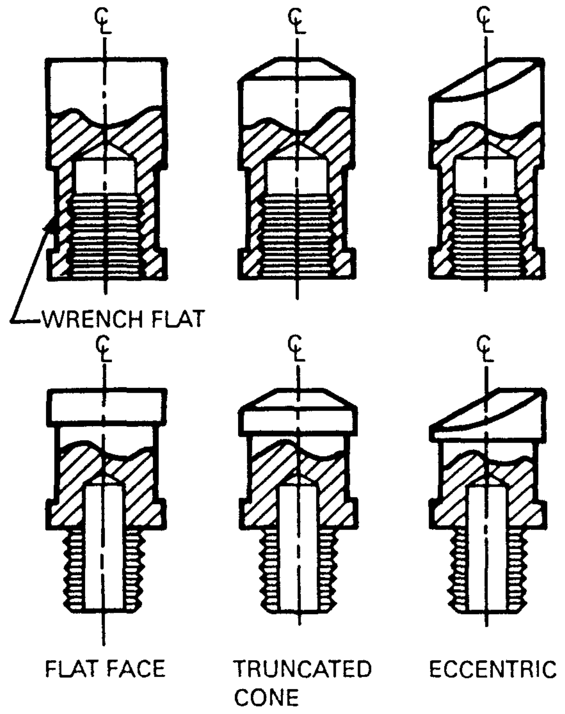

Figure 19.26–Typical Threaded Spot Welding Electrodes

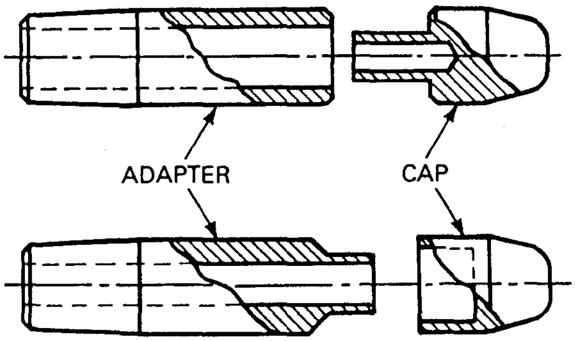

Figure 19.28–Male and Female Designs of Two-Piece Spot Welding Electrodes

Method of Manufacture

STRAIGHT ELECTRODES ARE machined from cold worked rods. Bent electrodes may be produced by cold forming of straight electrodes, by forging, or by casting. Forging or casting is normally used where the required shape cannot be produced by cold forming. Most bent electrodes are cold formed because they have distinct advantages over the others, including the following:

(1) The physical and mechanical properties of cold-drawn rod

(2) Placement of a water tube in the cooling hole prior to forming

(3) Lower manufacturing costs

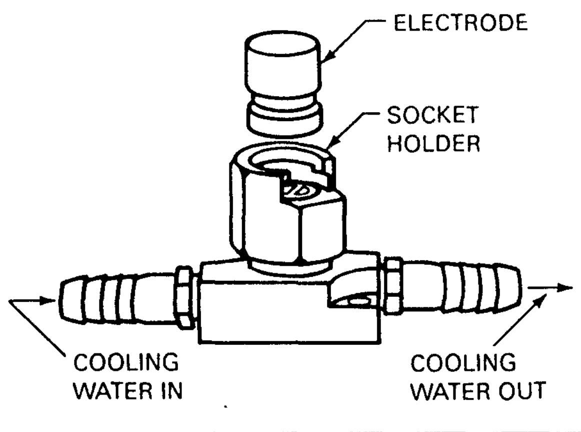

Figure 19.27–Straight Shanked Electrode with Socket Holder

Maintenance

A SPOT WELDING electrode has a specific face area in contact with the work. In use, this area will grow by mushrooming and the current and pressure densities will decrease at the same time. As a result, the weld will become smaller. In addition, the electrodes tend to pick up metal from the parts being welded. A small amount of pick up may not be harmful, but a considerable amount will cause the electrodes to overheat and mushroom faster.

It is not possible to predict how many welds can be made with a given setup before redressing of the electrodes is necessary. A periodic check of the weld quality as well as the electrode shape will help in determining the number of welds or assemblies that can be made before redressing. Then a schedule of electrode redressing should be set up as preventive maintenance to maintain weld quality.

A minor amount of redressing of electrodes in the machine is permissible using a plastic or metal paddle contoured on both sides to match the electrode face contour. The paddle is wrapped with fine abrasive cloth. The electrodes are brought against the abrasive cloth under a light load. The paddle is then rotated to redress the electrode faces.

Where a major amount of redressing is necessary, the electrode should be removed from the machine and refaced on a lathe. Alternatively, major redressing of the electrode may be done in the machine with a manual or power-operated dressing tool.

A file should never be used for redressing electrodes in the machine because the resulting electrode faces may be irregular in size and contour. Poorly dressed electrodes will reduce the quality of weld.

The following suggestions may be helpful in correctly using spot welding electrodes:

(1) Use standard electrodes and holders wherever possible
(2) Use the proper electrode material recommended for the application
(3) Use adequate water cooling and circulate it in the correct direction in the electrodes
(4) Align the electrodes properly; electrodes should not skid against the parts or be out of alignment when they are in contact with the parts
(5) Use only rawhide or rubber mallets for tapping electrodes into position and only ejector type holders or the proper tools for removing electrodes from the machine
(6) See that the machine is set up properly; the electrodes must contact the parts with minimum impact before current flows, and must remain in contact until termination of the current.

Specifications and Identification

SPOT WELDING ELECTRODES are covered by two standards:

(1) ANSI/RWMA Bulletin No. 16, Resistance Welding Standards, published by the Resistance Welder Manufacturer Association.
(2) AWS D8.6/SAE HS-J1156, Standard for Automotive Resistance Spot Welding Electrodes, published by the American Welding Society and the Society of Automotive Engineers.

These standards provide a code system for the various standard electrode designs. The code identifies the nose style, alloy class, shank size, and length. Methods are also given to identify bent electrode shapes, special-faced electrodes, and cap electrodes.

Straight electrodes are identified by a letter followed by four numbers with the following meanings:

(1) The letter indicates the nose style, as shown in Figure 19.22.
(2) The first digit indicates the Group A alloy class, as shown in Table 19.1.
(3) The second digit indicates the taper.
(4) The third and fourth digits indicate the overall length in 0.25-in. units.

For single bent electrodes, two digits are placed ahead of the letter to indicate the bend angle in degrees. For single and double bent electrodes, two additional digits are added to indicate the offset distance in 0.062-in. units.

ELECTRODE HOLDERS

ELECTRODES ARE MOUNTED on a spot welding machine by means of electrode holders. Various holder designs permit positioning the electrodes properly with respect to the work. The holders are clamped to the arms of the welding machine. Most of them have provisions for conducting cooling water to the electrodes, and some have an ejector mechanism for easy removal of the electrodes.

There are three fundamental holder designs: straight, offset, and universal or adjustable offset. These three basic types are available in standard sizes and designs for use with standard spot welding electrodes. Similar design principles are generally employed for special holders, with or without adaptors, for use with a great variety of special or standard electrodes.

The three types of standard holders are available as nonejector and ejector types. Straight electrode holders of both types are shown in Figure 19.29. With the ejector type, the electrode is removed by striking the ejector head or button with a hammer. With the nonejector type, the electrode taper is released by rotating the electrode with a wrench. Holders are available in different lengths and several diameters.

Offset and universal holders are produced with 90° and 30° heads, as shown in Figure 19.30. Low inertia holders which incorporate a spring for rapid follow-up are also available.

Multiple electrode holders are available for producing two or more spot welds simultaneously in parallel. These holders have spring, mechanical, or hydraulic force equalizing systems. The lower electrode may be a flat block that opposes all upper electrodes or individual electrodes mounted in a block. Since the welds are made by parallel circuits, the proper division of current to each weld will depend upon the relative resistances of the paths. The path of lowest impedance will conduct more current than the others, and weld size may vary with the current magnitude.

PROJECTION WELDING ELECTRODES

PROJECTION WELDING ELECTRODES must have flat surfaces that are larger than the projection diameter. It is common practice to use large, flat electrodes or rectangular bar stock.

Projection welding electrodes usually consist of an internally water-cooled holder with replaceable inserts at the projection locations. These inserts may be threaded electrodes or pieces of Group A or B electrode materials pressed or otherwise secured in the holder. An example of this design is shown in Figure 19.31.

Since the area of contact between each electrode and the adjacent part is larger than in spot welding, current and

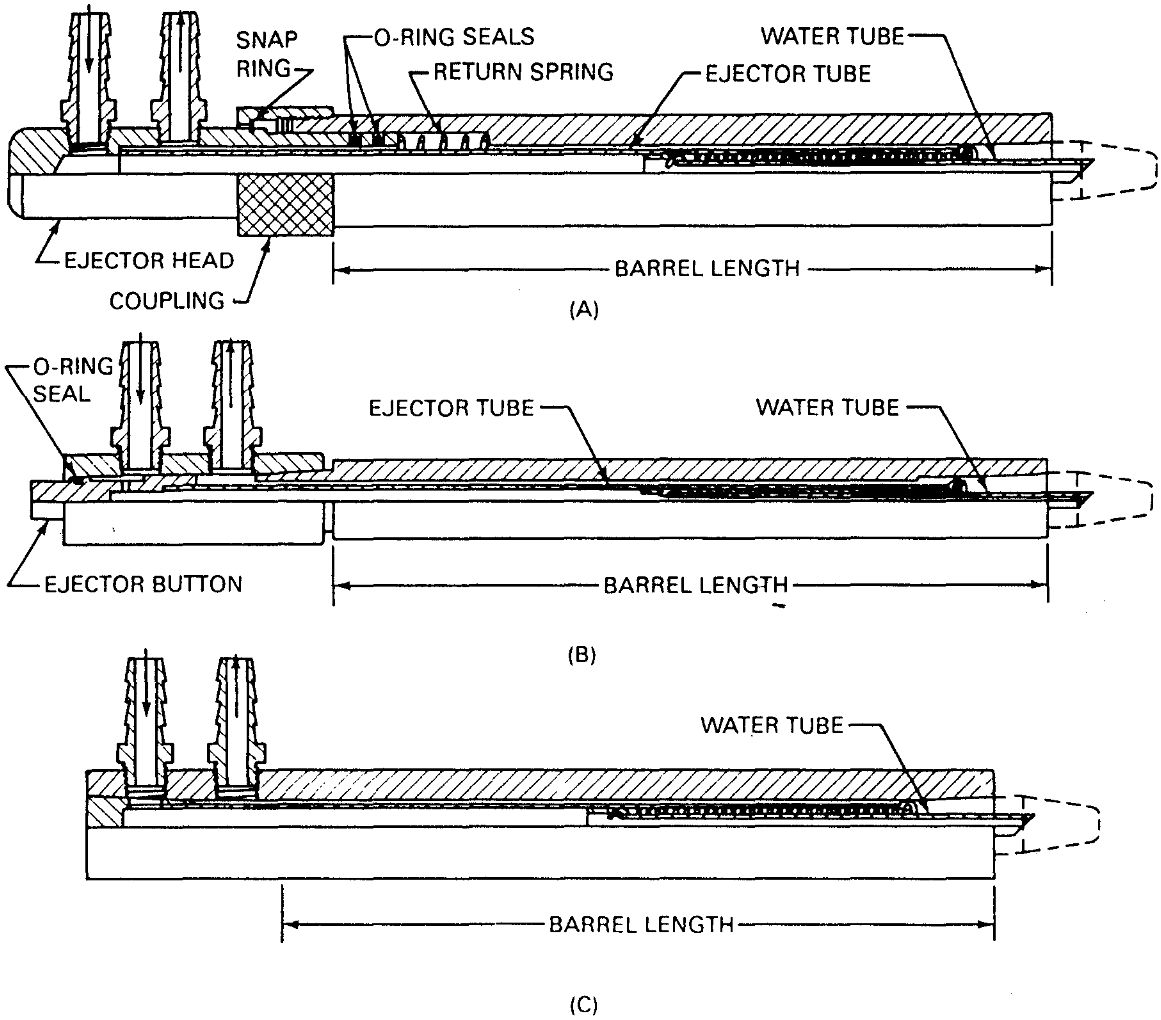

Figure 19.29–Typical Straight Spot Welding Electrode Holders: (A) and (B) Ejector Types, (C) Nonejector Type

pressure densities are lower. Therefore, electrode deterioration from wear, deformation, or pickup is not nearly as rapid as with spot welding. The electrodes do, however, eventually become pitted or deformed at the projection weld locations. When this deterioration interferes with proper electrode contact or weld quality, the electrodes or inserts must be redressed or replaced.

Selecting the best combination of opposing electrode materials for good heat balance will minimize deterioration. Regular cleaning of the electrodes to remove grease, dirt, flash, or other contamination will also prolong electrode life.

Multiple projection welding electrodes can be designed to compensate automatically for height variations or wear. Such equalizing electrodes generally employ some hydraulic or mechanical method to provide automatic floating or equalizing features.

SEAM WELDING ELECTRODES

SEAM WELDING ELECTRODES are wheels or disks. The five basic considerations are face contour, width, diameter, cooling, and method of mounting. The diameter and width of the wheel are usually dictated by the thickness, size, and shape of the parts. The face contour depends upon the requirements for current and pressure distribution in the weld nugget and the type of drive mechanism. The four basic face contours in common use are flat, single-bevel, double-bevel, and radius, as shown in Figure 19.32.

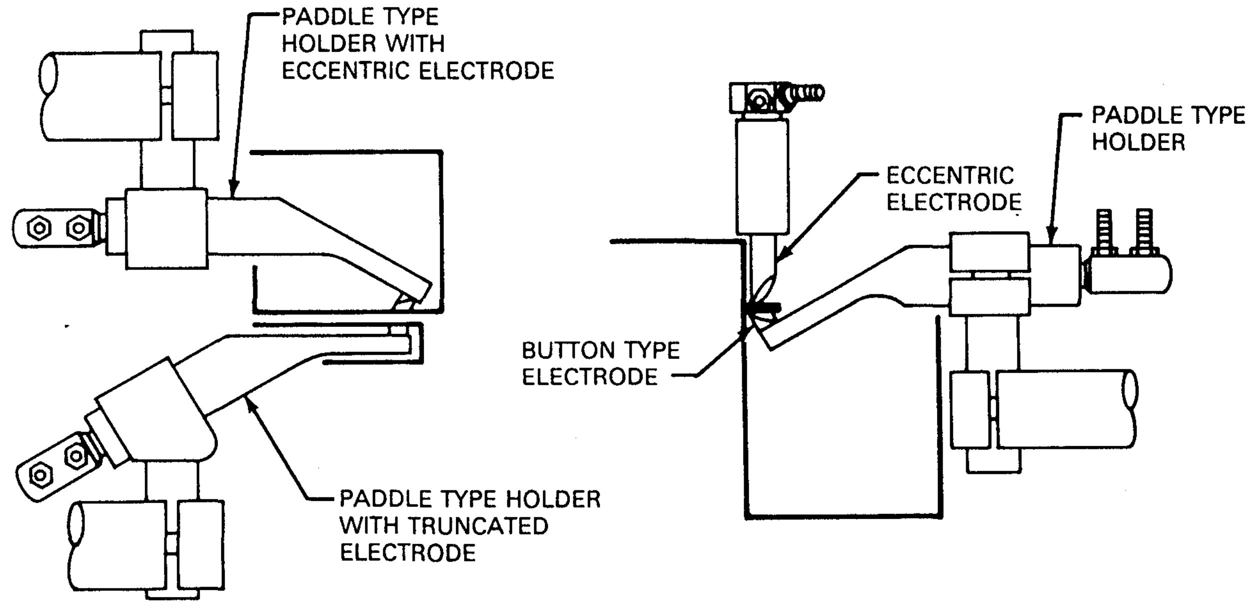

Figure 19.30–Various Combinations of Electrodes and Holders

The electrodes are usually cooled by either flooding or directing jets of water on both the electrodes and the work from top and bottom. Where those methods of cooling are unsatisfactory, the electrodes and shafts should be designed for internal cooling.

Cooling by simple flooding alone is not always adequate. A steam pocket may develop at the point where the electrode meets the work, which will keep cooling water from the immediate area. When flood cooling is unsuitable, water mist or vapor cooling may be effective.

A seam welding electrode is attached to the shaft with a sufficient number of bolts or studs to withstand the driving torque. The contact area with the shaft must be great enough to transmit the welding current with minimum heat generation.

Peripheral drive mechanisms, such as knurl or friction drives running against the electrode, require adequate work clearance. A knurl drive will mark the electrode face, which in turn will mar the surface of the weld. However, a knurl drive wheel tends to clean surface pickup from the electrode face.

Although the work and the drive method may require flat-faced electrodes with or without beveled edges, those electrodes are more difficult to set up, control, and maintain than radius-faced electrodes. In addition, radius faces give the best weld appearance.

Seam welding electrodes, like spot welding electrodes, have a predetermined area of contact with the parts which must be held within limits if consistent weld quality is to be maintained. Only minor dressing or touch up with light abrasives should be attempted with the electrode in the machine. Wheel dressers may be used for continuous electrode maintenance. Machining in a lathe is the preferred method of redressing an electrode to its original shape.

Precautions must be taken to prevent foreign materials from becoming embedded in the electrode wheel or work. Rough faces do not improve traction. Welding should be stopped while electrodes are still on the work.

FLASH AND UPSET WELDING ELECTRODES

FLASH AND UPSET welding electrodes are not usually in direct contact with the weld area as are spot and seam welding electrodes. They function as work-holding and current-carrying clamps, and are often referred to as such. They are normally designed to contact a large area of the workpiece, and the current density in the contact area is relatively low. Accordingly, relatively hard electrode materials with low conductivity can give satisfactory performance.

Since the electrodes must conform to the parts to be welded, there are no standard designs. Two important requirements are that the materials have sufficient conductivity to carry the current without overheating, and that the electrodes be rigid enough to maintain work alignment and minimize deflection.

The electrodes are mechanically fastened to the welding machine platen. They can be solid, one-piece construction of one of the RWMA Group A electrode materials in Classes 1 through 5. Service life can sometimes be in-

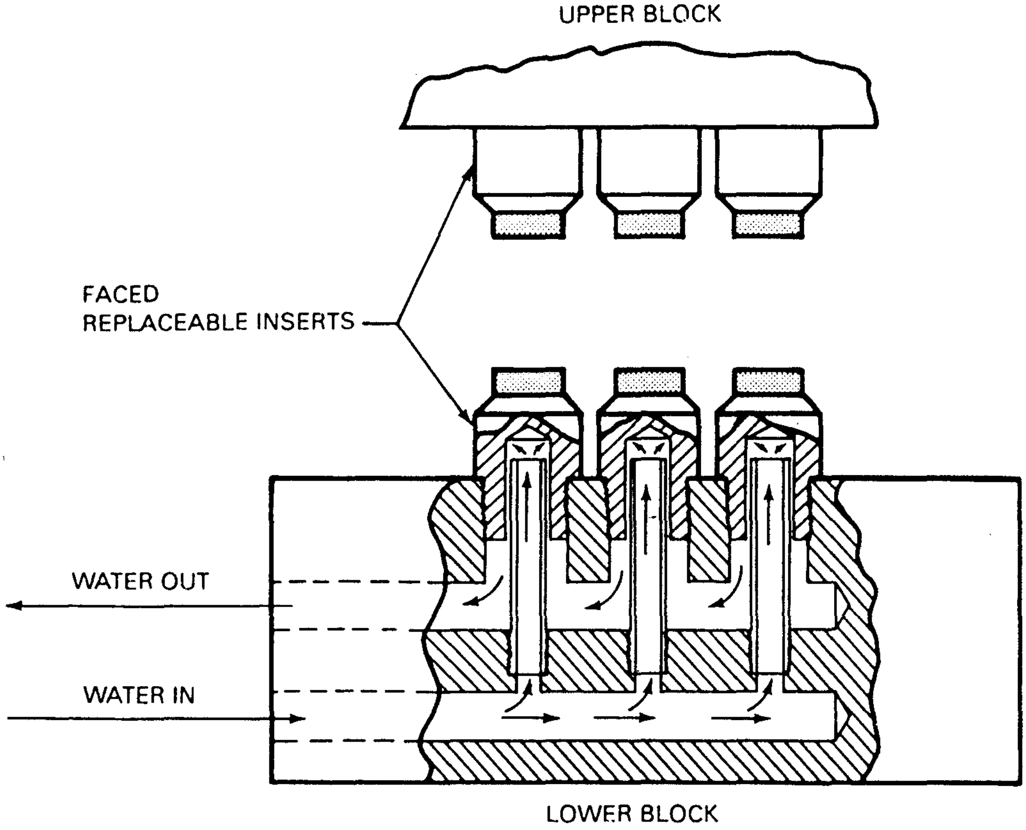

Figure 19.31–Typical Projection Welding Multiple Electrode Construction

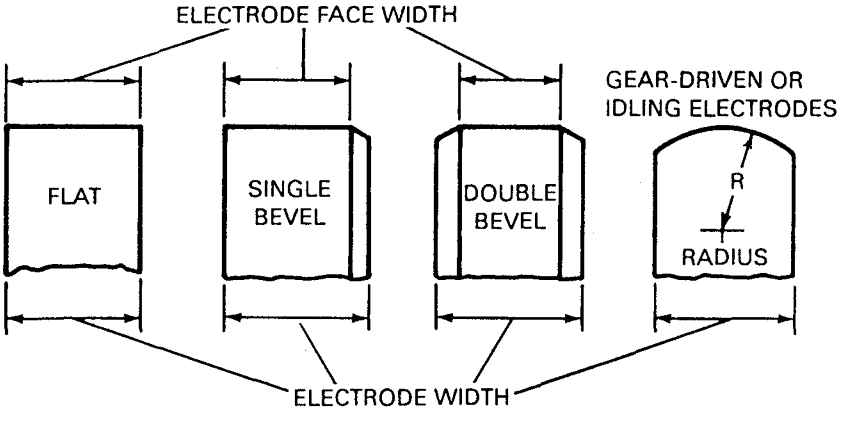

Figure 19.32–Seam Welding Wheel Face Contours

creased by using Class 2, 3, and 5 material with replaceable inserts of Class 3, 4, or one of the Group B materials at the wear points.

A varying amount of wear inevitably occurs, and this may result in decreased contact area and localized burning of the work. For good service, the electrodes should be kept cool, clean, and free of dirt, grease, flash, and other foreign particles. An antispatter compound may help prevent flash adherence. All fasteners and holding devices should be tight and properly adjusted, and their gripping surfaces should be properly maintained to avoid work slipping during welding.

POWER SUPPLY

POWER DEMAND FROM the line depends upon the welding method and the design of the welding machine. An adequate power source is one of the prerequisites for high-production resistance welding. A major part of the power source system for an industrial plant is within the plant itself. That part consists of the power source transformers and conductors.

POWER SOURCE TRANSFORMERS

IN CONSIDERING THE installation of a resistance welding machine, it is necessary to determine if the plant supply is adequate. This includes the kVA rating of the power source transformer and the size of the power source conductors. The power source transformer is connected to a 2300-, 4800-, 7500- or 13 000-volt primary feeder and produces 230 or 460 V power. It should not be confused with the welding transformer mounted in the welding machine. The power source conductors are the leads between the power source transformer and the welding machine.

The adequacy of the power source transformer and conductors is governed by two factors: the permissible voltage drop and the permissible heating. The permissible voltage drop is the determining factor in the majority of installations, but consideration must also be given to heating.

The size of the power source transformer for single-point welders should at least equal the value of the KVA demand during welding. Power source transformers have an impedance that is generally in the area of 5 percent. This means that at their KVA rating, the voltage drop on the secondary will be 5 percent. Further, the power conductors between the power source transformers and the welder will generally be sized to have no more than a 5 percent drop. This will add up to a 10 percent voltage drop at the welder, which is the maximum that most machinery manufacturers recommend for their products.

Table 19.3
Equivalent Continuous Loading of Resistance Welding Machines

Type of Welding	Equivalent Continuous Load, Percent of Sum of Name-Plate Ratings
Spot, projection (single-impulse)	20
Spot, projection (multiple-impulse)	40
Flash, multipoint spot, or projection	20
Seam	70

To determine the size of the power source transformer required to serve a welding machine on the basis of voltage drop, it is first necessary to determine the maximum permissible voltage drop specified by the machine manufacturer. Normally, it should not be greater than 5 percent. When the same power transformer is used with two or more machines, the voltage drop caused by one machine will be reflected in the operation of the second. Then it is advisable to confine the total voltage drop to not more than 10 percent for consistent weld quality. Voltage drop should be measured at the machine location. The percentage voltage drop is calculated by the following formula:

$$\text{Voltage drop, percent} = \frac{(\text{No-load voltage}) - (\text{Full-load voltage})}{\text{No-load voltage}} \times 100$$

BUS OR FEEDER SYSTEM

IN GENERAL, THE bus or feeder from the transformer to the machines should always be as short as possible and of low reactance design to minimize the voltage drop in the line. The simplest and most economical power line consists of insulated wires taped together in a conduit. When only two or three machines are to be served at a common location, this construction is economical and effective. Bus duct construction that permits easy tap connections at frequent intervals along its length is desirable in production plants where manufacturing layouts are continually changing.

Systems are available to interlock two or more machines to prevent simultaneous firing and the accompanying excessive voltage drop. Any scheme of interlocking will cause some curtailment in production. However, this can be minimized with a voltage monitoring interlock, set to operate only when the voltage drops below a preset value.

INSTALLATION

RESISTANCE WELDING MACHINES should be connected to the power line according to electrical codes and the recommendations of the machine manufacturer. The size of the primary cable should be appropriate for both thermal and voltage drop considerations.

Because many control units contain phase-shift heat control, the control power source must be in phase with the welding power source. The control power source should be fused separately from the welding power source.

Enclosed fusible isolation switches are frequently used for the power or welding circuit. These switches seldom have adequate interrupting capacity for safe disconnection under load. For emergency disconnecting purposes, a circuit breaker should be used. The rating of the breaker in carrying capacity should be sufficient to carry the maximum demand of the machine when its welding circuit is shorted. That may be from two to four times the machine nameplate rating. One of the advantages of a circuit breaker is that a push button can be installed on the welding machine. In an emergency the operator can quickly open the circuit by hitting this button.

When fuses are used, their size should be that recommended by the machine manufacturer. Manufacturers normally provide wiring diagrams which include recommended fuse ratings. The fuses should function for any normal demand or operation of the machine. The purpose of fuses is to interrupt a short circuit in the electrical system.

SAFETY

RESISTANCE WELDING PROCESSES are widely used in high production operations, especially in the automobile and appliance industries. These processes include projection, spot, seam, flash, upset, and percussion welding in a wide range of machine types. The main hazards which may arise with the processes and equipment are as follows:

(1) Electric shock due to contact with high voltage terminals or components

(2) Eye injury or fires caused by ejection of small particles of molten metal from the weld

(3) Crushing of some part of the body between the electrodes or other moving components of the machine

(4) Welding fumes from the parts themselves or from oil, lubricant, or other material on the parts

MECHANICAL

Guarding

INITIATING DEVICES ON welding equipment, such as push buttons and switches, should be arranged or guarded so as to prevent the operator from inadvertently activating them.

In some multiple-gun welding machine installations, the operator's hands can be expected to pass under the point of operation. These machines should be effectively guarded by suitable devices such as proximity-sensing devices, latches, blocks, barriers, or dual hand controls.

All non-portable, single-ram welding machines should be equipped with one or a combination of the following:

(1) Machine guards or fixtures which prevent the operator's hands from passing under the point of operation

(2) Dual-hand controls, latches, proximity-sensing devices, or any similar mechanism which prevents operation of the ram while the operator's hands are under the point of operation

All chains, gears, operating linkages, and belts associated with the welding equipment should be protected in accordance with ANSI Standard B15.1, Safety Standard for Mechanical Power Transmission Apparatus (latest edition).

Static Safety Devices

ON PRESS TYPE, flash, and upset welding machines, static safety devices such as pins, blocks, or latches should be provided to prevent movement of the platen or head during maintenance or setup for welding. More than one device may be required, but each device should be capable of sustaining the load.

Portable Welding Machines

Support Systems. All suspended portable welding gun equipment, with the exception of the gun assembly, should have a support system that can withstand the total shock load in the event of failure of any component of the system. The system should be fail safe. The use of adequate devices such as cables, chains, or clamps is considered satisfactory.

Movable Arm. Guarding should be provided around the mounting and actuating mechanism of the movable arm of a welding gun if it can cause injury to the operator's hands. If suitable guarding cannot be achieved, two handles should be used. Each handle should have an operating switch connected in series so both handles must be actuated to energize the machine. These handles must be located at safe distances from any shear or pinch points on the gun.

Stop Buttons

ONE OR MORE emergency stop buttons should be provided on all welding machines, with a minimum of one at each operator position.

Guards

EYE PROTECTION AGAINST expelled metal particles must be provided by a guard of suitable fire-resistant material, or by the use of approved personal protective eye wear. The use of safety glasses with side shields is recommended in all work areas. The variations in resistance welding operations are such that each installation must be evaluated individually. For flash welding equipment, flash guards of suitable fire-resistant material must be provided to control flying sparks and molten metal.

ELECTRICAL

Voltage

ALL EXTERNAL WELD initiating control circuits should operate on low voltage. It should not be more than 120 V for stationary equipment and 36 V for portable equipment.

Capacitors

RESISTANCE WELDING EQUIPMENT and control panels containing capacitors involving high voltages must have adequate electrical insulation and be completely enclosed. All enclosure doors must be provided with suitable interlock switches, and the switch contacts must be wired into the control circuit.

The interlocks must effectively interrupt power and discharge all high voltage capacitors into a suitable resistive load when the door or panel is open. In addition, a manually operated switch or suitable positive device should be provided to assure complete discharge of all high voltage capacitors.

Locks and Interlocks

ALL DOORS, ACCESS panels, and control panels of resistance welding machines must be kept locked or interlocked. This is necessary to prevent access by unauthorized persons.

Grounding

THE WELDING TRANSFORMER secondary should be grounded by one of the following methods:

(1) Permanent grounding of the welding secondary circuit
(2) Connection of a grounding reactor across the secondary winding with a reactor tap to ground

As an alternative on stationary machines, an isolation contactor may be used to open all of the primary lines.

The grounding of one side of the secondary windings on multiple spot welding machines can cause undesirable transient currents to flow between transformers. This can happen when either multiphase primary supplies or different secondary voltages, or both, are used for the several guns. A similar condition may also exist with portable spot welding guns, when several units are used on the same fixture or assembly or on another that is nearby. Such situations require use of a grounding reactor or isolation contactor.

INSTALLATION

ALL EQUIPMENT SHOULD be installed in conformance with ANSI/NFPA No. 70, National Electric Code (latest edition). The equipment should be installed by qualified personnel under the direction of a competent technical supervisor. Prior to its production use, the equipment should be inspected by competent safety personnel to ensure that it is safe to operate.

Additional information on safe practices for resistance welding equipment may be found in ANSI Z49.1, Safety in Welding and Cutting (latest edition).

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CHAPTER 20

HIGH-FREQUENCY WELDING

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CHAPTER 20

HIGH-FREQUENCY WELDING

INTRODUCTION

GENERAL DESCRIPTION

HIGH-FREQUENCY WELDING includes those processes in which the coalescence of metals is produced by the heat generated from the electrical resistance of the work to high frequency current, usually with the application of an upsetting force to produce a forged weld.

There are two processes that utilize high-frequency current to produce the heat for welding: *high frequency resistance welding* (HFRW), and *high frequency induction welding* (HFIW), sometimes called *induction resistance welding*. The heating of the work in the weld area and the resulting weld are essentially identical with both processes. With HFRW, the current is conducted into the work through electrical contacts that physically touch the work. With HFIW, the current is induced in the work by coupling with an external induction coil. There is no physical electrical contact with the work.

With low frequency (50 Hz – 360 Hz), direct current or "square wave" resistance welding, much higher currents are required to heat the metal and large electrical contacts must be placed very close to the desired weld area. The voltage drop across the weld is very low, and the current flows along the path of least resistance from one electrode to the other. With high-frequency welding, by contrast, the current is concentrated at the surface of the part. The location of this concentrated current path in the part can be controlled by the relative position of the surfaces to be welded and the location of the electrical contacts or induction coil. Heating to welding temperature can be accomplished with a much lower current than with low frequency or direct current resistance welding.

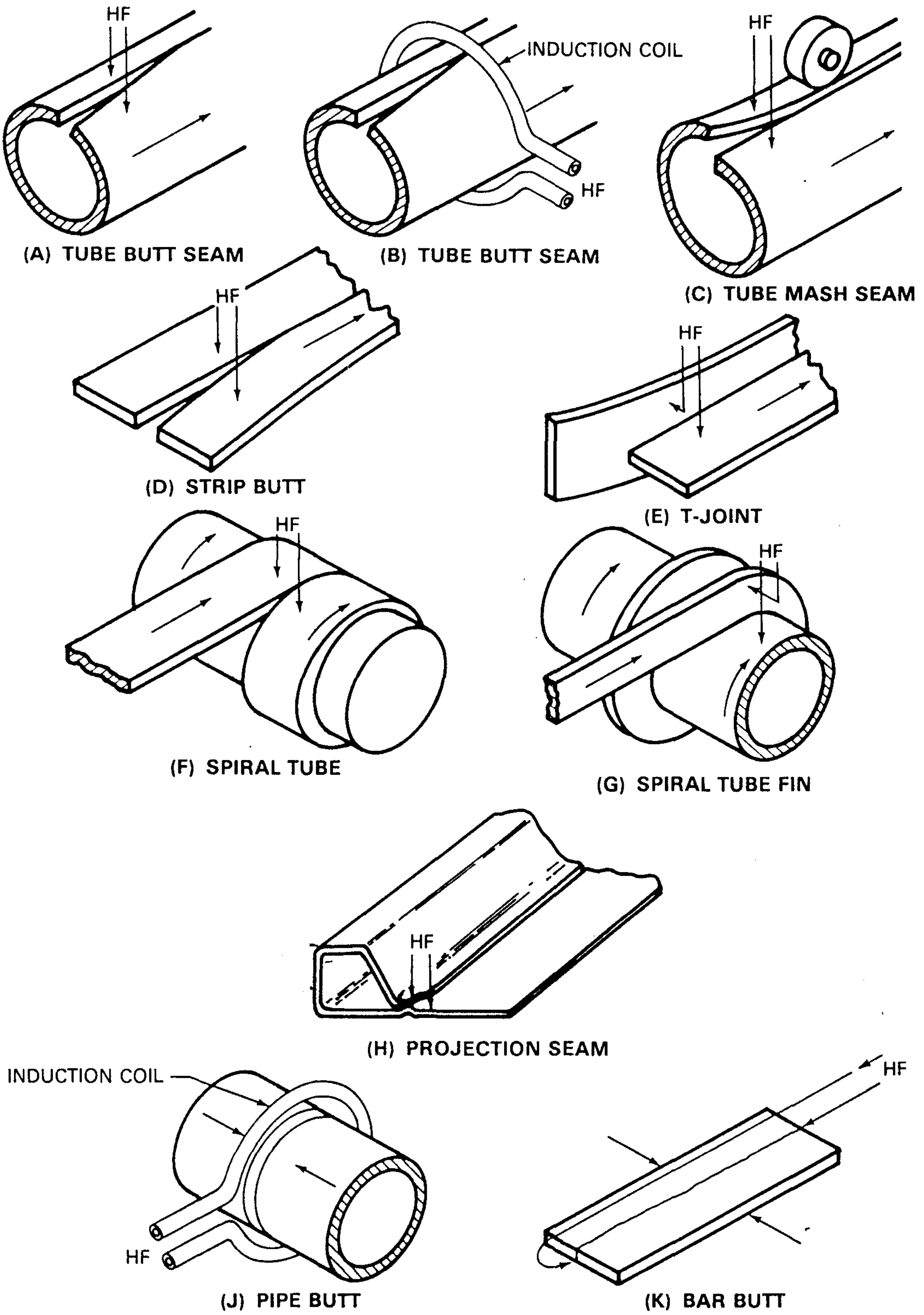
Although the welding process depends upon the heat generated by the resistance of the metal to high-frequency current, other factors must also be considered for successful high-frequency welding. Because the concentrated high-frequency current heats only a small volume of metal just where the weld is to take place, the process is extremely energy efficient, and welding speeds can be very high. Maximum speeds are normally limited by mechanical considerations of materials handling, forming and cutting. Minimum speeds are limited by material properties and weld quality requirements.

The fit of the surfaces to be joined and the manner in which they are brought together is important if high-quality joints are to be produced. Flux is not usually used but can be introduced to the weld area in an inert gas stream. Inert gas shielding of the welding area is generally needed only for joining reactive metals such as titanium and also for certain stainless steel products. Typical high-frequency welding applications are shown in Figure 20.1.

HISTORY

IN THE LATE 1940's and early 1950's, emphasis was on the development of procedures and equipment for high-frequency induction butt end welding of pipes and tubes. Successful welding operations were conducted using 10 kHz motor-generator power sources equipped with induction coils that could be opened for removal of the finished work. The first mobile installation for joining pipe in the field was utilized by a utility company in the streets of New York City. The unit produced welded butt joints in pipe up to 12 in. (305 mm) in diameter with wall thicknesses up to 5/16 in. (8 mm). With this process, pipe ends were pressed together and induction heated to forge welding temperature in approximately 60 seconds.

In 1949, the first high-frequency induction welding system for the continuous "forge welding" of the longitudinal seam in small steel tubes was developed. This used a 10 kHz motor generator with split return induction coil over the seam similar to those now used for continuous normalizing of the welded seam in pipe. This unit was successful


(A) TUBE BUTT SEAM

(B) TUBE BUTT SEAM

(C) TUBE MASH SEAM

(D) STRIP BUTT

(E) T-JOINT

(F) SPIRAL TUBE

(G) SPIRAL TUBE FIN

(H) PROJECTION SEAM

(J) PIPE BUTT

(K) BAR BUTT

Figure 20.1–Basic High-Frequency Welding Applications

and operated for many years, but it had the disadvantage of heating a large portion of the tube. The unit was eventually replaced by a 400 kHz HFRW system.

In 1952, Thomas Crawford made tests on the continuous induction welding of the longitudinal seam of various metal tubes including some tubes with cables inside. The tests were made at a frequency of 400 kHz, and employed an induction coil surrounding the tube. Induction welding of tube and pipe has become very successful for smaller diameters up to about 6 in. (150 mm). It is now becoming more popular for larger diameters, up to 20 in. (500 mm) in some installations.

In 1952, W. C. Rudd and Robert Stanton invented a 400 kHz process for welding a large variety of continuous joints. The Rudd and Stanton process introduced the welding current directly into the work by means of sliding contacts. The sliding contacts permitted the production of butt, lap, and tee joints in pipe, strip, and structural products. Successful tests were made in 1954 on butt welding the longitudinal seam in aluminum tubing. This led to the first commercial installation in 1955, for the welding of aluminum irrigation tubing, and the mill operated for nearly twenty years.

Subsequently, over 3000 installations of various forms of the system have been installed around the world. A large variety of metals have been welded.

High-frequency welding is an automated process, and is not adaptable to manual welding.

ADVANTAGES AND LIMITATIONS

HIGH-FREQUENCY WELDING processes offer several advantages over low frequency and direct current resistance welding processes. One characteristic of the high-frequency processes is that they can produce welds with very narrow heat-affected zones. The high-frequency welding current tends to flow only near the surface of the metal because of the "skin effect" and along a narrow controlled path because of the "proximity effect". These effects are described in Principles of Operation later in the chapter. The heat for welding, therefore, is developed in a small volume of metal along the surfaces to be joined. A narrow heat-affected zone is generally desirable because it tends to give a stronger welded joint than with the wider zone produced by many other welding processes. With some alloys the narrow heat-affected zone and absence of cast structure may eliminate the need for postweld heat treatment to improve the metallurgical characteristics of the welded joint.

The shallow and narrow current flow path results in extremely high heating rates and therefore high welding speeds and low-power consumption. A major advantage of the continuous high-frequency welding process is its ability to weld at very high speeds. For instance, a 1/2 in. (12 mm) wall steel pipe with a diameter ranging from 8 to 48 in. (200 to 1200 mm) can be HFRW welded at speeds over 100 fpm (30 m/s) with a 600 kW output welder. Smaller tube diameters such as 1 to 2 in. (25 to 50 mm) with light walls in the range of .025 to 0.065 in. (0.6 to 1.7 mm) can be induction welded at speeds ranging from 200 to 800 fpm (60 to 240 m/min.) using welders with 100 kW to 400 kW output.

High-frequency welding can also be used to weld very thin wall tubes. Wall thicknesses down to less than 0.005 in. (0.13 mm) are presently being welded on continuous production mills. The process is equally adaptable to large diameter pipes with wall thicknesses up to 1.0 in. (25 mm).

The process is adaptable to many metals including low carbon and alloy steels, ferritic and austenitic stainless steels, and many aluminum, copper, titanium, and nickel alloys.

Because the time at welding temperature is very short and the heat is localized, oxidation and discoloration of the metal as well as distortion of the part are minimal. Materials that would normally be damaged from prolonged exposure to heat can be welded with high-frequency welding processes. For example, electrical cable sheathing with the cable inside is welded with HFIW.

High-frequency welding power sources have a balanced three-phase input power system. Using conventional vacuum tube welding power sources, as much as 60 percent of the energy is converted into useful heat in the work. Solid-state high-frequency power sources, which have even higher efficiencies, are now becoming available.

As with any process, there are also limitations. The equipment operates in the radio frequency range, and therefore special care must be taken in its installation, operation, and maintenance to avoid radiation interference in the plant's vicinity.

As a general rule, the minimum speed in carbon steel is about 25 fpm (0.125 m/s). For products which are only required in small quantities, the process may be uneconomical unless the technical advantages justify the application.

Because the process utilizes localized heating in the joint area, proper fit-up is important. Equipment is usually incorporated into mill or line operation and must be fully automated. The process is limited to the use of coil, flat, or tubular stock with a constant joint symmetry throughout the length of the part. Any disruption in the current path or change in the shape of the vee can cause significant problems. Also, special precautions must be taken to protect the operators and plant personnel from the hazards of high-frequency current.

FUNDAMENTALS OF THE PROCESS

HIGH-FREQUENCY CURRENT in metal conductors tends to flow at the surface of the material at relatively shallow depth. This is commonly called the *skin effect.* The effect of frequency on the depth of penetration for several metals is shown in Figure 20.2. Penetration is also a function of temperature as indicated in Figure 20.2. For example, the depth of current penetration in steel at 1470°F (800°C) is about 0.03 in. (0.8 mm) at 450 kHz and nearly 0.22 in. (5.5 mm) at 10 kHz. At room temperature the penetration in steel is about 0.002 and 0.010 in. (0.05 and 0.25 mm) at 450 and 10 kHz respectively.

The high-frequency current path at the surface of the workpiece is controlled by the nearness of its own return flow path. This phenomenon, called *proximity effect,* is illustrated in Figure 20.3.

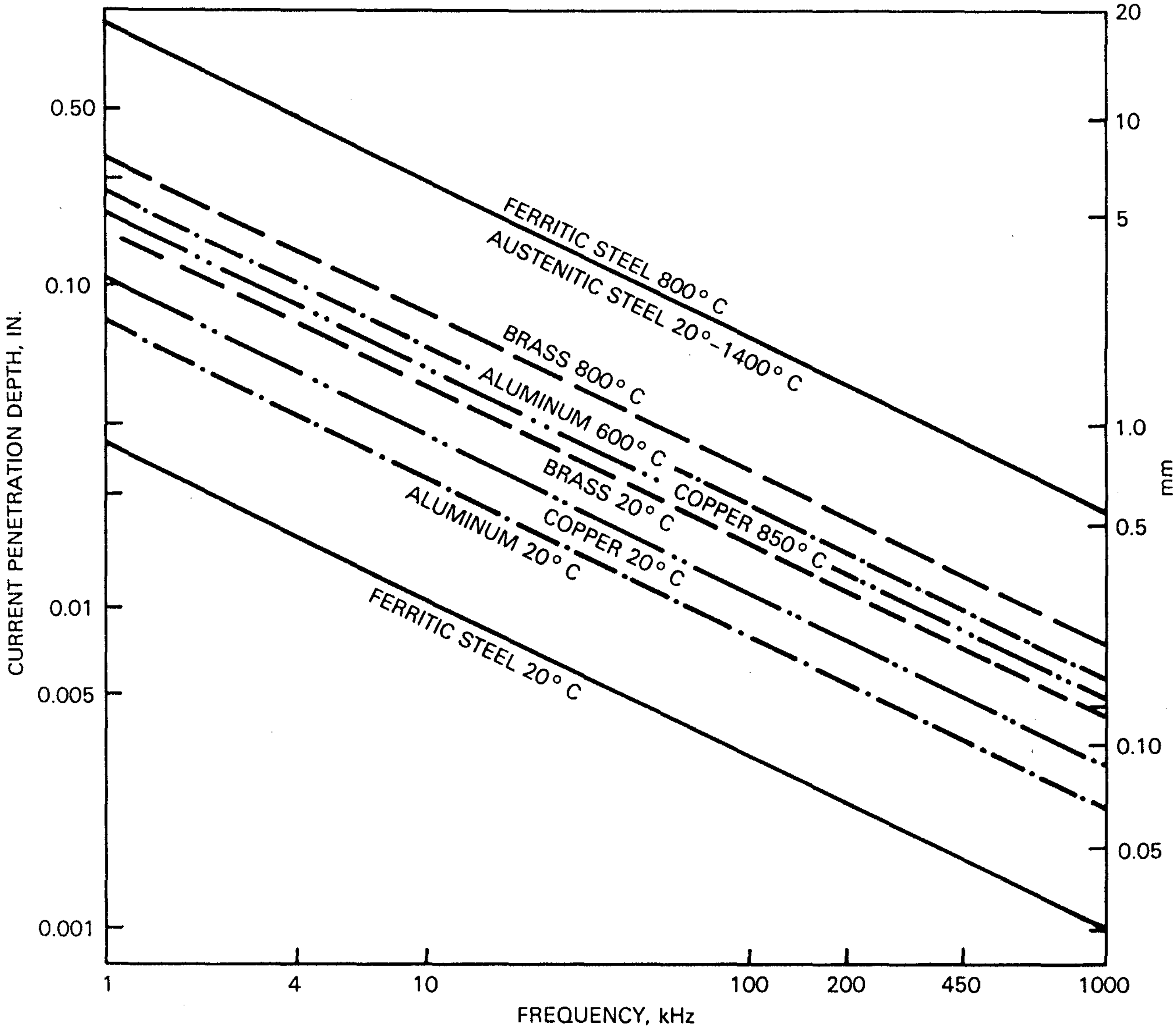


Figure 20.2–Effect of Frequency on Depth of Current Penetration Into Various Metals at Selected Temperatures

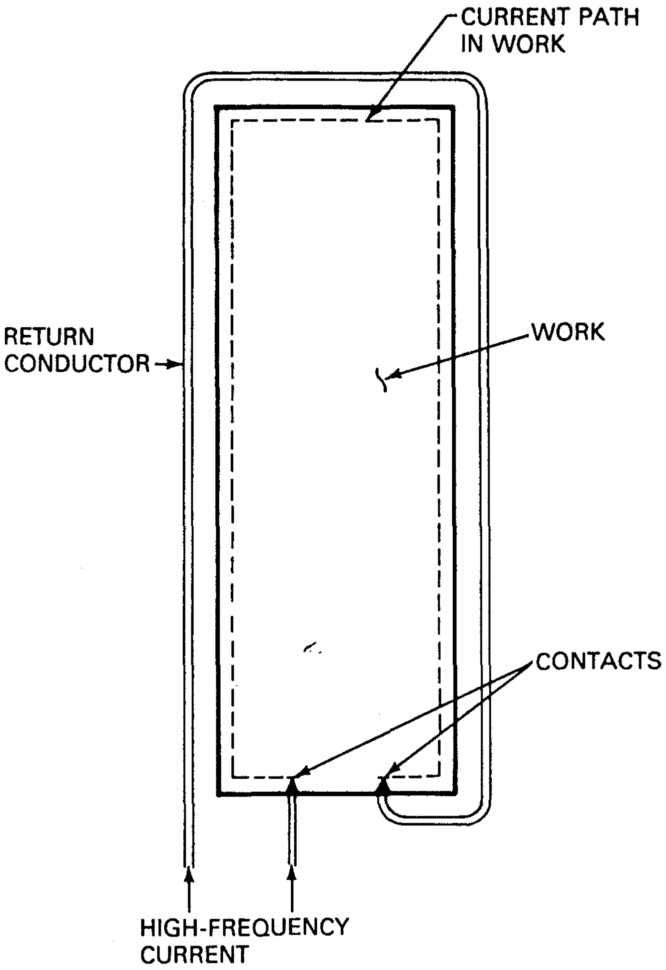


Figure 20.3—Restriction of the Flow Path of High-Frequency Current by the Proximity Effect of the Return Conductor

Both the skin effect and proximity effect become more pronounced with increasing frequency. Therefore, the effective resistance of the current path in the work increases as the frequency increases because as frequency increases the current is confined to a shallower and narrower path. This current concentration is advantageous because extremely high heating rates and high temperatures can be achieved in a localized area. Moreover, these high temperature concentrations can be positioned where they are needed at the surfaces to be welded.

Current patterns (high-temperature concentrations) in the work piece at frequencies of 60 Hz and 10 000 Hz are illustrated in Figure 20.4. In Figure 20.4(A), the return conductor is positioned parallel and close to the plate. The 60 Hz current flowing in the steel plate travels in opposite phase to the current in the adjacent proximity conductor. In this case, the size and shape of the proximity conductor have a negligible effect on the distribution of the current in the steel plate. As a result, the current flows fairly uniformly throughout the plate cross section.

When a 10 000 Hz current is applied to the same system, as shown in Figure 20.4(B), the current in the work is confined to a relatively narrow band immediately beneath the proximity conductor. This narrow band is the path of lowest inductive reactance to the current in the plate. The shape and magnetic surroundings of the proximity conductor have considerable effect on the distribution of the current in the work, but have no effect on the depth of current penetration.

Two round proximity conductors at different distances from the work are illustrated in Figure 20.4(C). The closer

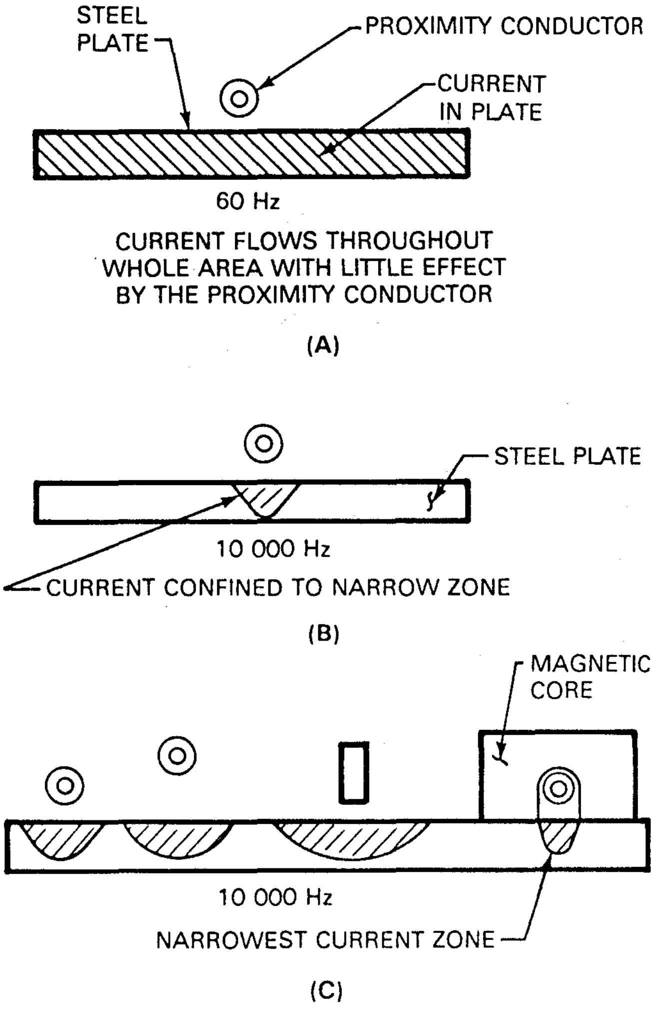


Figure 20.4—Current Depth and Distribution Adjacent to Various Proximity Conductors

proximity conductor develops a more confined current path. A rectangular proximity conductor with the narrow edge at the same distance from the work as the close round conductor exhibits a broader current distribution in the workpiece. If a magnetic core is placed around the proximity conductor, the current is further confined and heating takes place directly beneath the proximity conductor as shown.

If the two conductors with currents flowing in opposite directions are sheets placed edge to edge in a plane with a small gap between them, the proximity effect will cause the two adjacent edges to heat. The skin effect will confine the current to a shallow depth at those edges. This is the situation which occurs during the butt welding of the longitudinal seam of tube and pipe using either the HFIW or HFRW process.

Almost all high-frequency welding techniques employ some force to bring the heated metals into intimate contact during coalescence. During the application of force, an upset or flash occurs in the weld area. In many cases, the flash is removed after welding.

PROCESS VARIATIONS

HIGH-FREQUENCY INDUCTION WELDING

Tube Seam Welding

HIGH-FREQUENCY INDUCTION welding is generally used to weld continuous seam tube and pipe. The tube is formed from metal strip in a continuous roll-forming mill and enters the weld area with the edges to be welded slightly separated. In the weld area, they converge in a "vee" until they touch at what is referred to as the *weld point.* An induction coil, typically made of copper tubing, or copper sheet with attached cooling tubes, encircles the tube slightly ahead of the weld point. A current is induced by this induction coil which flows both around the tube immediately underneath the coil and along the tube edges between the induction coil and the weld point. This is illustrated in Figure 20.5.

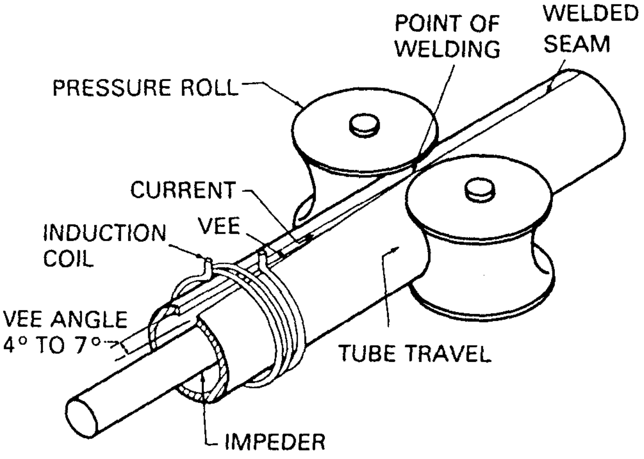


Figure 20.5–Joining a Tube Seam by High-Frequency Induction Welding

The high-frequency current follows in a localized path down one side of the vee consisting of the two edges being welded and back along the other due to the skin and proximity effects. The edges are resistance heated to a shallow depth. Welding speed and power level are adjusted so that the two edges are at welding temperature when they reach the weld point. At that point, pressure rolls forge the hot edges together and upset them to produce a weld. Hot metal containing impurities from the faying surfaces of the joint is squeezed out in both directions. The upset metal is normally trimmed off flush with the base metal. In the case of very thin wall tubes where the wall thickness is of the order of two times the depth of current penetration or less, a magnetic core called an *impeder* is required inside the tube. An impeder will limit the current flowing around the inside circumference of the tube which detracts from the current available to heat the metal at the vee and reduces the efficiency of the process.

The impeder is normally made of a ferrite material, and it must be cooled to prevent its temperature rising to the curie point where it becomes nonmagnetic. As the pipe or tube gets larger, the losses around the outside circumference of the tube become larger relative to the heating in the vee, making the process progressively less efficient. Therefore, induction welding is more efficient for smaller sizes of tube and pipe, and high frequency resistance welding becomes more competitive for larger sizes.

Butt Welding of Hollow Pieces

HFIW OF INDIVIDUAL pieces can be done only when the induced current can circulate in a closed circuit path. A typical application is the welding of butt joints between sections of pipe or tubing. A narrow induction coil is placed around the joint. High-frequency current in the coil induces a circulating current concentrated in the area of the butted pipe joint which is heated very rapidly. When the metal reaches welding temperature, it is upset to pro-

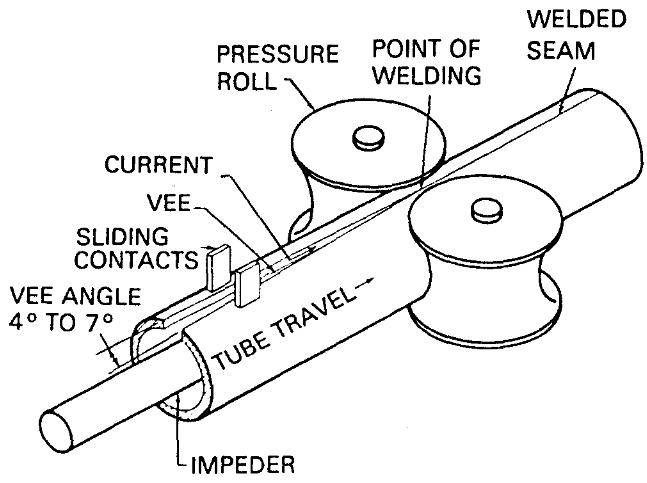


Figure 20.6–Joining a Tube Seam by High-Frequency Resistance Welding

duce a forge weld. The placement of the coil in this application is shown in Figure 20.1(J). This process is used for welding high-pressure boiler tube with diameters of from about 1 to 3 in. (25 to 75 mm) and with wall thicknesses up to about 0.375 in. (10 mm). It has also been used for joining pipe up to about 12 in. (300 mm) in diameter in the field. Welding times range from 10 to 60 seconds per joint.

HIGH-FREQUENCY RESISTANCE WELDING

Continuous Seam Welding

THIS APPLICATION IS generally similar to high-frequency induction welding, particularly when welding tube or pipe as shown in Figure 20.6. In this case, however, the high frequency current is introduced into the work with a pair of small sliding contacts placed on either side of the seam to be welded ahead of the weld point. The welding current travels directly from one contact along one edge of the welding vee to the weld point and back along the opposite edge to the other contact. The edges are forced together by weld pressure rolls at the weld point. When welding large diameter tube there is virtually no current flowing around the outside circumference of the tube and, therefore, the efficiency of the process does not decrease with increasing tube diameter. A current can flow around the inside circumference of the tube and, for smaller diameter tubes, an impeder is used to minimize this current flow.

Continuous HFRW seam welding is not confined to the welding of closed shapes such as tube and pipe. It can be adapted to many other products. Some of these are illustrated in Figure 20.1(D), (E), (F), and (H). High-frequency welded beams are produced from low carbon or high-strength low alloy materials. The high-strength low alloy steel beams are used in commercial vehicle and trailer frames where their high-strength-to-weight ratio is particularly valuable. Nonferrous beams have been produced for special applications. High frequency welded finned tubes are widely used in heat exchange applications.

Finite Length Welding

TECHNIQUES ARE AVAILABLE for butt welding the ends of two strips together. This is done by passing a high-frequency current through the joint area. The current is introduced at each end of the joint by small contacts and is confined to the area of the joint by a proximity conductor. Generally, a magnetic core is used to assist in narrowing the current path, as shown in Figure 20.4 (C). By selection of the proper frequency, the depth of penetration of the current can be adjusted to heat the joint through its thickness. When the joint reaches welding temperature, forging force is applied, and the hot metal is upset. Joints are made in this fashion at rates as high as 1000 joints per hour. The use of a proximity conductor in the HFRW of strip butt joints is illustrated in Figure 20.7.

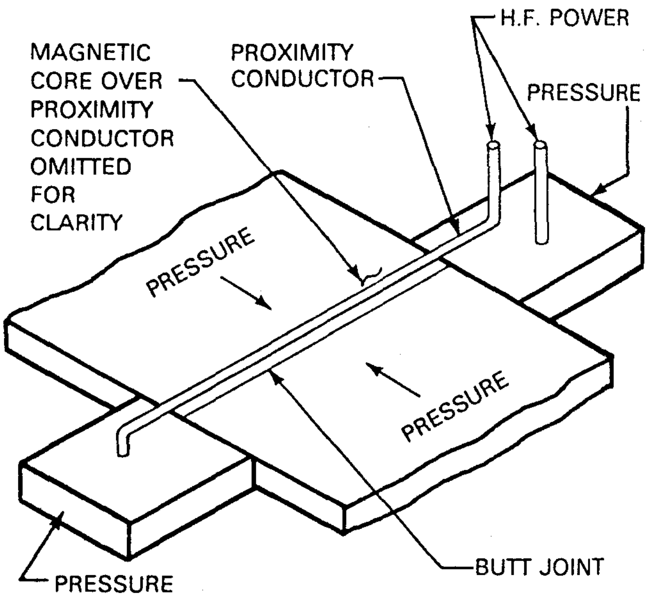


Figure 20.7–Joining Strips Together Using High-Frequency Welding

EQUIPMENT

POWER SOURCES

EXCEPT FOR A few special applications, such as tube and end and strip butt welding, vacuum tube oscillators with output power ranging from 50 to 1200 kW at frequencies ranging from 200 to 500 kHz are used for high-frequency welding. A basic circuit for a typical high frequency oscillator is shown in Figure 20.8.

Units can be manufactured for special line voltages, but typical input voltages are either 460 V, 60 Hz, 3-phase, or 380 V, 50 Hz, 3-phase. After the incoming circuit breaker and contactor, there is a 3-phase SCR (thyristor) voltage regulator. The regulator is designed both to maintain a preset voltage when the line voltage varies and also to enable the preset voltage to be controlled either automatically or by the welder operator. In automatic operation, control is dependent upon variables such as the weld temperature or the mill speed.

The plate transformer converts this controlled voltage to a high voltage which is then rectified to provide the direct current required for the oscillator circuit. The filter choke and filter capacitor reduce the ripple in the dc to an acceptable level, typically less than one percent. The oscillator circuit converts the direct current to high-frequency alternating current for the output transformer. The output transformer converts the high voltage-low current power to the low voltage-high current power required for welding.

Vacuum tube oscillators inherently have high output impedance (high voltage-low current) and must be fed into high impedance loads. The inductors and the workpiece contact circuits in high-frequency welding are low impedance (low voltage-high current) loads. An impedance matching output transformer is required to transfer energy efficiently from the oscillator to the work. Power is transferred most efficiently from the high-frequency generator to the work when the impedance of the work circuit matches the impedance of the generator. For induction welding, variable impedance matching transformers are often used in which the primary winding can be moved relative to the secondary winding to match the relatively wide impedance range typical of induction applications.

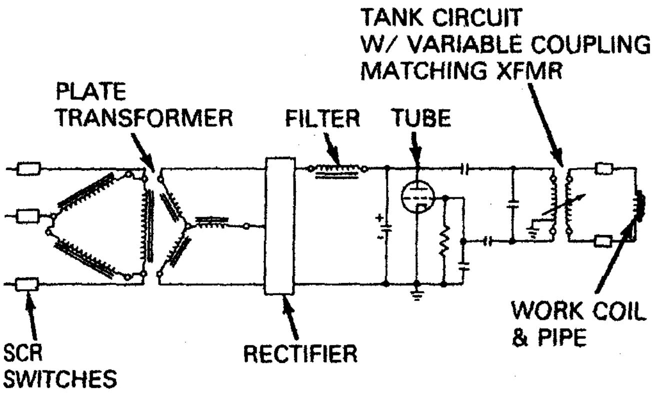


Figure 20.8–Schematic Circuit for a Typical High-Frequency Oscillator

The secondary winding of the impedance matching transformer is in series with the induction coil or the contacts and workpiece. This forms the low voltage-high current welding system. The connecting leads should have the lowest possible impedance to obtain high efficiency and to minimize the voltage drop in the leads. This may be achieved by using short, wide leads made of flat copper plate separated by approximately 1/16 in. (1.6 mm) of insulation. Power losses in poorly designed leads or incorrectly matched transformers can seriously degrade the performance of a high-frequency welding system.

SOLID-STATE WELDING POWER SOURCES

FULLY TRANSISTORIZED SOLID-STATE welding power sources have now been developed which are expected to displace vacuum tube units in the future. A number of units are in operation under production conditions for tube welding applications.

The efficiency of a typical vacuum tube unit is between 50 and 65 percent depending on its age, design, and operating conditions. Solid-state power sources are smaller in size and have already demonstrated efficiencies of over 80 percent. Higher efficiencies can be expected as this technology develops. Economies result from a significant decrease in power consumption and a reduction in cooling water consumption. In addition, the incoming wiring and switchgear required for these units is smaller. The quality of welds made by these units has been found to be comparable to those made by vacuum tube units.

INDUCTION COILS

AN INDUCTION COIL, also called an *inductor,* is generally fabricated of copper tubing, copper bar, or copper sheet. It is normally water cooled. The highest efficiency is obtained when the induction coil completely surrounds the workpiece. The coil may have one or more turns as required by the application. The strength of the magnetic field which induces the heating current in the workpiece diminishes rapidly as the distance between the coil and the workpiece is increased. Typical spacing between coil and workpiece ranges from about 1/8 in. (3 mm) for small di-

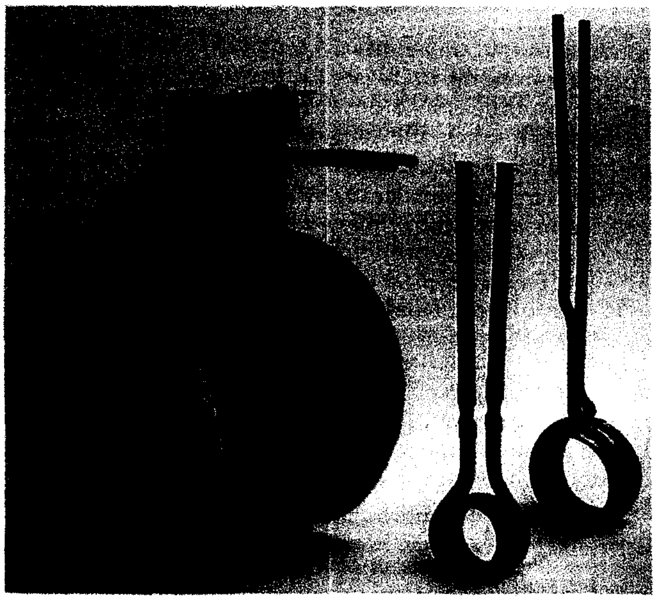


Figure 20.9—Typical Inductor Coils

ameter products up to 1 in. (25 mm) for large diameters. Some typical induction coils are shown in Figure 20.9.

CONTACTS

THE HIGH-FREQUENCY current transfer contacts are usually made of a copper alloy or of hard metallic or ceramic particles in a copper or silver matrix. The contacts are *silver brazed to heavy water-cooled copper mounts.* Replacements can be made by exchanging the mount and the contact tip assembly. Contact tip area ranges from 0.25 to 1 in.^{2} (160 to 650 mm^2) depending upon the current to be carried. Welding currents are usually in the range of 500 to 5000 A. Consequently, both internal and external cooling for the contact tip and mount is required.

The force of the contact tip against the work is usually in the range of 5 to 50 pounds (20 to 220 N) for a continuous welding system. It depends upon the contact size, the surface condition of the part, the contact material being used, and the current required. Welding current is determined by the thickness of the part being joined and the welding speed. Contact life is dependent upon a number of factors including the contact material, the contact pressure, the material being joined and the welding current. Contact life can be as low as 1000 ft (300 m) under very severe conditions of high current and poor workpiece surface condition such as heavy wall steel pipe, to over 300 000 ft (90 000 m) for light wall nonferrous materials. A typical contact system showing the flexible adaptors with pneumatic pressure regulation is shown in Figure 20.10.

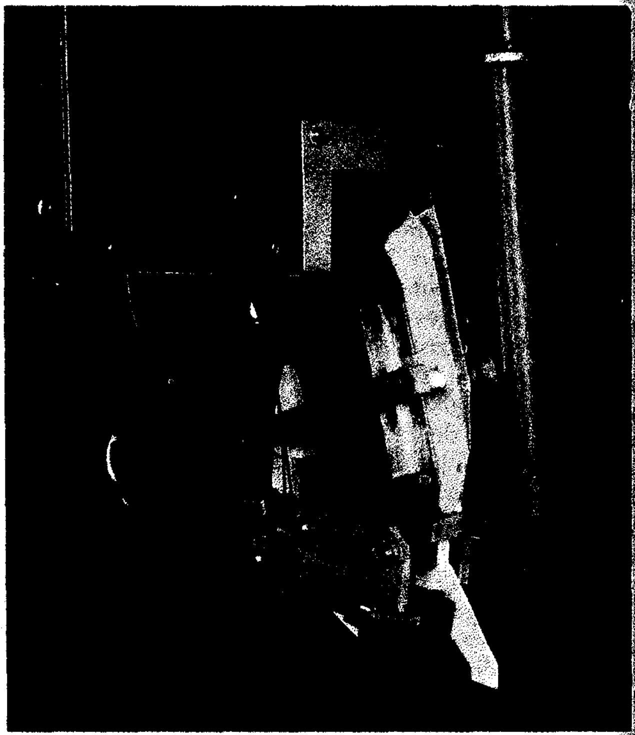


Figure 20.10—Typical Welding Contact Assemblies

IMPEDERS

WHEN WELDING TUBE and pipe with both the HFIW and HFRW processes, current can flow on the inside surface of *the tube as well as on the outside surface.* This current flows in parallel with the welding current and results in a substantial power loss at the joint edges. Because the lost power does not heat the joint edges, the weld temperature cannot be reached unless the welding speed is reduced or the power increased. To minimize this loss, an impeder is placed inside the tube in the weld area. The impeder increases the inductive reactance of the current path around the inside wall of the tube. The higher inductive reactance reduces the undesirable inside surface current. Thus, higher welding speeds are attainable for a given power input.

Impeders are typically made of one or more ferrite bodies and are usually cooled with water or mill coolant to keep their operating temperature below the Curie point where they lose their magnetic properties. Impeders are particularly important when a mandrel must run through the tube in the weld area in order to perform an inside weld bead treatment such as inside scarfing or bead rolling. Without impeders, such a mandrel, even though it should always be made of a nonmagnetic material such as austenitic stainless steel, reduces the inductive reactance of the

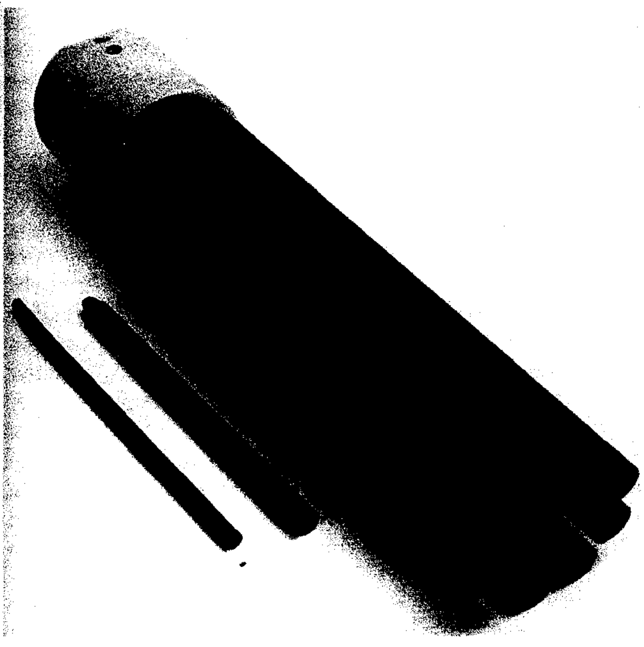


Figure 20.11–Typical Impeders

current path around the inside wall of the tube. The mandrel also reduces efficiency because it is induction heated due to the voltage induced in it by this same inside current. Impeders must therefore be placed on top of the mandrel immediately below the weld vee area or preferably completely surrounding the mandrel.

The impeder should extend from a point at or slightly upstream of the apex of the welding vee to a point at least 1-1/2 tube diameters upstream of the welding contact or the upstream edge of the induction coil in order to obtain the maximum beneficial effect. Some typical impeder arrangements are shown in Figure 20.11. Impeders are generally not needed when welding large diameter tube and pipe with the HFRW process.

CONTROL DEVICES

Input Voltage Regulators

HIGH-SPEED, HIGH-FREQUENCY seam welding requires accurate control of the weld power level. Short-term transient power fluctuations can result in intermittent weld imperfections, and a long-term drift in the power level will lead to less than optimum welding conditions. Thus, it is important that the power be automatically and continuously regulated. Today, virtually all high-frequency generators use silicon controlled rectifiers (thyristors) for power regulation. Their control circuits are designed to continuously correct for changes in input voltage, to regulate the output power, and to rapidly turn off the power in response to overload or fault conditions. For continuous operation, it is essential that the welding power be essentially free from line frequency ripple, particularly when welding thin wall nonferrous metals at high speed. Excessive fluctuations in power can cause intermittent lack of fusion along the weld seam called *stitching*. Filters are used on the rectifier output to reduce the dc voltage ripple to one percent or less.

Speed Power Control

IN ORDER TO maintain proper welding conditions at different mill speeds and especially to minimize scrap when the mill is started and stopped, the weld power can be automatically adjusted as a function of mill speed. This system is most effective when welding low carbon steel tube, and can virtually eliminate any unwelded seam when the mill is stopped and restarted. The system will also reduce scrap when welding stainless and alloy steels and nonferrous materials, but typically a small unwelded length of product results when stopping and starting a mill running these materials.

Weld Temperature Control

VARIATIONS IN WELD temperature can be caused by variations in strip thickness and welding speed as well as deterioration of the impeder. These variations can be minimized by the addition of a weld temperature control. This reads the output of an optical pyrometer aimed at the weld vee and automatically adjusts the weld power to maintain a constant preset value.

MECHANICAL EQUIPMENT

MECHANICAL EQUIPMENT IS required in both the continuous and finite length high-frequency welding processes. The weld edges must be precisely aligned mechanically, and this alignment must be maintained as the upset pressure is applied to consummate the weld. The condition of the edges to be welded is also important. A mill-slit edge is normally satisfactory, if the edges are not damaged during shipment from the slitting mill. For both precision thin wall tubing and high-quality heavy wall tubing, the strip edges should be trimmed on the welding line. The edges can be trimmed with a stationary cutting tool or with a milling cutter. When welding large diameter pipe using single strand rolled to width material, the edges are often slit off in line immediately ahead of the forming section of the pipe mill.

In continuous seam welding, the edges to be joined are brought together to form a vee. The included angle of the vee is about four to seven degrees. If the vee angle is too small, arcing across the vee may occur, and it is difficult to maintain the vee apex at a constant location. If the vee is too wide, mechanical and thermal control of the edges may be lost and they may tend to buckle. The optimum vee angle depends on the tooling design and the base metal. Variations in the angle and length of the vee will cause variations in the weld quality.

The edges of the vee should be parallel to each other in the plane perpendicular to the weld travel. If the edges are closer on the inside as they approach the apex, then the inside edges will draw more current due to the proximity affect and become overheated relative to the outside edges. This will cause excessive upset inside the pipe or insufficient upset at the outside, or both, leading to difficulty in removing the inside upset and possible weld defects at the outside.

Both the outside and the inside flash can be removed using single point tools arranged closely behind the weld point. The inside flash may be left as welded or rolled smooth for some products.

ACCESSORY EQUIPMENT

FOR CERTAIN BASE metals, such as medium and high carbon or alloy steels, the products are postweld heat-treated. Low carbon steels may be annealed or stress relieved to restore ductility which was reduced during forming, welding, and sizing.

In most cases, only the weld zone is heat-treated. This is called *seam annealing*, but generally the seam is normalized and not fully annealed. Seam annealing is performed in line by induction heating immediately following the upset removal operation. A special linear inductor is used to seam anneal at a frequency of 1 to 3 kHz depending on the wall thickness of the pipe. Low frequencies are more efficient on wall thicknesses over 3/8 in. (10 mm), but they are extremely noisy. For this reason, tubes less than 1/2 in. (13 mm) thick are often seam annealed at frequencies between 2.5 and 3 kHz.

Some applications require the complete tube to be heat-treated. This heat treatment may be performed in line after welding and sizing using induction heating. The induction heating frequency used depends on the base metal, diameter, wall thickness, and the required temperature. Medium frequencies between 1 kHz to 10 kHz are usually used although higher frequencies may be needed for small diameter tubing. An inert atmosphere may be provided during heating and cooling to prevent surface oxidation. Tubes may also be heat-treated off-line.

CONSUMABLES

AS A GENERAL rule, there are no true consumables used in HFIW, and only the welding contacts are consumed in HFRW. As mentioned earlier, the contacts must be replaced from time to time. Typical contact life is between 1000 ft (300 m) to 300 000 ft (91 km) of tube or pipe. Filler metal is not used in any high-frequency welding process currently in production.

A flux or inert gas may be used when welding titanium, some grades of stainless steel, or brass tubing, but these are special situations.

APPLICATIONS

Base Metals

ALMOST ALL ENGINEERING metals and alloys can and have been joined by high-frequency welding. The exceptions are metals that cannot be hot formed, are unstable at elevated temperatures, or have unsatisfactory properties that cannot be restored by mechanical or thermal postweld treatments. Such a material would be cast iron. Reactive metals can be protected with an inert atmosphere. Inert shielding may be unnecessary because the weld cycle time is very short. High-conductivity metals such as pure copper are satisfactorily welded, and dissimilar metals can be readily joined. However, in dissimilar metals, the weld temperature is limited to the lower melting point of the two metals.

Metals with large nonmetallic inclusions, with large grain size, and with damaged or contaminated faying surfaces can be difficult or impossible to weld satisfactorily. Uniformity of dimensions, strength, and electromagnetic and thermophysical properties are desirable for consistent high quality welding.

JOINT DESIGN

THE FAYING SURFACES of butt, tee, and lap joints should be parallel in the plane perpendicular to the weld travel. This will assure uniform surface heating in the weld vee.

Unequal heating of the faying surfaces of tee welds is unavoidable. The thinner member will typically be at a higher temperature.

The direction of the upset should be perpendicular to the faying surfaces. Shearing forces during upset usually result in voids, contamination, or hot-tearing.

Metallurgical Considerations

BEFORE UPSETTING, A small layer of molten metal forms on one or both faying surfaces. Below the molten layer a heat-affected zone forms in which metallurgical changes occur. The weld thermal cycle is brief, and therefore the metallurgical reactions may not be completed resulting in unusual metastable structures.

Materials which can be hardened by heating and quenching have hard weld zones that may require postweld heat treatment. Work-hardened base metals are softened in the narrow heat-affected zone. Precipitation hardened materials may be partially annealed or overaged.

The joint upsetting process which occurs downstream of the weld apex not only forces most of the molten metal and the contaminants out of the joint, but also hot-works the adjacent metal. This may result in grain refinement and improved mechanical properties immediately next to the bond plane. The upset also creates a sharp rotation of the base metal so that laminar inclusions in the base metal adjacent to the bond plane may become substantially parallel to the bond plane resulting in heat-affected-zone discontinuities known as *hook cracks*.

Weld discontinuities are principally the result of significant, thin, flat nonmetallics at the weld interface. The discontinuities are usually caused by inadequate heating or inadequate upset. Inadequate heating or upset can be constant or variable due to unstable operation. If enough weld power is available, weld quality generally improves with increasing weld speed.

Faying surfaces with mechanical damage or containing excessive contaminants are a common cause of defects.

Typical Uses

BY FAR THE greatest number of high-frequency welding machines are used to make pipe and tube. There are over 40 American Society for Testing Materials standards covering all types of tubes and pipes. Some of these products require welds made only by high-frequency welding, and others specify high-frequency welding as well as other methods. There are also a number of American Petroleum Institute (API) specifications for line pipe and other oil country goods which allow high-frequency welding.

A 1000 kW induction welder in operation on a heavy wall structural tube mill is illustrated in Figure 20.12. The formed open seam tube proceeds from the right of Figure 20.12 through the induction coil. The edges are heated between the induction coil and the weld pressure roll assembly, and the hot-welded seam cools rapidly beyond the weld pressure rolls. The weld bead removal stand is hidden behind the structure supporting the upper weld pressure rolls. The weld temperature control pyrometer is mounted on this structure with its air-purged sight tube pointing to the weld point.

Longitudinal butt welded tube and pipe is made from several metals in many sizes. At the small end of the spectrum is automotive radiator tube made of either aluminum or brass. Radiator tube can be as small as 3/8 in. (10 mm) diameter and is induction welded in production in wall thicknesses as low as 0.0045 in. (0.11 mm). At the opposite end of the spectrum is API steel line pipe. Line pipe as large as 48 in. (1.2 m) diameter and 1 in. (25 mm) thick has been produced using the contact method. Among the metals welded by HFRW and HFIW are low carbon, high-strength low alloy, high-strength carbon and alloy steels, stainless steels, aluminum and aluminum alloys, copper and copper alloys, some nickel and titanium, and other nonferrous alloys.

Most tubing is produced in a round shape but tubes can be rolled to other shapes such as square or rectangular. Complex, roll-form shapes, which in some cases require two longitudinal welded seams, are also produced. There are also a number of specialized applications such as the welding of tapered lamp posts and the welding of a metal sheath around an electrical cable. Thin walled, lap-welded tubing may also be high-frequency welded.

Helically wound pipe and tube can also be HFRW using lap or butt joints. Corrugated culvert pipe in diameters between 2 ft (600 mm) to 8 ft (2400 mm) are helically wound. Other operations may be integrated with the HFW mill either before or after welding. For example, hole patterns may be punched in the strip prior to forming and welding. A flying cutoff can be synchronized with the hole pattern providing a finished tubular part complete with the required hole pattern and needing no subsequent drilling or punching.

Zinc or aluminum coated tubing can be welded from precoated base metals. After the weld has been made and the outside weld bead removed, a metal spray can recoat the weld area to provide a complete coating. Alternatively, steel strip can be welded and then cleaned, full-body induction heated, and passed through a molten zinc bath to produce a galvanized tube directly from uncoated strip.

Tubes can also be hot-or cold-stretch reduced in line after welding. Induction heating is generally used to heat the tube prior to hot stretch reducing. Alternatively, the tubes can be cold stretch reduced in line and subsequently stress relieved by induction heating prior to coiling or cutting to length.

A.P.I. line pipe and some other tubular specifications require that the weld seam be normalized after welding. This heat treatment eliminates any untempered martensite in the weld heat-affected zone. The in line heat treatment is performed using a special linear inductor that induction heats the weld area to a width of between one and three times the wall thickness of the tube. The heated area is then allowed to air cool prior to final water quenching, sizing, and cutoff. The entire tube may also be fully heat-treated either in line or off line after cutoff.

Structural shapes such as I and H beams as well as tee sections can be high-frequency welded from flat strip using specially constructed structural welding mills. A typical range of structural member sizes is shown in Table 20.1. Structural shapes are made commercially from low carbon

Table 20.1
Typical Range of Sizes for High Frequency Welded Structural Steel Shapes

	In.	mm
Section Height	3 to 20	75 to 500
Section Width	2 to 12	50 to 300
Web Thickness	.08 to .40	2 to 10
Flange Thickness	.12 to .50	3 to 12

Note: Tooling can be provided for I, T, and H Sections. The sections may be symmetrical or assymetric. The flanges of I and H Sections may be of different widths or thicknesses.

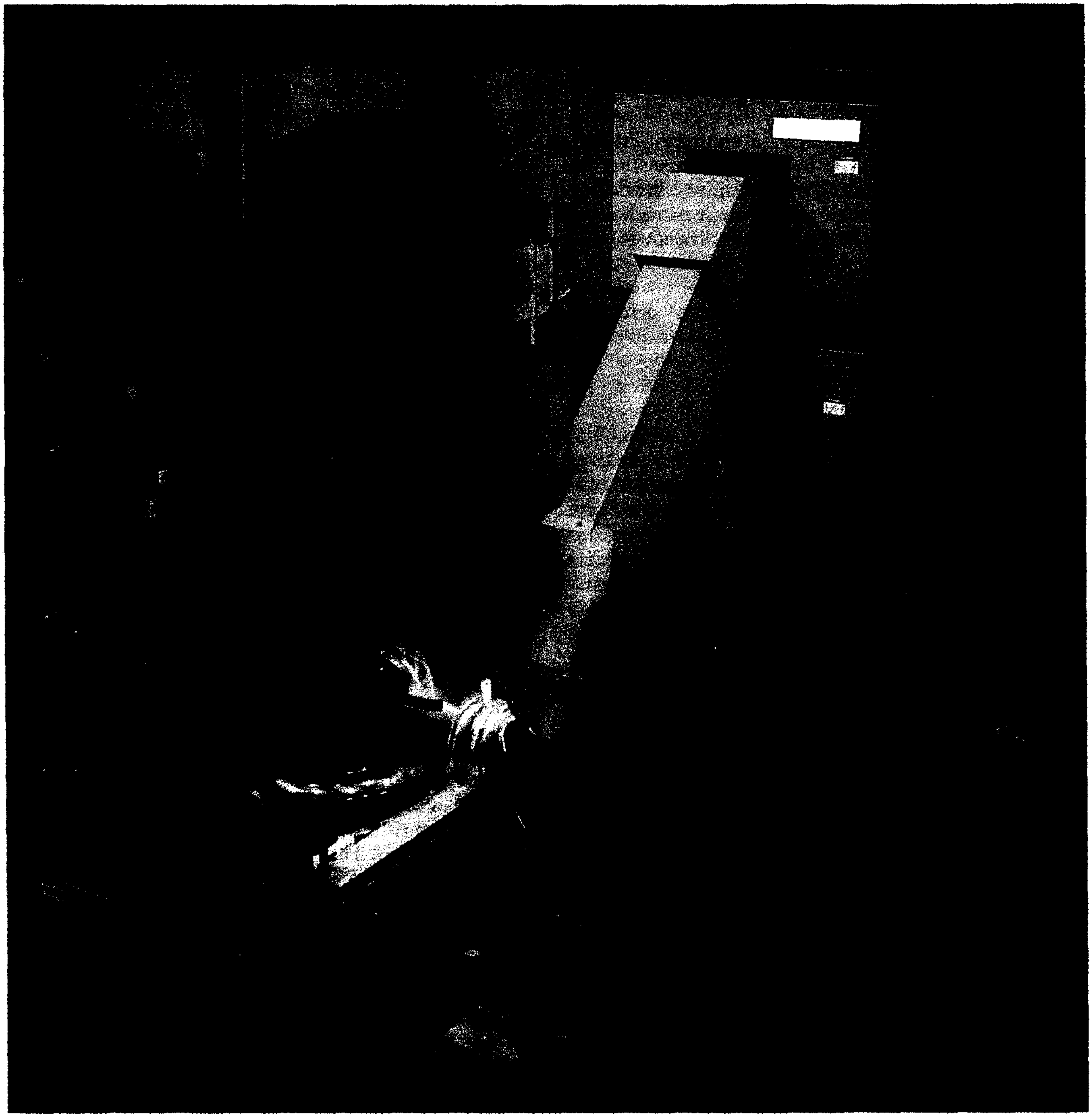


Figure 20.12–1000 kW Induction Welder

and high-strength low alloy steels. Stainless steels, titanium, and aluminum have also been welded on a laboratory scale. For some special applications, stiffening ribs can be formed into the web of the beam immediately after welding to increase its resistance to buckling.

Two different geometries of finned tubing can also be fabricated by high frequency welding. In one, the fin is helically wound on edge onto a tube and simultaneously welded to the surface of the tube. The fin and tube may be either of the same material or of different materials. In the other, fins are welded longitudinally to tubes for the manufacture of boiler water walls.

Tubes can be welded to strip or sheet metal for solar absorber plates or freezer liners. Two strips can be welded together with a butt or lap joint. These can be the same or different metals.

In addition to these continuous processes, high-frequency welding can also be used for making finite length joints between the ends of two tubes or the ends of two strips. Lower frequencies between 3 and 10 kHz are usually used to weld finite length metal weldments. Examples of a few products that can be fabricated by high frequency welding are shown in Figure 20.13.

Mechanical Properties

HIGH-FREQUENCY WELDS are autogenous hot-forged welds where most molten metal on the faying surfaces immediately prior to the forging operation is expelled leaving little or no cast structure in the joint area. The mechanical properties of the subsequent welded joints depend upon the inherent strength of the base metal after rapid heating, forging, and cooling. Low carbon and high-strength, low alloy steels and nonheat treatable aluminum weldments can be used in the as-welded condition. The joint is as strong as the base metal. Medium and high carbon steels may form martensite in the weld heat-affected zone, and therefore these weldments are almost always postweld heat-treated. Heat treatable grades of aluminum are softened by the rapid heating and quenching that occurs during welding. Postweld heat treatment is usually required to restore strength to the weld zones. Steel structural shapes are usually made either from low carbon or high-strength, low alloy steels, and therefore these sections are used in the as-welded condition.

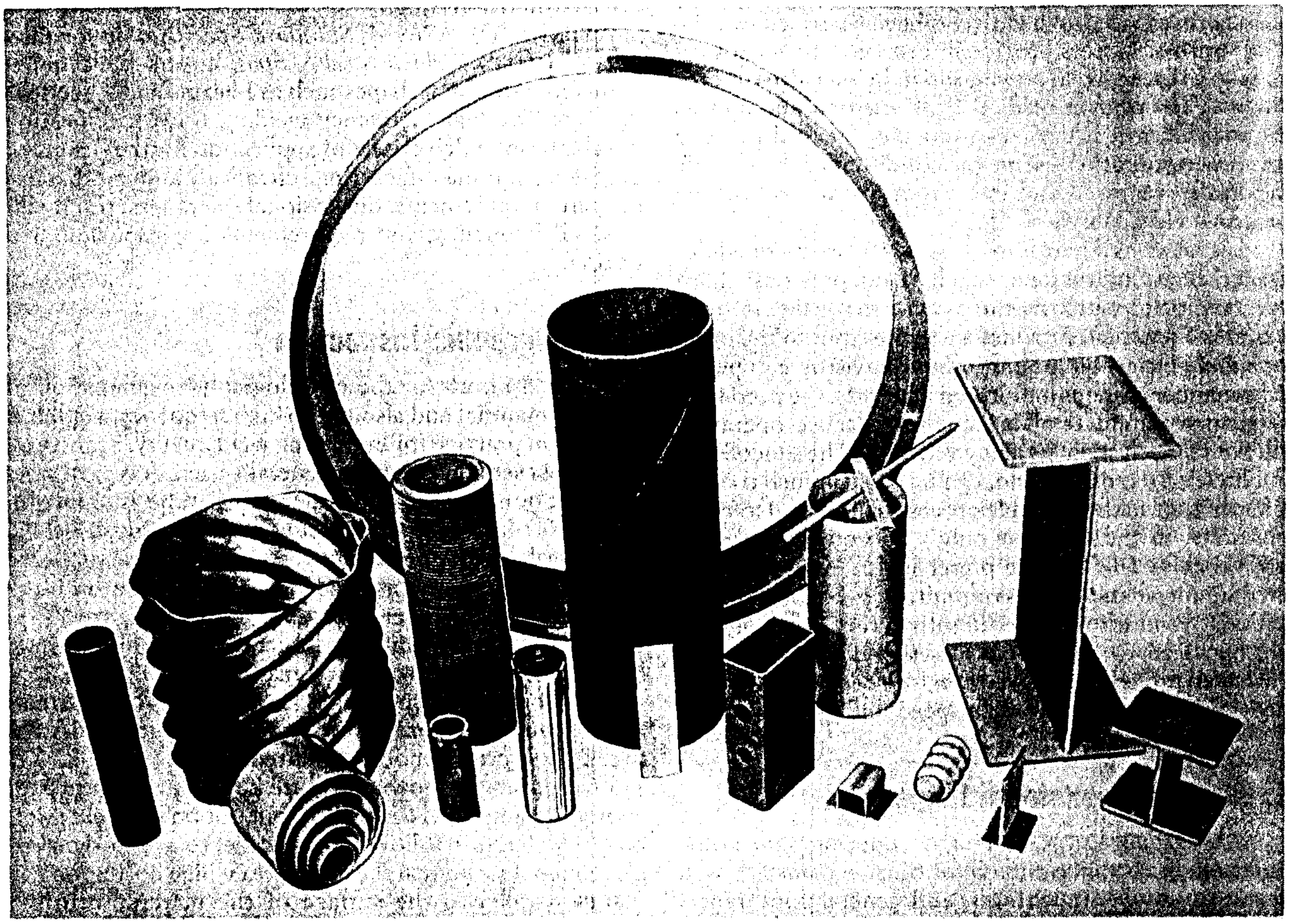


Figure 20.13–Some Products Produced by High-Frequency Welding

INSPECTION AND QUALITY CONTROL

PROCESS CONTROL

VIRTUALLY ALL HIGH-FREQUENCY welding systems are continuous mills. Fully automated mills contain strip accumulators to allow continuous operation even when the start of a new coil of strip is being welded to the end of the previous coil. The only reason for a mill with an accumulator to stop would be a fault condition or a planned shutdown. Thus, the best method of quality assurance in a high-frequency mill is by means of process control.

Theoretically, if the mill has been set up to make a satisfactory product and if every possible mill variable is monitored and remains constant, then the product quality will remain constant. However some variables are either not known or not properly understood. Others may be known but cannot be effectively monitored or controlled. However, the most important variables are known and can be controlled, and by doing so, the most consistant product quality is achieved.

Basic process control has always been practiced by tube mill operators. Meters provide information on such variables as mill speed, weld power, and individual drive motor current. The operator reads the information and adjusts the variable when it deviates from the standard practice value. Operators also observe the condition of the outside bead as it is removed and infer from this inspection the probable weld quality.

Today, however, there is increasing availability of equipment either to monitor items that have not previously been monitored or to better monitor those that have. In most cases, this equipment provides a visual output to the operator and an electronic output to a supervisory computer. As the number of items monitored increases, the need for a supervisory computer also increases because operators cannot effectively manage many variables. The supervisory computer, on the other hand, can be programmed to continuously scan all the available process sensors and to communicate with the operator only when one or more of these variables falls outside preset limits. As mill speeds increase, automatic process monitoring becomes more necessary. Failure to correct unsatisfactory welding variables may lead to large scrap losses at high mill speeds. Automated process control is therefore becoming increasingly common on modern high-speed mills.

Visual and Dimensional Inspection

A TYPICAL SPECIFICATION for a high frequency welded tube will include acceptance criteria for outside diameter, wall thickness, ovality, straightness, and general appearance. Other high frequency welded products are also required to meet specified dimensional tolerances. In most cases, the dimensional checks are done manually on a small sample of the total amount of the product produced. For critical products, noncontact gauging systems based on ultrasonics, lasers, or similar techniques can be used to provide continuous measurement of wall thickness and outside diameter.

Product Testing Procedures

TEST REQUIREMENTS FOR tubular products are described in the ASTM A450/A450M, *Standard Specification for General Requirements for Carbon, Ferritic Alloy and Austenitic Alloy Steel Tubes*. This specification covers mandatory and nonmandatory requirements for a large variety of tubular products. The nonmandatory requirements would be mandatory if they are specified in the product specification or the purchase documents. ASTM A450/A450M covers requirements for chemical and mechanical testing, product dimensional tolerances, hydrostatic testing and nondestructive testing.

ASTM A769/A769M, *Standard Specification for Electric Resistance Welded Steel Shapes*, covers the requirements for structural shapes such as I beams and T sections produced by high frequency welding. This specification covers the intended classes of application for the structural products, the manufacturing, chemical, and mechanical property requirements, dimensional tolerances, test methods and frequency, and requirements for inspection and testing.

Metallographic Inspection

THIS IS USED both for the metallographic examination of the base material and also of the high frequency weld. It is a common practice for evaluating weld quality. Transverse weld cross sections are most generally used. A typical weld cross section in a small diameter steel tube is shown in Figure 20.14. The outside upset has been removed, but the inside flash has not been removed. A large diameter, heavy wall steel tube in the as-welded condition with both the outside and inside upset removed is shown in Figure 20.15. This high quality hydraulic cylinder tubing is subsequently heat-treated and drawn over a mandrel.

Metallographic inspection is also valuable for determining the cause of failure in mechanical tests such as flattening tests. A cross section of flattening-test failure in API J55 well casing is shown in Figure 20.16. The failure path shown in Figure 20.16 is close to but not on the weld interface. The fracture follows lines parallel to and at right angles to the flow lines in the upset area which correspond to planes parallel to the surface of the material prior to upsetting.

The cause of failure can be traced, in this case, to a lack of ductility in the through-thickness direction of the hot-

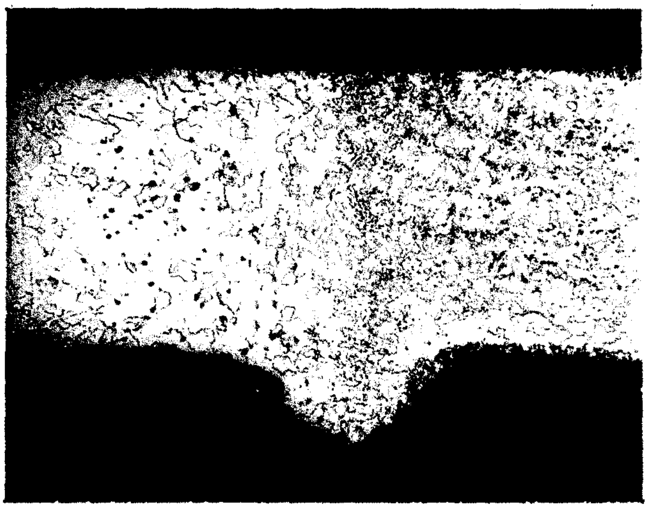


Figure 20.14—Cross Section Through High-Frequency Weld in 1.25 in. (32 mm) Diameter, 0.043 in. (1.1 mm) Wall Structural Tubing (Magnification 50x)

rolled material. A longitudinal cross section of the base metal (parallel to the rolling direction) is shown in Figure 20.17. Numerous nonmetallic inclusions lying in planes parallel to the surfaces of the material are evident. These nonmetallics result in weakness in the through thickness direction. Low ductility in the through-thickness direction is common in hot-rolled metals. It is improved by reducing the elongated nonmetallic inclusions in the metal.

Nondestructive Inspection

REQUIREMENTS FOR NONDESTRUCTIVE inspection of HFW tubes are provided in ASTM A450/A450M, *Standard Specification for General Requirements for Carbon, Ferritic Alloy and Austenitic Alloy Steel Tubes*, and other documents referenced by that specification.

Ultrasonic testing is described in ANSI/ASTM E213, *Standard Recommended Practice for Ultrasonic Inspection of Metal Pipe and Tubing*, and ANSI/ASTM E273, *Standard Method for Ultrasonic Inspection of Longitudinal and Spiral Welds of Welded Pipe and Tubing.*

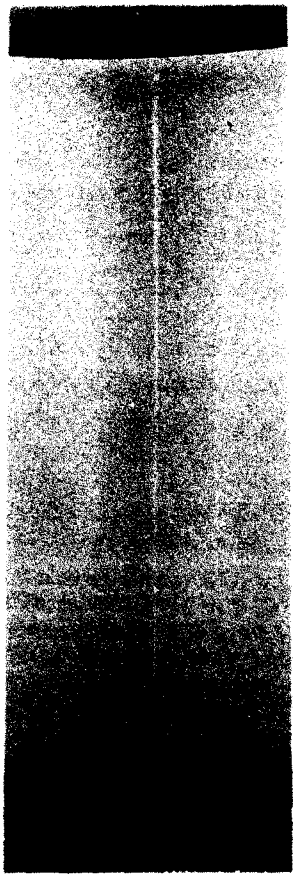


Figure 20.15—High-Frequency Welded Hydraulic Cylinder Tubing 11.25 in. Diameter, 0.65 in. Wall (As-Welded) (Magnification 6x)

Eddy-current testing procedures are described in ANSI/ASTM E309, *Standard Recommended Practice for Eddy-Current Examination of Steel Tubular Products Using Magnetic Saturation*, and ASTM E426, *Standard Recommended Practice for Electromagnetic (Eddy Current) Testing of Seamless and Welded Tubular, Austenitic Stainless Steel and Similar Alloys.* For smaller diameter tubes, coils encircling the tube are normally used, and for larger diameters, sector coils located over the weld seam can be used. A typical system consists of an exciting coil which induces eddy currents into the tube and a sensor coil that reads the resulting magnetic flux created by the induced currents. The exciting and sensor coils are typically packaged together as a single unit. A discontinuity in the welded seam will disturb the normal current flow pattern. The disturbed current will induce a magnetic field that differs from that produced in tube without a discontinuity. The sensor coil detects the difference.

Flux-leakage testing is described ANSI/ASTM E570, *Standard Recommended Practice for Flux Leakage Examination of Ferromagnetic Steel Tubular Products.* The tube is first magnetized to a level approaching its magnetic saturation. Discontinuities cause a leakage of the magnetic flux which is found by a magnetic detector.

In all of these methods, calibration standards are prepared by testing tubes of the same size and material as the one to be inspected. These test tubes contain known discontinuities such as drilled holes or transverse, tangential, or longitudinal notches, and they are used to simulate the

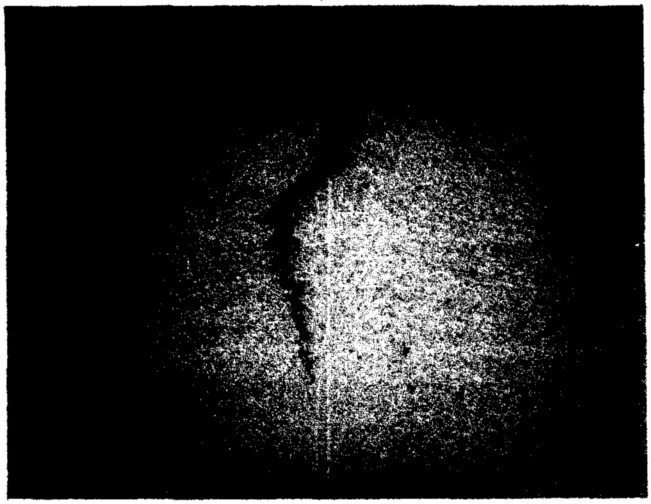


Figure 20.16–Cross Section of High-Frequency Weld in API J-55 Well Casing 4.5 in. O.D x 0.189 Wall Showing Flattening Crush Test Failure Near Bond Plane (Magnification 15x)

Figure 20.17–Longitudinal Section Through the Base Metal of the Pipe Shown in Figure 20.16.

type of discontinuity which may occur in the welding process. When a signal exceeding the magnitude of that required by the calibration procedures occurs, a marking system, typically a paint spray, identifies the location of the potential defect. In many cases, because of the high speed of the high-frequency welding process, it is difficult to discriminate between real weld defects and other discontinuities which may not be cause for rejection; therefore, the marked areas may subsequently be retested off line to verify the on line test.

Weld testing procedures such as x-ray, magnetic particle, and liquid penetrant are generally not applicable to high-frequency welding.

Ultrasonic testing, eddy-current testing, flux-leakage testing, or all three, may also be performed after subsequent processing such as stretch reduction, drawing, or cold expansion has been performed. Such subsequent processing may enlarge a discontinuity and make it easier to detect.

WELD PROCEDURE AND PERFORMANCE QUALIFICATIONS

WELDING PROCEDURES FOR high-frequency welding depend on the design of the mechanical equipment which forms and upsets the material, the type of product being produced, and the process being used—HFIW or HFRW. Because of the wide variety of mechanical equipment used together with the large number of product types produced, there are no standard welding procedures published on this subject. General guidelines are available from the equipment manufacturers, but the actual procedures used for any particular product are usually developed by the mill operator management.

SAFETY

THE HEALTH AND safety of the welding operators, maintenance personnel, and other personnel in the area of the welding operations must be considered in establishing operating practices. Design, construction, installation, operation, and maintenance of the equipment, controls, power supplies, and tooling should conform to the requirements of Federal (OSHA), State, and local safety regulations, as well as those of the company.

Voltages in high-frequency generators range from 400 to 30 000 volts and can be lethal. Proper care and safety precautions should be taken while working on high-frequency generators and their control systems to prevent injury. Modern units are equipped with safety interlocks on access doors and automatic safety grounding devices that prevent operation of the equipment when the access doors are open. The equipment should never be operated with panels or high-voltage covers removed or with interlocks and grounding devices blocked. The new fully transistorized units will use significantly lower voltages, usually less than 1500 V, but such voltages are still dangerous, and the same safety practices must be observed.

The high voltage-high frequency leads should be encased in grounded metal ducts both for safety and to minimize E.M.I. (electromagnetic interference) radiation. Low-voltage induction coils and contact systems should always be properly grounded for operator protection. High-frequency currents are more difficult to ground than low-frequency currents, and grounding lines should be short and direct to minimize inductive impedance. Care should be taken to prevent the high-frequency magnetic field around the coil and leads from heating adjacent metal parts of the mill by induction.

Personnel injuries from direct contact with high-frequency voltages, especially at the upper range of welding frequencies, tend to produce severe local tissue damage. However, fatalities are unlikely because the current flows on the surface of the victim's body.

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CHAPTER 21

ELECTRON BEAM WELDING

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CHAPTER 21

ELECTRON BEAM WELDING

INTRODUCTION

PROCESS HISTORY

SINCE ELECTRON BEAM welding (EBW) was initially used as a commercial welding process in the late 1950's, the process has earned a broad acceptance by industry. First employed by the nuclear industry, and then shortly thereafter by the aircraft and aerospace industries, the process was quickly recognized as having the capacity for enhancing both the quality and reliability of the highly critical parts used by these industries. The process also reduced the manufacturing costs.

During this initial period of commercial application, the process was limited strictly to operation in a high vacuum chamber. However, a system was soon developed that required a high vacuum only in the beam generation portion. This permitted the option of welding in either a medium vacuum chamber or a nonvacuum environment. This advancement led to its acceptance by the commercial automotive and consumer product manufacturers. As a consequence, EBW has been employed in a broad range of industries worldwide. Since the late 1960's the process has provided both very shallow and extremely deep single-pass autogenous welds with a minimal amount of thermal distortion of the workpiece.

PROCESS OVERVIEW

EBW IS A fusion joining process that produces coalescence of materials with heat obtained by impinging a beam composed primarily of high-energy electrons onto the joint to be welded. Electrons are fundamental particles of matter, characterized by a negative charge and a very small mass. For EBW they are raised to a high-energy state by being accelerated to velocities in the range of 30 to 70 percent of the speed of light.

Basically, an electron beam welding gun functions in much the same manner as a TV picture tube. The primary difference is that a TV picture tube uses a low-intensity electron beam to continuously scan the surface of a luminescent screen, and thereby produces a picture. An electron beam welding gun uses a high-intensity electron beam to continuously bombard a weld joint, which converts that energy to the level of heat input needed to make a fusion weld.

In both of these cases, the beam of electrons is created in much the same manner, using an electron gun that typically contains some type of thermionic electron emitter (normally referred to as the gun "cathode" or "filament"), a biasing control electrode (normally referred to as the gun "grid" or "grid cup"), and an anode. Various supplementary devices, such as focus and deflection coils, are also provided to focus and deflect this beam. In EBW, the total beam generating system (gun and electron optics) is called either the electron beam gun/column assembly, or simply the electron beam gun column.

FUNDAMENTALS OF THE PROCESS

PRINCIPLES OF OPERATION

THE HEART OF the electron beam welding process is the electron beam gun/column assembly, a simplified representation of which is shown in Figure 21.1. Electrons are generated by heating a negatively charged emitting material to its thermionic emission temperature range, thus causing electrons to "boil off" this emitter or cathode and be attracted to the positively charged anode. The precisely configured grid or bias cup surrounding the emitter provides the electrostatic field geometry that then simultaneously accelerates and shapes these electrons into the beam. The beam then exits the gun through an opening in the anode.

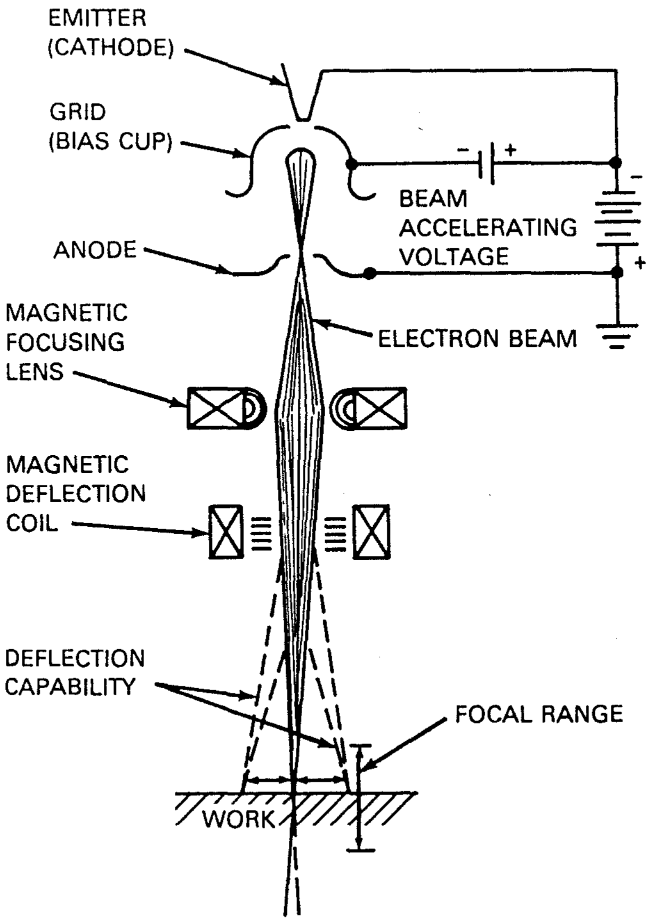

Figure 21.1–Simplified Representation of a Triode Electron Beam Gun Column

In a diode (cathode-anode) gun, this beam-shaping electrode and the emitter are both at the same electrical potential, and together are referred to as the cathode. In a triode (cathode-grid-anode) gun, the two are at different potentials; consequently the beam-shaping grid can be biased to a slightly more negative value than the emitter, in order to control beam current flow. In this case, the emitter alone is called the cathode (or filament) and the beam-shaping electrode is called the bias (or grid) cup. Since, in both cases, the anode is incorporated into the electron gun, beam generation (acceleration and shaping) is accomplished completely independent of the workpiece.

Upon exiting the gun, this beam of electrons accelerates to speeds in the range of 30 to 70 percent of the speed of light when gun operating voltages are in the range of 25kv to 200 kv. The beam then continues on toward the workpiece. Once the beam exits from the gun, it will gradually broaden with distance traveled, as illustrated in Figure 21.1. This divergance results from the fact that all the electrons in the beam have some amount of radial velocity, due to their thermal energy, and in addition, all experience some degree of mutual electrical repulsion. Therefore, in order to counteract this inherent divergence effect, an electromagnetic lens system is used to converge the beam, which focuses it into a small spot on the workpiece. The beam divergence and convergence angles are relatively small, which gives the concentrated beam a usable focal range, or "depth-of-focus", extending over a distance of an inch or so, as illustrated in Figure 21.1.

In practice, the rate of energy input to the weld joint is controlled by the following four basic variables:

(1) The number of electrons per second being impinged on the workpiece (beam current)

(2) The magnitude of velocity of these electrons (beam accelerating voltage)

(3) The degree to which this beam is concentrated at the workpiece (focal beam spot size)

(4) The travel speed with which the workpiece or electron beam is being moved (welding speed)

The maximum beam accelerating voltages and currents that can be achieved with commercially available electron beam gun/column assemblies vary over the ranges of 25 to 200 kV and 50 to 1000 mA, respectively, and the electron beams produced by these systems can generally be focused to diameters in the range of 0.01 to 0.03 in. (0.25 to 0.76 mm).

The resulting beam power levels and power densities attainable from these units can reach values as high as 100 kW and 10^7W/in.^{2} (1.55 x 10^4 W/mm^2), respectively. Such power densities are significantly higher than those possible with arc welding processes.

The potential welding capability of an electron beam system is indicated by the maximum power density that the system is capable of delivering to the workpiece. This comparison factor depends upon the maximum beam power (current x voltage) and the minimum focal spot size attainable with the system. At this writing, electron beam welding systems with beam power levels up to 300 kW and power densities in excess of 10^8W/in.^{2} (1.55 x 10^5 W/mm^2) have been built, but these are not yet commercially available.[1]

At power densities on the order of 10^5W/in.^{2} (1.55 x 10^2 W/mm^2), and greater, the electron beam is capable of instantly penetrating into a solid workpiece or a butt joint and forming a vapor capillary (or "keyhole") which is surrounded by molten metal. As the beam advances along the joint, molten metal from the forward portion of the keyhole flows around its periphery and solidifies at the rear to form weld metal. In most applications, the weld penetration formed is much deeper than it is wide, and the heat-affected zone produced is very narrow. For example, the width of a butt weld in 0.5 in. (13 mm) thick steel plate may be as small as 0.030 in. (0.8 mm) when made in a vacuum. This stands in remarkable contrast to the weld zone produced in arc and gas welded joints, where penetration is achieved primarily through conduction melting.

Since the EB weld results from a keyhole that the beam forms, the angle of incidence with which the beam impinges on the surface of a workpiece can affect the final angle at which the keyhole (and thus the resulting weld zone) is produced with respect to that surface.

An electron beam can be readily moved about by electromagnetic deflection. This allows specific beam spot motion patterns (circles, ellipses, bow tie shapes, etc.) to be generated on the surface of a workpiece when an electronic pattern generator is used to drive the deflection coil system, as illustrated in Figure 21.2. This deflection capability can, in certain instances, also be used to provide beam travel motion. In most instances, however, deflection is used to adjust the beam-to-joint alignment, or to apply a deflection pattern. This deflection modifies the average power density being input to the joint, and results in a change in the weld characteristics achieved. However, as previously noted, care must always be taken when using any type of beam deflection to ensure that the beam angle of incidence does not adversely affect the final weld results. It especially must not cause part of the weld joint to be missed.

PROCESS VARIATIONS

THREE BASIC MODES of electron beam welding are now used. These are high vacuum (EBW-HV), medium vacuum (EBW-MV), and nonvacuum (EBW-NV). The principal difference between these process modes is the ambient pressure at which welding is done. With the high-vacuum (often referred to as "hard vacuum") mode, welding is done in the pressure range of 10^{-6} to 10^{-3} torr.[2] For medium vacuum, the pressure range is 10^{-3} to 25 torr. Within this range, the pressure span from about 10^{-3} to 1 torr is often called a "partial" or "soft" vacuum, and from about 1 to 25 torr, a "quick" vacuum. Nonvacuum electron beam welding is done at atmospheric pressure, and thus is sometimes called "atmospheric" EBW. In all cases, the electron beam gun pressure must be held below 10^{-4} torr for stable and efficient operation.

High vacuum and medium vacuum welding are done inside a vacuum chamber. This imposes an evacuation time penalty to create the "high purity" environment. The medium vacuum welding machine retains most of the advantages of high vacuum welding, with shorter chamber evacuation times, resulting in higher production rates. Nonvacuum EB welding, although it incurs no pumpdown time penalty, is not suitable for all applications because the welds it produces are generally wider and shallower than equal power EB welds produced in a vacuum.

With medium-vacuum operation, the beam is generated in high vacuum and then projected into a welding chamber operating at higher pressure. This is accomplished by providing an orifice below the beam generation column that is large enough to pass the beam, but still small enough to impede any significant back diffusion of gases into the gun chamber.

In nonvacuum electron beam welding equipment, the beam is generated in high vacuum and then projected through several specially designed orifices, separating a series of differentially pumped chambers, before finally emerging into a work environment that is at atmospheric pressure. For nonvacuum electron beam welding directly in the atmosphere, beam accelerating voltages of greater than 150 kV are normally required. However, if the atmospheric pressure environment around the weldment is a gas such as helium, beam accelerating voltages lower than 150 kV can sometimes be employed.

Figure 21.3 shows the three basic modes of electron beam welding. A fixed electron beam gun column is shown mounted on the exterior of the high- and medium-vacuum enclosures to illustrate these two modes. A mobile electron beam gun column may also be mounted on the interior of high- and medium-vacuum enclosures, as illustrated in Figure 21.4. This is commonly employed to provide a higher degree of gun column motion capability.

High Vacuum Welding

HIGH VACUUM (10^{-3} torr or lower) is the required environment for all electron guns. Thus, even though special

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[1] The Welding Research Institute of Osaka University in Japan has a 300 kw electron beam welding machine which they are presently using to investigate single-pass EB joining of extremely heavy sections.

[2] A torr is the accepted industry term for a pressure of one millimeter of mercury. Standard atmospheric pressure can be expressed as 760 torr or 760 mm of mercury.

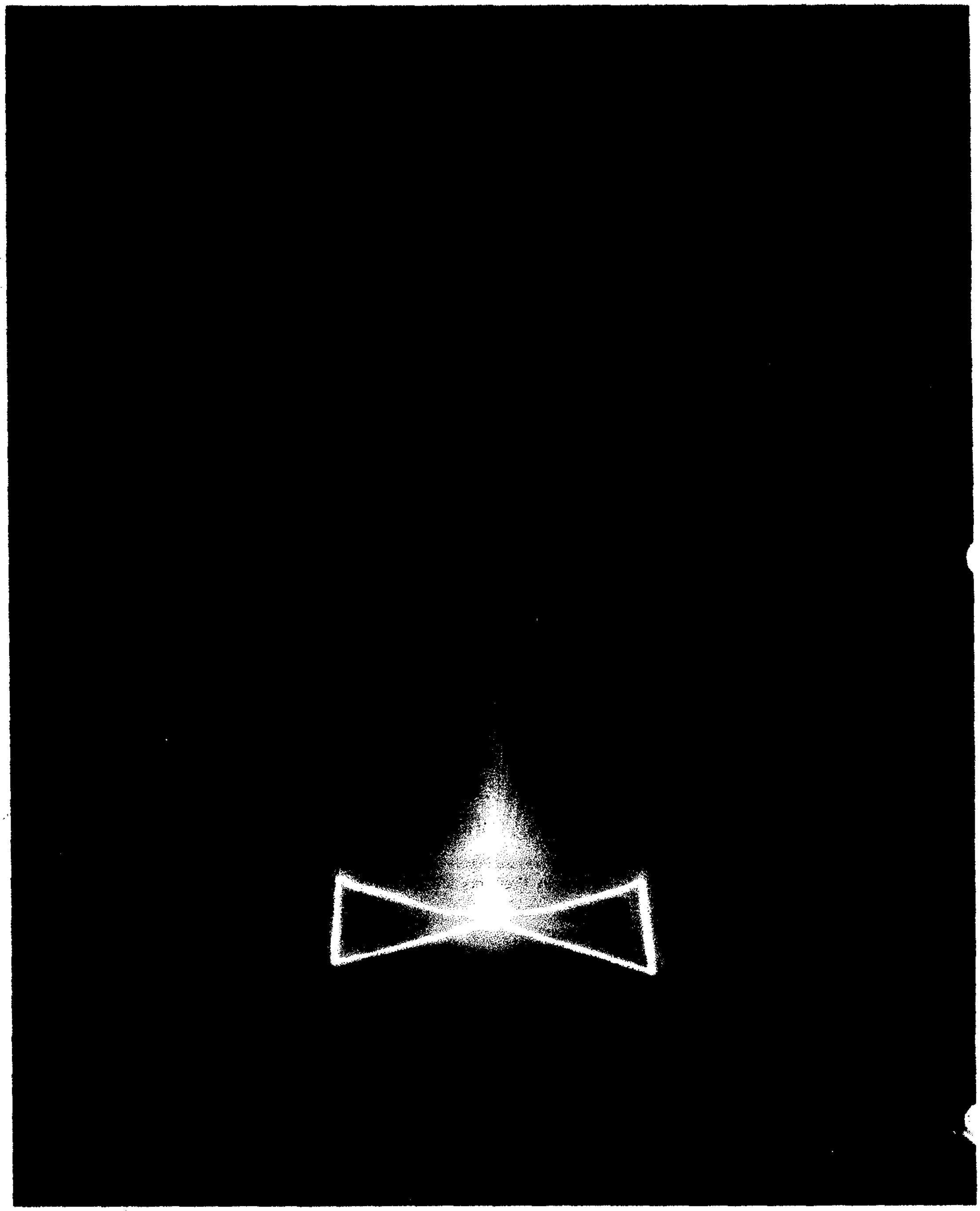


Figure 21.2–Beam Deflection Capability of an Electron Beam Column as Shown by a "Bow Tie" Pattern on a Workpiece

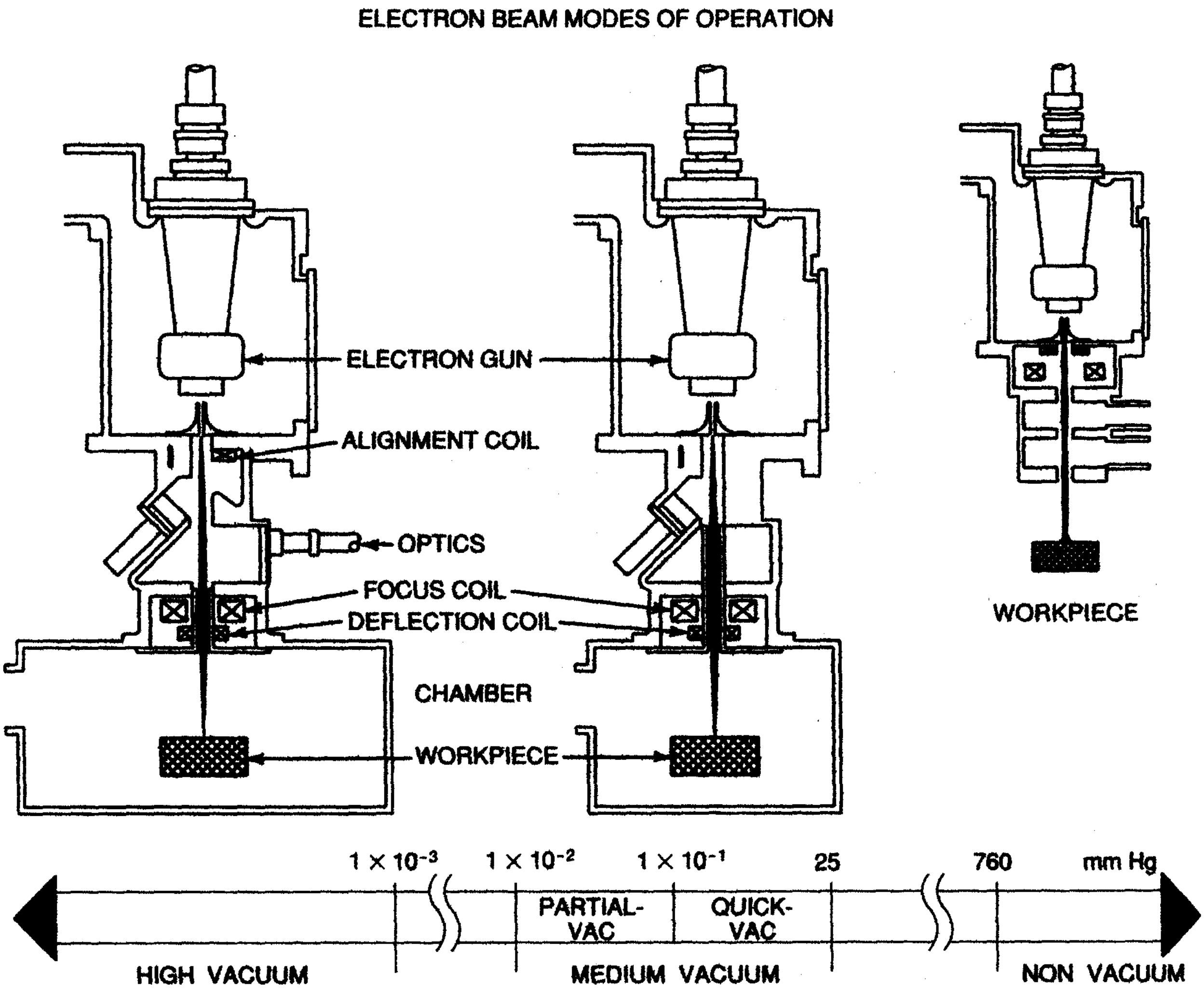


Figure 21.3—The Basic Modes of Electron Beam Welding, with a Corresponding Vacuum Scale

methods allow the beam to enter higher pressure environments, the gun itself will not operate effectively at pressures much greater than 10^{-4} torr.

The principal advantages of electron beam welding in high vacuum are as follows:

(1) Maximum weld penetration and minimum weld width can be achieved, thereby producing a minimum of weld shrinkage and distortion. A high depth-to-width ratio is achieved because of the high-energy density of the beam and the resultant keyhole mode of melting.

(2) Maximum weld metal purity is possible due to the relatively clean environment provided by a high vacuum.

(3) The relatively long gun-to-work distances possible in a hard vacuum improve the operator's ability to observe the welding process and to weld normally inaccessible joints.

Since the electrons in the beam would be scattered by collisions with any residual gas molecules that may be present in the beam's path, and because the frequency with which these collisions occur varies directly with both the concentration of gas molecules and the total distance traveled, the use of a high-vacuum environment minimizes scatter (particularly when long beam travel distances must be employed).

The high vacuum minimizes exposure of the hot weld zone to oxygen and nitrogen contamination, and concurrently causes gases evolved during welding to move rapidly away from the weld metal, thereby improving weld metal purity. For this reason, high vacuum welding is better suited for welding highly reactive metals than the medium and nonvacuum process variations.

Production of high vacuum requires pumping times which significantly limit production rates. This pump-down limitation can be offset somewhat if a number of

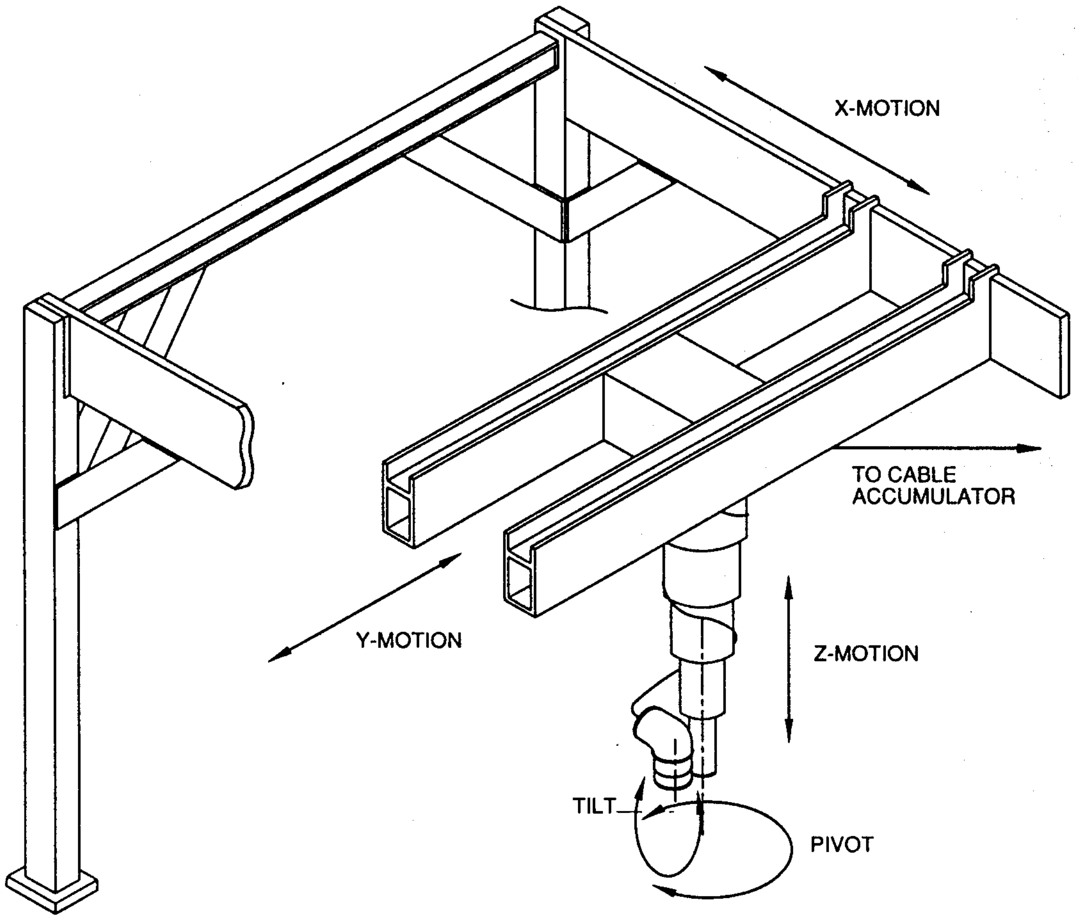


Figure 21.4—Mobile EB Gun / Column Multi-Axis Motion System

assemblies are welded in a single load and the chamber volume is small. The number of parts that can be welded, per batch load, will be limited by the chamber size employed. As a result, high vacuum welding is generally more suitable when relatively low production rates are involved. Various types of "air-to-air" part transfer schemes have been developed which allow parts to be moved in and out of a high-vacuum region without needing to vent it. These procedures make it possible to use high vacuum EBW on certain high-production joining applications, such as welding bimetallic saw blades.

Medium Vacuum Welding

A PRINCIPAL FEATURE of medium vacuum welding is the ability to weld without pumping the welding chamber to very low pressure (high vacuum). When the chamber is small, the pumping time required may be a matter of only a few seconds, which is of major importance in economical processing. This makes medium vacuum welding ideally suited for use in the mass production of parts that involve repetitive welding tasks, and where a welding chamber of minimum volume can be used. For example, gears can be successfully welded to shafts in their final machined or stamped condition, without subsequent finishing to maintain close dimensional tolerances. Such an operation is shown in Figure 21.5.

Because medium vacuum welding is done at pressures with a significant (100 ppm) concentration of air, this mode of EBW is less desirable than high vacuum EBW for reactive metals. In addition to requiring specialized postweld heat treatment, many refractory metals require an ultrapure welding environment.

This higher concentration of air also scatters the beam electrons, enlarging the beam diameter and decreasing the power density. This results in welds that are slightly wider, more tapered, and less penetrating than similar type welds produced under high-vacuum conditions.

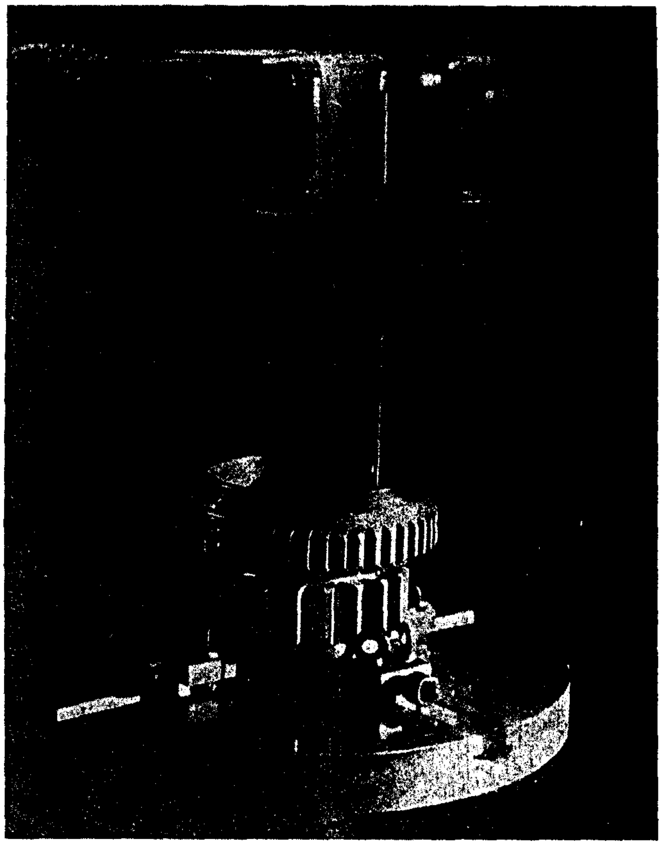


Figure 21.5–Electron Beam Welding a Gear in Medium Vacuum

Nonvacuum Welding

THE MAJOR ADVANTAGE of nonvacuum welding is that the work need not be enclosed in a vacuum chamber. Elimination of chamber evacuation time results in higher production rates and a lower cost per piece. Also, the size of the weldment is not limited by the size of the chamber.

These advantages, however, are gained at the expense of not being able to achieve the depth-to-width ratios, weld penetrations, and gun-to-work distances attainable in a vacuum. The welding atmosphere is not as "pure" as it is with high and medium vacuum welding, even when inert gas shielding is employed. Although the use of a workpiece vacuum enclosure is not required, some type of radiation shielding must still be provided to protect personnel from the X-rays generated when the electron beam strikes the work.

Operating conditions for nonvacuum welding differ from the other two variations. Beam dispersion increases rapidly at ambient pressure, as shown in Figure 21.6. The nonvacuum gun-to-work distance, even when a helium gas environment is being employed, should be less than about 1.5 inches (38 mm). This restriction requires that the weld joint should not be shielded from the electron beam by the shape of the workpiece.

The depth of penetration achieved in nonvacuum electron beam welding is affected by beam power level, travel speed, gun-to-work distance, and the ambient atmosphere through which the beam passes. Figure 21.7 shows weld penetration as a function of travel speed for three different beam power levels. Note the increase in travel speed to be gained for a given penetration as the power level is increased.

Nonvacuum electron beam welding appears to demonstrate more efficient penetration at power levels above 50 kW. This result is attributed to a decreased gas density produced by local heating of the air by the high-energy electron beam.

The graph in Figure 21.8 shows the effect of the ambient atmosphere, gun-to-work distance, and travel speed on the weld penetration. Penetration is greater with helium, which is lighter than air, and lower with argon, which is heavier than air. For a given penetration and gun-to-work distance, higher travel speeds can be achieved in a helium shielding gas.

Many materials have been welded successfully using the nonvacuum technique. They include carbon, low alloy, and stainless steels; high-temperature alloys; refractory alloys; and copper and aluminum alloys. Some of these metals can be welded directly in air while others require inert gas protective atmospheres to avoid excessive oxygen and nitrogen contamination.

With 60 kW nonvacuum equipment, it is possible to produce single-pass welds in many metals 1 in. (25.4 mm) thick, at relatively high speeds. Figure 21.9 is a cross section of a nonvacuum weld in 3/4 in. (19 mm) Type 304 stainless steel plate.

ADVANTAGES AND LIMITATIONS

ELECTRON BEAM WELDING has unique performance capabilities. The high-quality environment, high-power densities, and outstanding control solve a wide range of joining problems.

The following are advantages of electron beam welding:

(1) The EBW directly converts electrical energy into beam output energy. Thus the process is extremely efficient.

(2) Electron beam weldments exhibit a high depth-to-width ratio. This feature allows for single-pass welding of thick joints.

(3) The heat input per unit length for a given depth of penetration can be much lower than with arc welding. The resulting narrow weld zone results in low distortion, and fewer deleterious thermal effects.

Figure 21.6–Electron Beam Dispersion Characteristics at Various Pressures

(4) A high-purity environment (vacuum) for welding minimizes contamination of the metal by oxygen and nitrogen.

(5) The ability to project the beam over a distance of several feet in vacuum often allows welds to be made in otherwise inaccessible locations.

(6) Rapid travel speeds are possible because of the high melting rates associated with this concentrated heat source. This reduces welding time and increases productivity and energy efficiency.

(7) Reasonably square butt joints in both thick and relatively thin plates can be welded in one pass without filler metal addition.

(8) Hermetic closures can be welded with the high- or medium-vacuum modes of operation while retaining a vacuum inside the component.

(9) The beam of electrons can be magnetically deflected to produce various shaped welds; and magnetically oscillated to improve weld quality or increase penetration.

(10) The focused beam of electrons has a relatively long depth of focus, which will accommodate a broad range of work distances.

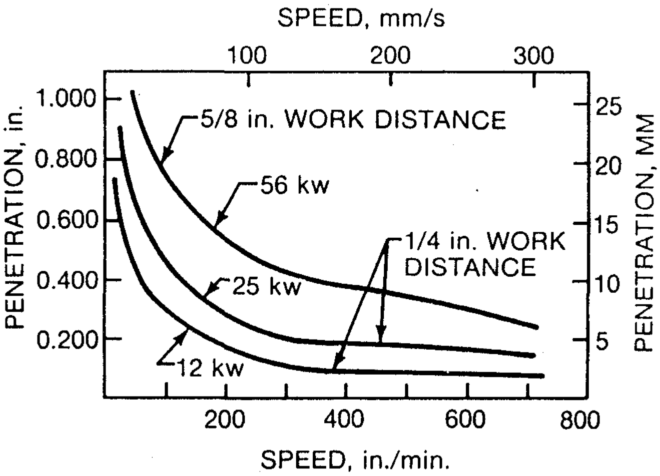


Figure 21.7–Effect of Travel Speed on Penetration of Nonvacuum Electron Beam Welds in Steel (175 kV in Air)

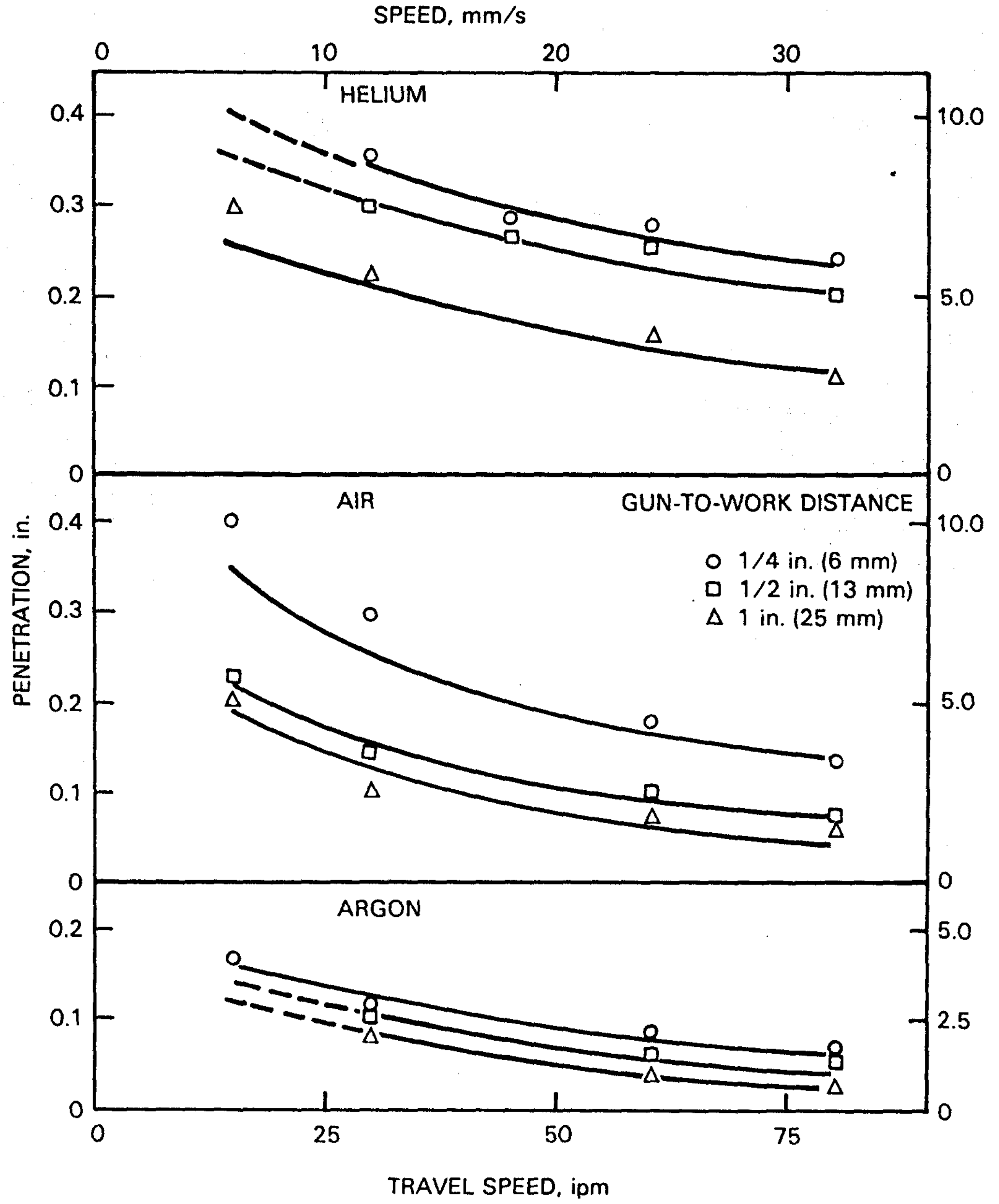


Figure 21.8–Penetration Versus Travel Speed for Nonvacuum Electron Beam Welds in AISI 4340 Steel in Helium, Air, and Argon with Three Gun-to-Work Distances (175 kV, 6.4 kW)

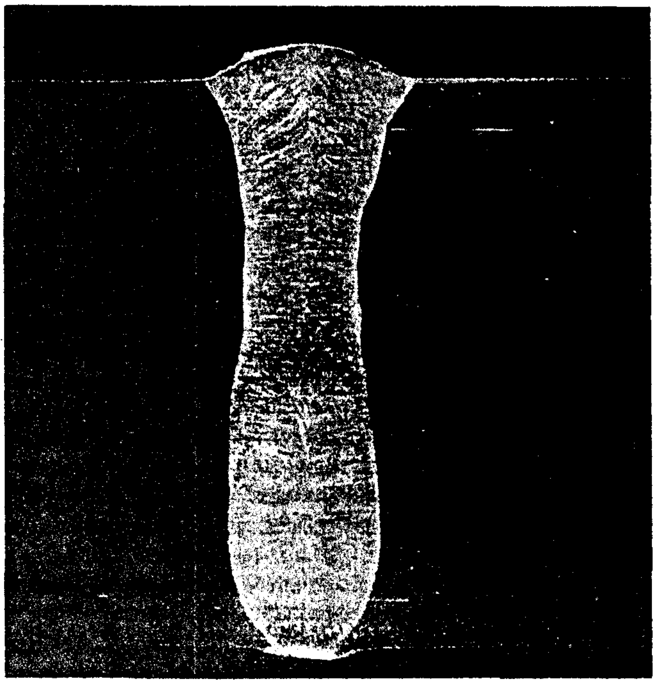


Figure 21.9—A Cross Section of a Nonvacuum Electron Beam Weld in 3/4 in. (19 mm) Stainless Steel Plate Made in Air With 12 kW of Power

(11) Full penetration, single-pass welds with nearly parallel sides, and exhibiting nearly symmetrical shrinkage, can be produced.

(12) Dissimilar metals and metals with high thermal conductivity such as copper can be welded.

Some of the limitations of electron beam welding are as follows:

(1) Capital costs are substantially higher than those of arc welding equipment. Depending on the volume of parts to be produced, however, the final "per piece" part costs attainable with EBW can be highly competitive.

(2) Preparation for welds with high depth-to-width ratio requires precision machining of the joint edges, exacting joint alignment, and good fit-up. In addition, the joint gap must be minimized to take advantage of the small size of the electron beam. However, these precise part-preparation requirements are not mandatory if high depth-to-width ratio welds are not needed.

(3) The rapid solidification rates achieved can cause cracking in highly constrained, low ferrite stainless steel.

(4) For high and medium vacuum welding, work chamber size must be large enough to accommodate the assembly operation. The time needed to evacuate the chamber will influence production costs.

(5) Partial penetration welds with high depth-to-width ratios are susceptible to root voids and porosity.

(6) Because the electron beam is deflected by magnetic fields, nonmagnetic or properly degaussed metals should be used for tooling and fixturing close to the beam path.

(7) With the nonvacuum mode of electron beam welding, the restriction on work distance from the bottom of the electron beam gun column to the work will limit the product design in areas directly adjacent to the weld joint.

(8) With all modes of EBW, radiation shielding must be maintained to ensure that there is no exposure of personnel to the x-radiation generated by EB welding.

(9) Adequate ventilation is required with nonvacuum EBW, to ensure proper removal of ozone and other noxious gases formed during this mode of EB welding.

EQUIPMENT

HIGH-VACUUM, MEDIUM-VACUUM, AND nonvacuum EBW equipment employs an electron beam gun/column assembly, one or more vacuum pumping systems, and a power supply. High- and medium-vacuum equipment operates with the work in an evacuated welding chamber. Although nonvacuum work does not need to be placed in a chamber, a vacuum environment is necessary for the electron beam gun column.

All three basic modes can be performed using so-called high-voltage equipment, i.e., equipment using gun columns with beam accelerating voltages greater than 60 kV. Nonvacuum electron beam welding performed directly in air requires beam accelerating voltages greater than 150 kV. High vacuum and medium vacuum welding can also be performed with so-called low-voltage equipment (i.e., equipment with gun columns that employ beam accelerating voltages of 60 kV and lower). Because high-voltage gun columns are generally fairly large, they are usually mounted on the exterior of the welding chamber, and are either fixed in position or provided with a limited amount of tilting or translational motion, or both. Low-voltage gun columns are usually small. Some units are "fixed" externally. Others are internally mounted "mobile" units capable of being moved about, with up to five axes of combined translational motion, in a manner similar to that illustrated in Figure 21.4.

ELECTRON BEAM GUNS

IN GENERAL, ELECTRON beam welding guns are operated in a space-charge-limited condition. When a gun is operated in this condition, the beam current produced at any accelerating voltage is proportional to the 3/2 power of the accelerating voltage ($I = KV^{3/2}$), where the constant of proportionality, K, is a function of gun geometry.

Besides acceleration voltage, a broad range of conditions must be satisfied if an electron gun is to deliver the required power and power density.

Optimum gun performance depends upon gun configuration, emitter characteristics, total power capabilities, and focusing provisions. For a given metal and joint thickness, characteristically narrow welds can be made if (1) sufficient beam power is available to permit rapid travel speed, and (2) the beam power density is great enough to develop and continuously maintain a vapor hole to the depth of penetration required.

An electron beam gun generates, accelerates, and collimates the electrons into a directed beam. The gun components can logically be divided into two categories: (1) elements that generate free electrons (the emitter portion), and (2) elements that produce a useful beam, or electrodes that accelerate and form the electrons into a beam. The emitter may be either (1) a directly (resistance) heated wire or ribbon type filament, or (2) a rod or disc type filament indirectly heated by an auxiliary source, such as electron bombardment or induction heating. The specific emitter design chosen will affect the characteristics of the final beam spot produced on the work.

Only self-accelerated guns, similar to the Pierce and Steigerwald telefocus gun configurations, are used for electron beam welding. They have superior focusing and power capabilities, and also permit placing the gun anode and workpiece at earth ground potential.

The Pierce gun was originally designed as a diode capable of producing a rapidly converging beam with the primary focal point close to the anode, and having a beam divergence that was uniform thereafter. The Steigerwald telefocus gun was originally designed as a triode which produced a gradually converging beam, with its primary focal point some distance from the anode. Current Pierce and Steigerwald gun designs are modifications of the original designs.

When a change in beam current is desired at a given accelerating voltage in a diode gun, the cathode-to-anode spacing in the gun must be changed. This changes the proportionality constant, K, of the gun. Several spacers are supplied by the manufacturer to provide a wide range of operating conditions. Each spacer has a range of beam power, beam spot size, and control sensitivity.

Diode guns control the beam current at a given voltage by controlling the power to, and thus the temperature of, the electron emitter. Electron emission is related to both emitter temperature and accelerating voltage.

The triode-type gun is similar to the diode gun except that the beam-forming electrode ("grid cup") is biased with a variable negative voltage relative to the emitter. In this type of gun, the emitter is simply referred to as the *filament*. This makes it easy to vary the beam current at any constant accelerating voltage. Thus, both the accelerating voltage and beam current can be varied independently within limits.

The ability to control beam current with a bias voltage allows rapid changes in beam current. Electronic switching circuits permit users to repetitively pulse the beam current. Beam current pulsing helps to minimize heat input to the workpiece, while still achieving deep weld penetrations. This capability is not as extensively used for welding as it is for drilling. Accurate control of the beam current slope rates is extremely useful in many welding applications, particularly on circular welds at the start/finish overlap region.

All gun/column assemblies employ an electromagnetic lens to focus the electron beam into a small spot on the workpiece. Electromagnetic deflection coils usually oscillate the beam in a repetitive or nonrepetitive fashion. These deflection coils are generally positioned immediately below the electromagnetic focusing lens, and are used to deflect the electron beam from its normal axial position. Two sets of deflection coils at 90° will trace classical lissajous figures on the work surface. Sinusoidal beam deflection perpendicular to the direction of welding will broaden the weld bead to simplify manual tracking of weld seams. Circular and elliptical deflection tends to reduce weld porosity. More complex deflection patterns may also be employed, both to enhance weld penetration and to improve weld quality.

The modified Pierce and Steigerwald guns used today weld with both "high" and "low" beam accelerating voltages. Similar power levels are available with low- and high-voltage guns. Beam power is the product of the accelerating voltage and the beam current. Therefore, operation at high voltage requires less beam current than operation at low voltage for an equivalent beam output power. In high- or medium-vacuum applications, both low- and high-voltage equipment will produce similar-quality welds in most metals. However, differences in the weld cross section produced at the same beam power will exist, because one system operates with a low voltage and high current and the other with high voltage and low current.

POWER SUPPLIES

Electron Gun Power Supplies

THE GUN POWER source used for an electron beam welding machine is an assembly of at least one main power supply and one or more auxiliary power supplies. It produces high-voltage power for the gun and auxiliary power for the emitter and beam control. Depending upon whether the gun is a diode type or a triode type, the high-voltage power supply consists of two or more of the following components:

(1) A main high-voltage dc power supply that provides the constant beam accelerating voltage and total beam current

(2) An emitter (filament) power supply with either ac or dc output

(3) A bias electrode power supply that impresses a voltage between the emitter and the bias electrode (grid cup) to control beam current

The main high-voltage power supply and auxiliary-beam-generation power supplies are frequently placed together in a common oil-filled tank. A high-purity, electrical-grade transformer oil serves both as an electrical insulating medium and as a heat transfer agent to carry heat from the electrical components to the tank walls. The components are typically supported from the cover plate of the tank so that they can be removed from the tank with the cover plate; however, removal of these components is rarely required.

Another high-voltage insulating material occasionally used in EBW power supplies is sulfur hexafluoride gas at pressures up to 45 psi. A power supply with this gas insulation is considerably more compact and lighter than an oil-insulated unit of the same rating. The components in both the main high-voltage power supply and the auxiliary supplies are primarily transformers, diodes (rectifiers), capacitors, and resistors. Electron tube diodes were initially used in the main power supply by some manufacturers, but solid-state diodes, usually silicon, are presently used. Cost, regulation, physical size, ability to absorb transients of voltage and current, and thermal capability are just some of the considerations which affect the choice of components and insulating medium.

Main High-Voltage Power Source

THIS POWER UNIT converts line input power to high-voltage dc power for the electron beam gun. Power ratings commercially available are in the range of 3 to 100 kw, but up to 300 kw is readily attainable. Units are designed for a particular electron beam gun type (high or low voltage). Some typical machine ratings that are commercially available are shown in Table 21.1.

The maximum allowed voltage ripple in the dc output varies, depending upon the desired quality of beam focus. Excessive voltage ripple will produce an undesirable beam current ripple that may affect weld quality. Voltage ripple is usually controlled below one percent.

The inherent decrease in output voltage with increasing load is typically in the range of 15 to 20 percent. Various controls and regulators compensate for this voltage decrease and minimize the effects of line voltage variations, as well as the effects of temperature and other factors that influence the stability of the output voltage. Sophisticated controls eliminate all of the effects mentioned and maintain a stable accelerating voltage to within 1 percent of the selected value. Other less costly controls eliminate only some of the effects, but they are adequate for less critical applications. Some of the controls used, in approximate order of increasing sophistication and performance, include:

Table 21.1
Typical Electron Beam Welding Machine Ratings

Rating, kW	Output kV, max	 mA, max
3	30	100
3	60	50
6	30	200
7.5	150	50
15	60	250
15	150	100
25	175	144
25	150	167
30	60	500
35	200	175
45	60	750
60	175	345
100	100	1000

(1) Line voltage regulator (constant-voltage transformer)

(2) Servo-operated variable transformer with feedback from the high-voltage output

(3) Motor-generator with electronic exciter and feedback from the high-voltage output

(4) Electronic regulation with both current and voltage feedback available

Emitter Power Supply

DIRECTLY HEATED WIRE or ribbon filaments (emitters) are the most common. Filaments may be hairpin shaped or may be a more complex shape. The current that heats the filament can be ac or dc, but dc is preferred because the magnetic field created by the filament heating current may affect the beam's direction. The cyclic nature of ac heating currents causes the beam spot to oscillate with a small, but significant, amplitude about a fixed point.

Since the magnitude of magnetic effects will increase with the heating current, filtering must be used even with dc heating currents to reduce any ripple present to three percent.

Current and voltage ratings of a filament power supply depend upon the type and size of the directly heated filament. For 0.020 in. (0.5 mm) diameter tungsten wire filaments, the supply would be rated for 30A at 20V. Ribbon-type filaments have a much larger emitting area than wire type filaments. Ribbons require power supplies rated for higher currents and lower voltages (30 to 70A at 5 to 10V). High dc filament heating currents will produce a certain amount of initial beam deflection, but this is a static feature which can usually be corrected by beam alignment devices normally built into the gun/column assembly.

Indirectly heated emitters are also used. Here, an auxiliary bombardment or inductive-type heat source indirectly heats the gun emitter to electron emission temperatures. The power supply for driving the auxiliary electron gun used to heat a disc emitter by bombardment would be rated for 100 to 200 mA at several kilovolts. The power supply for indirectly heating a "bolt type" emitter, heated in a radial mode, would be rated for 2 to 3 amps at 400 to 600 volts.

Bias Voltage Supply

THE BIAS VOLTAGE supply for a triode style gun is usually designed to give complete control of beam current from zero to maximum. To do this, the dc power supply applies a variable voltage on the beam-shaping electrode (grid cup), making it negative with respect to the emitter. A voltage in the range of 1500 to 3000 V is needed to cut off the beam current. For maximum beam current, the voltage is 100 to 300 V. Here again the bias supply must also have no greater than one percent beam current ripple. Various electronic input power control devices are used to provide pulsing, ramping, etc. of the beam current.

Some electron beam equipment uses a self-biasing system. The bias voltage is derived partially from the main accelerating voltage through a voltage divider, and partially from the voltage across a series resistor in the main power circuit. This system does not have a separate bias supply.

Electromagnetic Lens and Deflection Coil Power Supplies

THE ELECTROMAGNETIC LENS (focusing lens shown in Figure 21.1) is generally powered by a solid-state constant-current power supply. The strength of the magnetic field varies with the current flowing through the coil. The current provided to the coil must remain constant, to produce a beam spot with consistent size, even when the voltage drop across the coil changes with temperature variations.

Beam deflection coils (Figure 21.1) are also powered by solid-state devices. Two sets of coils at 90° are usually placed at the base of the gun column for x and y deflection of the beam. Programming of the power sources for the two sets of coils can provide beam movement along either axis singularly or both axes simultaneously. Complex geometric beam patterns (circle, ellipse, square, rectangle, hyperbola, etc.) can be produced by electronic control. The ripple on the dc input to both the deflection coils and the electromagnetic lens must be low to minimize adverse effects of beam instability on weld quality.

VACUUM PUMPING SYSTEMS

VACUUM PUMPING SYSTEMS are required to evacuate the electron beam gun chamber, the work chamber for high- and medium-vacuum modes, and the orifice assembly used on the beam exit portion of the gun/column assemblies for medium vacuum and nonvacuum welding. Two basic types of vacuum pumps are used. One is a mechanical piston or vane type, to reduce pressure from 1 atmosphere to about 0.1 torr. For medium vacuum welding, these mechanical pumps are generally operated in conjunction with a Roots-type blower, another kind of mechanical pump. The other is an oil-diffusion- type pump used to reduce the pressure to 10^{-4} torr or lower. Sequencing these pumps to produce the needed vacuum can be accomplished by manual or automatic operation of valves in the system. Commercial electron beam welding equipment has standarized on automatic valve sequencing.

The vacuum system for an electron beam gun chamber consists of a mechanical roughing pump and a diffusion pump. A similar system is used to evacuate a high-vacuum-mode work chamber. Both systems may be ducted to their chambers through a water-cooled or liquid nitrogen-cooled (optically dense) baffle, if necessary, to prevent any oil from backstreaming out of the diffusion pump into the gun or work areas. Today, however, most diffusion pumps have some form of integrated cold cap to capture backstreaming pump oil, so baffles are rarely needed. In addition, turbomolecular pumps and cryogenic pumps are presently being used, which entirely eliminate any possibility that pump oil will enter the gun or chambers. A combination of diffusion and mechanical pumping is shown in Figure 21.10.

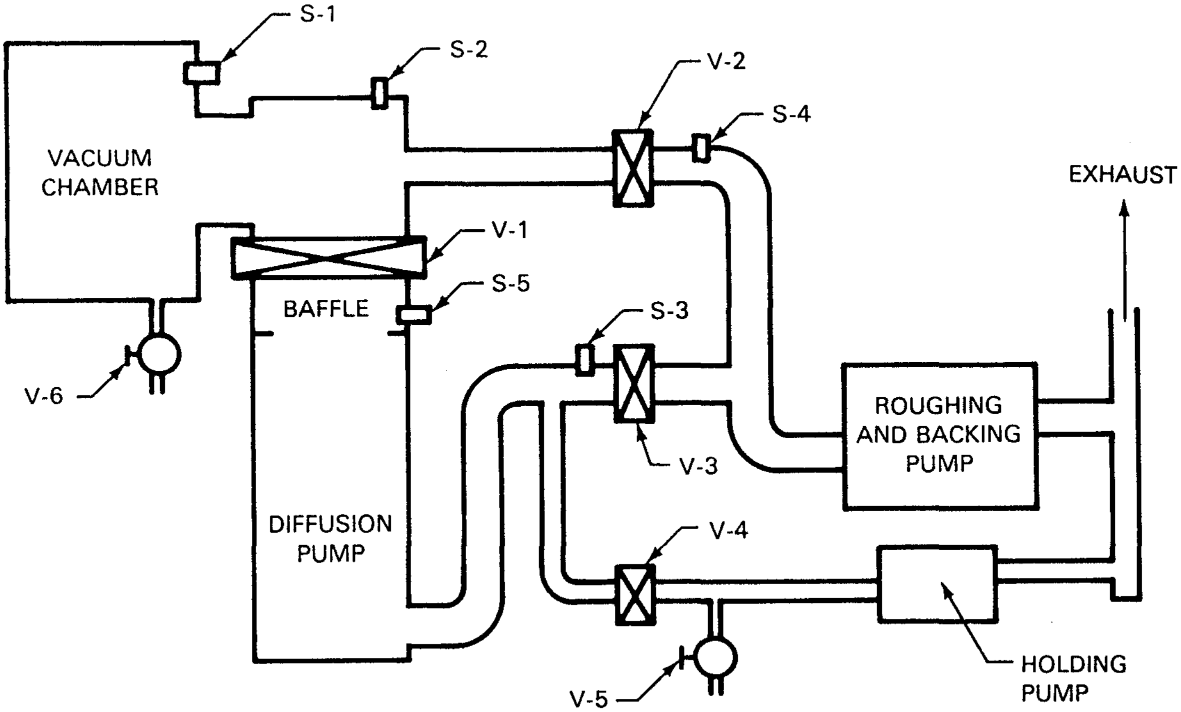
The vacuum pumping system can be mounted on the same base as the vacuum chamber and connected to it with rigid ducting. The primary exception to this rule is the mechanical roughing pump, which must be connected to the system with a flexible tube in order to minimize any chance of its vibration being transmitted to the welding chamber. A large diameter vacuum valve isolates the diffusion pump from the chamber during the roughing portion of the pumping cycle. A small mechanical pump keeps the isolated diffusion pump at low pressure.

The roughing and diffusion pumping periods are normally controlled by automatic sequencing of pneumatic or electric vacuum valves. Automatic evacuation cycles are accomplished with pressure-sensing relays that activate the appropriate valves in the preprogrammed sequence. The control units are designed to protect the vacuum system in case of accidental pressure rise in the chamber.

For medium vacuum welding, the work chamber is evacuated with a mechanical vacuum pumping system of high capacity. The types and sizes of mechanical pumps used in the system will depend upon the work chamber size, the work load, and the desired production rate. Automatic evacuation cycles speed production.

With nonvacuum welding equipment, the electron beam gun chamber is evacuated with a combination mechanical-diffusion pumping system. The various pressure stages in the orifice assembly through which the electron beam exits from the gun/column assembly are pumped with a series of mechanical vacuum pumps.

In vacuum EBW, the evacuation process and its rate depend upon the capabilities of the pumps, the work and fixturing load, the size of the chamber, and the total leakage rate of the system. The total leakage rate is the increase



VALVES
V-1 — HIGH VACUUM
V-2 — ROUGHING
V-3 — BACKING
V-4 — HOLDING
V-5 — VACUUM RELEASE
V-6 — VACUUM RELEASE

VACUUM SENSORS
S-1 — ION TYPE
S-2 — THERMOCOUPLE TYPE
S-3 — THERMOCOUPLE TYPE
S-4 — THERMOCOUPLE TYPE
S-5 — ION TYPE

Figure 21.10–Vacuum Pumping System for High-Vacuum Operation

in chamber pressure per unit of time attributed to both real leaks and virtual leaks in the system.

Real leaks are actual holes or voids in the chamber capable of passing air or gas. A *virtual leak* is the semblance of a real leak somewhere in the vacuum system; in actuality, this type of leak results from the outgassing of absorbed or occluded gases on the interior surfaces of the system, when under vacuum. For satisfactory system operation, no in-leakage (real leaks) should be detectable with a helium mass spectrometer leak detector having a sensitivity of 1 x 10^{-4} standard mm^3/s of helium.[3] In addition, a pressure rate-of-rise test should be conducted to ensure that no detrimental virtual leaks are present. This test is conducted by isolating the chamber to be tested from the pumping system (without exposing it to atmosphere) immediately after doing a four-hour preparatory pump down of the chamber. A customary limiting value for a rate-of-rise test is in the range of 1 to 2 x 10^{-2} torr (10 to 20 micron) per hour, averaged over a 10-hour test period.

LOW-VOLTAGE SYSTEMS

WORK CHAMBERS OF low-voltage systems are usually made of carbon steel plate. The thickness of the plate is designed to provide adequate x-ray protection and the structural strength necessary to withstand atmospheric pressure. Lead shielding may be required in certain areas of the chamber to ensure total radiation tightness of the system.

The weldment inside the chamber may be observed by direct viewing through leaded glass windows. However, the effectiveness of this technique depends upon the dis-

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[3] See ASTM B498 for a description of this method of leak testing.

tance between the operator and the weld joint, and upon the shape of the workpiece. When direct viewing is difficult, an optical viewing system may be provided to give the operator a magnified view of the weld seam. It can be used for setup operations, inspection of the weld, alignment of the weld joint with respect to the electron beam, and positioning of the gun to center the sharply focused electron beam on the weld seam.

Closed-circuit television is also used, to provide another method of viewing. It may have both its light source and television camera mounted in a readily serviceable location outside of the chamber, or both items may be located inside the chamber. An optical protection system of some type is normally employed to shield the viewing equipment from metal spatter and metal vapor deposition. The closed-circuit television system permits continuous monitoring of welds and minimum operator exposure to the intense light from the weld.

HIGH-VOLTAGE SYSTEMS

HIGH-VOLTAGE ELECTRON BEAM systems operate above 60 kV, and generally are designed to operate at voltages between 100 kV and 200 kV (with beam powers up to 100 kW). The electron beam gun/column assembly of a high-vacuum welding machine is housed in an external vacuum chamber, mounted on either the top or side of the welding chamber, as illustrated by Figure 21.11. This mounting may involve either a stationary or sliding style of seal. In the latter case, the motion of the gun/column assembly will normally be limited to a single (x or y) axis of motion. Any other required axis of motion must be provided by the weldment, for example, the type of x, y, z, or rotary motion of the workpiece that is commonly employed.

The external location of the high-voltage gun reduces its maneuverability, but provides ready access to the gun components for service. This arrangement also provides the operator with a view of the beam spot and the weld through optics that are relatively coaxial with the electron beam (Figure 21.11). A view of the back side of a $10 bill through such a slightly oblique (but still effectively coaxial) optical system is shown in Figure 21.12. Direct viewing may also be provided through lead glass windows in the chamber walls.

Work chambers for this equipment are usually welded carbon steel boxes of ribbed design, externally clad with lead for x-ray protection of personnel.

Nonvacuum electron beam welding machines do not require a vacuum chamber around the workpiece. The electron beam gun column may be fixed atop an x-radiation shielding box containing the workpiece and travel carriage. Another arrangement is to place both this gun column and the workpiece in an x-ray shielded room, making both capable of transverse motion, and then operating the equipment remotely from outside the room.

SEAM TRACKING METHODS

WITH ELECTRON BEAM welding, as with other automatic welding processes, the relative positions of the beam spot and the weld joint must be established accurately prior to starting to weld. This relationship must then be accurately maintained throughout the entire welding cycle. This total requirement is somewhat complicated in electron beam welding because (1) the beam spot is very small and produces a relatively narrow weld bead; (2) welding is performed at relatively high travel speeds; and (3) the workpiece is contained in a vacuum chamber or radiation enclosure, making continuous observation difficult. As previously mentioned, most high vacuum electron beam systems are equipped with a viewing system that permits the operator to observe the weld joint and the beam spot. The initial correct position of the electron beam in relation to the joint can easily be established with a viewing system. On medium vacuum and nonvacuum systems, where operator viewing is not normally provided, this initial beam-to-joint alignment is accomplished through precise handling (tooling and fixturing) of the part.

For welding long or slightly irregular joints, a means for automatically maintaining proper beam-to-joint alignment is desirable. Optical viewing of welding and manual correction for deviations in the joint path is, at best, difficult, although some equipment is used in this fashion.

Two methods are used to maintain beam position along a nonlinear joint. The first involves programming by analog or continuous path numerical controls. This method is applicable where parts have been machined precisely to a required contour and are accurately positioned for welding.

The second method uses an adaptive electromechanical control. This control has a tracking device that follows the weld joint and signals the control to adjust the work or gun position to keep the beam on the joint. Stylus and contour seam tracking devices employ the same electrical circuitry and may be quickly interchanged to accomplish various tracking requirements.

The stylus-type "seam tracking" system has a probe, or stylus, that rides in the joint. Lateral (cross seam) movements of the probe, resulting from a change in joint position, are converted to electrical signals by a transducer. The electrical signals drive a positioning servomotor that moves the work or gun to maintain the preset alignment. The electrical signals from this system define a right-error, a left-error, and the null or correct gun position. Alternatively, the electron beam itself can be deflected electronically to accommodate changes in the location of the joint.

A contour-type system involves a simple modification of the stylus-type seam tracking system which permits edge welding of certain types of assemblies using the weldment as a cam. A preloaded ball-type stylus rides against the edge of the weldment as the work is rotated or driven linearly. As a proximity control to accommodate changes in vertical position of the weld joint, the stylus is used to maintain

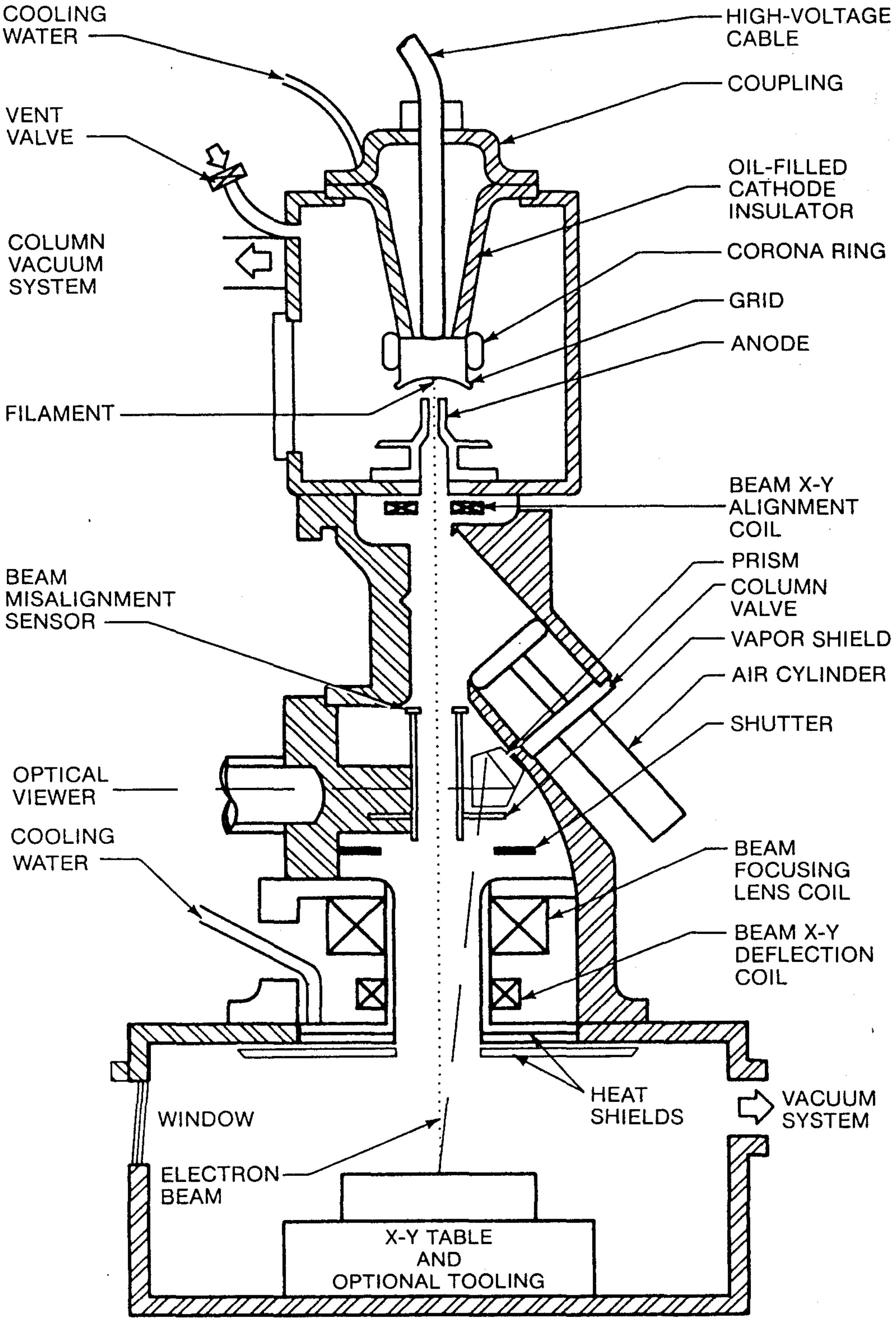


Figure 21.11–Cross Section of Column and Work Chamber

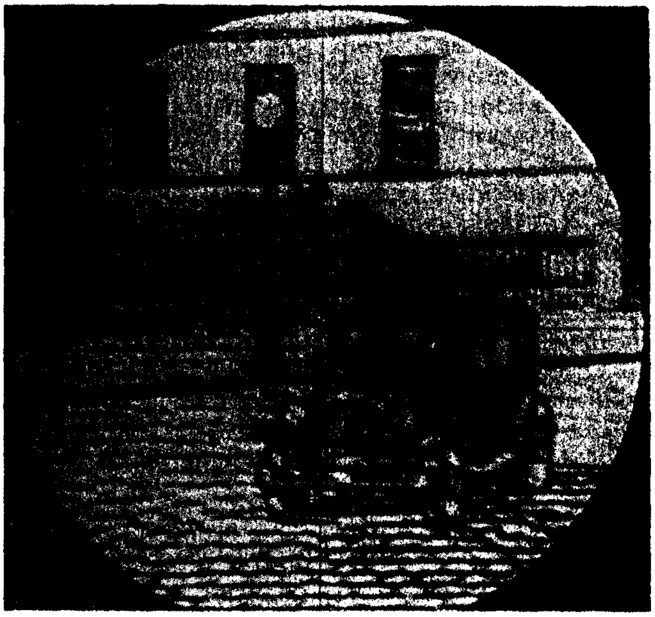


Figure 21.12–The Optical System for an Electron Beam Column Provides Magnification for Viewing Fine Work (This Example Shows a Partial View of the Reverse Side of a U.S. $10.00 Bill to Demonstrate the Capability)

a constant gun-to-work distance by feeding the tracking signal to a servomotor drive on the z axis.

An electronic joint-finding system is also available (Figure 21.13) which can be used for both "seam locating" and "seam tracking" functions. This unit taps into the same electron beam used for welding as a means for sensing the joint position. It finds the joint location by recognizing the absence of rays reflected by the joint in the midst of rays from the work surface, thereby eliminating any need to calibrate an auxiliary joint sensing device.

Once the vacuum chamber has been closed and evacuated for welding, a finely focused electron beam is aimed at the weld joint and scanned back and forth across it. This action produces a secondary electron emission or backflow that can be "collected" and continuously monitored. As the beam is traversed back and forth, the magnitude of secondary electron backflow being measured will decrease each time the beam passes across the joint. Thus, if the monitor signal is displayed as a visible oscilloscope trace, the resulting discontinuity in the oscilloscope line trace will indicate where the joint is with respect to the beam column centerline. Consequently, this method provides an easy means for initially aligning the beam column centerline with the joint.

By initially scanning the entire joint in discrete steps, probable misalignments can be anticipated and corrected during welding.

The stylus, contour, and electronic seam tracking devices are often used in conjunction with a record-and-playback tape system, where the joint can be traced and its location recorded. Then the joint is welded using playback programmed control of the beam or work position.

On systems equipped with CNC controls, programmed periodic scans by the welding beam across the joint during welding indicate the exact location of the joint, which the system repositions. The CNC control assumes on-line, "real time" seam tracking.

WORK-HANDLING EQUIPMENT

THE RESPONSE OF work-handling mechanisms must be accurate and well defined to maintain the relative positions of the electron beam and the weld joint during the entire welding operation. Their design and manufacture should follow good machine tooling practices. Ruggedness, repeatability, smoothness, accuracy, and suitability for operation in a vacuum (if so required) are prime requirements. Also, the magnetic susceptibility of the materials must be considered. Since travel speed affects weld geometry, this variable must be controlled accurately and be repeatable. In general, electric motor drives having an accuracy of about +2 percent of set speed are adequate.

Most electron beam welding machines provide standard mechanisms for linear and rotary motion of the workpiece relative to the electron beam. Horizontal linear motion is usually provided by movement of a work table or by movement of the electron gun. Rotary motion about a vertical axis is achieved with a motor-driven horizontal rotary table. Chambers can be equipped with external platform devices that allow the work table (and any work-handling mechanisms) to be withdrawn from the vacuum chamber, for ease of loading and fixturing the parts.

Figure 21.14 shows an x-y work table on its external platform. An adjustable (0 to 90 degree) rotary work positioner and tailstock have been mounted on the table. Rotary motion about a horizontal axis can be provided using the rotary positioner and tailstock. The positioner is power-driven. Simple linear, rotary, and circular joints can be aligned with the electron beam using these mechanisms.

It is often desirable to weld circular joints in several parts during a single loading of the chamber. In this case, the components are arranged on an eccentric table attached to a motor driven horizontal rotary table. The eccentric table holding the parts can position each piece in turn under the electron beam. The circular weld motion is made with the eccentric table. Programmed indexing of the eccentric table from piece to piece can be added.

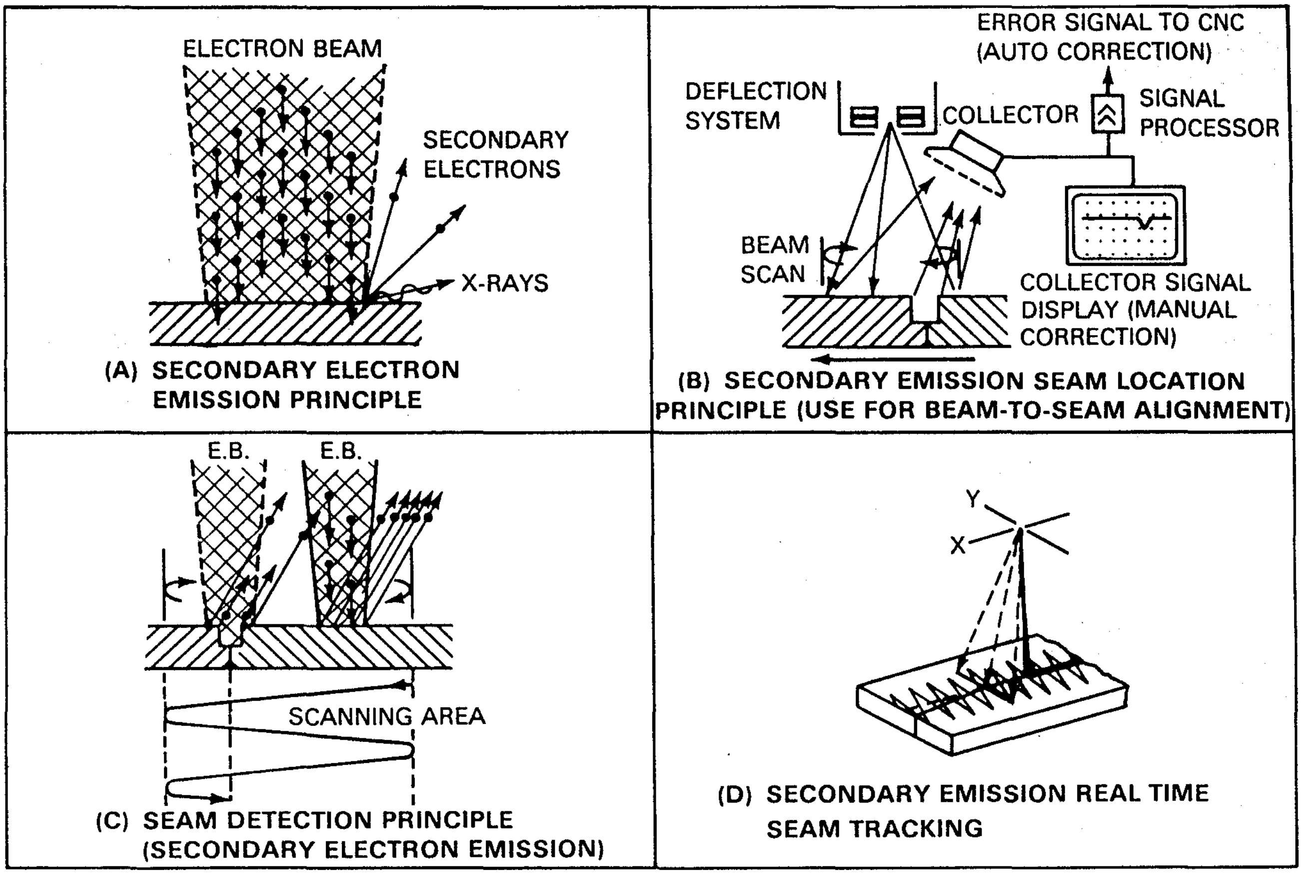


Figure 21.13–Principle for Seam Finding and Tracking Using Secondary Emission

Multiple-spindle rotary fixtures are also frequently used when making circumferential welds in a group of similar parts. The parts are again batch loaded, and then successively indexed into welding position by a motor drive. The joint on each part can be positioned for welding by linear movements of the work table on which the rotary fixture is mounted. It is possible to automate the entire operation. An example of a special purpose rotary fixture is shown in Figure 21.15.

CONTROLS

SINCE ALL THE operating variables of an electron beam welding system are directly controllable, the process is readily adaptable to computer numerical control (CNC). Movement of the workpieces or the gun, as well as electron beam deflection, can be preprogrammed in any combination. The beam current itself is also programmable. Thus, the beam can easily be changed from one discrete level to another, or changed at a specified rate. This ease of "upslope/downslope" control, and the capability for producing various beam deflection patterns, enhance the capacity of the process to produce extremely high-quality welds. Other variables, including the accelerating voltage, beam focus, emitter power, chamber pressure, as well as other auxiliary functions, can also be part of the program for control or monitoring. Electron beam welding systems perform computerized contour welding of intricately-shaped parts, where beam power and travel speed must be varied as a function of position along the weld path, as well as parts requiring multipass weld programs.

MEDIUM-VACUUM EQUIPMENT

EQUIPMENT FOR MEDIUM vacuum electron beam welding is basically a modification of standard high-vacuum equipment. An "aperture tube" (an orifice that allows beam passage, but impedes gas flow) is added into the gun column

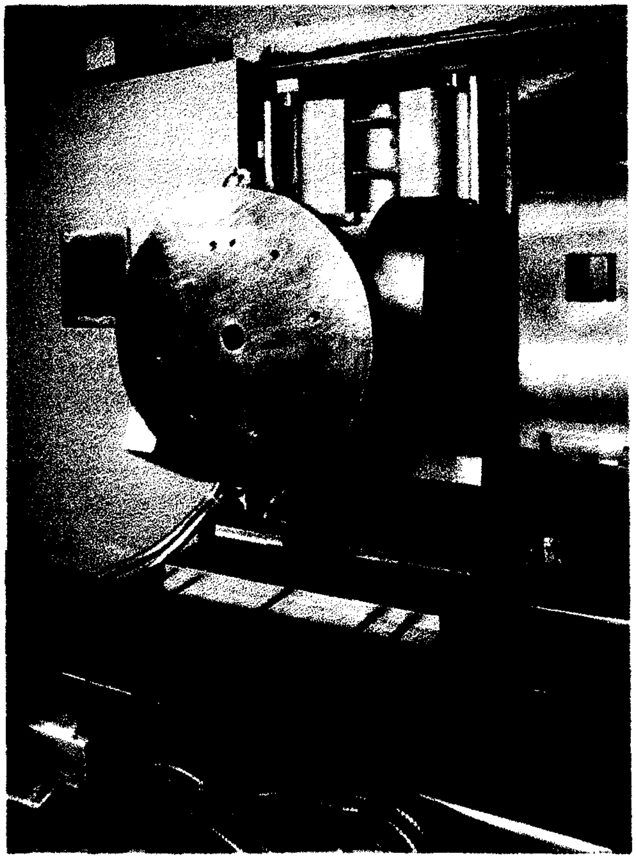


Figure 21.14—Table With X-Y Drive and Rotary Positioner from Electron Beam Work Chamber

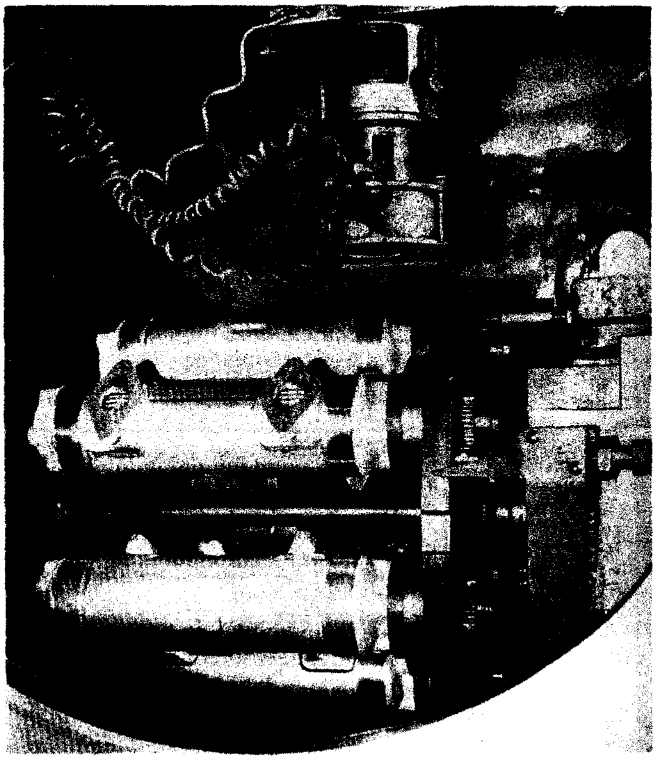


Figure 21.15—A Loaded Rotary Welding Fixture in Location Beneath the Electron Beam Gun

assembly, thereby allowing the separately pumped gun region to remain under high vacuum when the chamber is operated at a medium vacuum level. As on high-vacuum equipment, a column valve is used to isolate and maintain the gun region under high vacuum during chamber venting, and the aperture which is added helps to maintain a vacuum of 10^{-4} torr or better in the gun region during beam operation, while still allowing the beam to impinge on a workpiece located in a medium-vacuum environment. Thus, on medium-vacuum equipment, the chamber is cyclically vented as new parts are loaded and rapidly repumped down to some medium-vacuum welding level without the gun region being exposed to atmosphere. This permits high-volume part production. Both low- and high-voltage EBW systems are produced for medium vacuum welding.

General purpose medium-vacuum systems, such as the one shown in Figure 21.16, are used advantageously in short production runs. However, most medium-vacuum units are especially tooled for specific part assemblies. Figure 21.17 illustrates typical medium- vacuum tooling concepts. In each case, the work chamber and tooling are an integral assembly, specifically designed for a single-part design.

Various medium-vacuum welding systems are used for high- production applications. For example, a machine with a single welding station and multiple-loading stations can have a production capability in the region of 200 parts per hour. A dual welding station machine, on the other hand, could increase that production capability up to 500 parts per hour. The production rates in the final analysis are dependent upon the design of the parts.

Another method for achieving high production with medium-vacuum equipment is shown in Figure 21.18. Here, a sliding seal is used to provide intermediate vacuum zones before and after the separately pumped medium-vacuum welding chamber. This method maintains a series of continuously pumped vacuum zones which eliminate the need for evacuation time, thus enabling the high- production capability of a dial feed table to be fully utilized

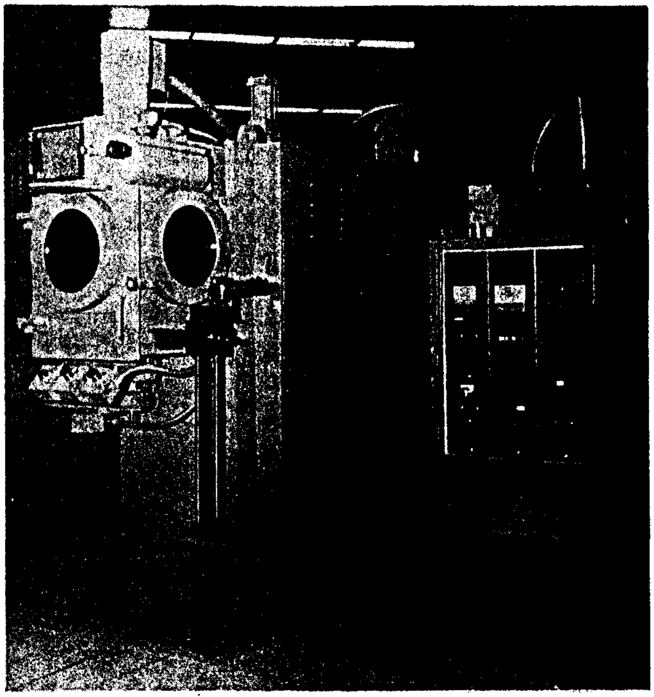


Figure 21.16–A General Purpose Medium Vacuum Electron Beam Welding Machine

and allowing production rates in excess of 500 parts per hour to be attained.

NONVACUUM EQUIPMENT

A BEAM OF electrons passing through a gas is primarily scattered by the shell electrons of the gas atoms or molecules. As the gas pressure increases, scattering becomes more severe (Figure 21.6). This produces a noticeable broadening of the beam profile and a decrease in beam-power density, but not necessarily a loss in total beam power.

An electron beam must be generated in high vacuum. To weld with the beam at atmospheric pressure, the beam is passed through a series of chambers or stages operating at progressively higher pressures. In addition, the electron velocity (accelerating voltage) must be high enough to minimize the scattering effect of the atmosphere.

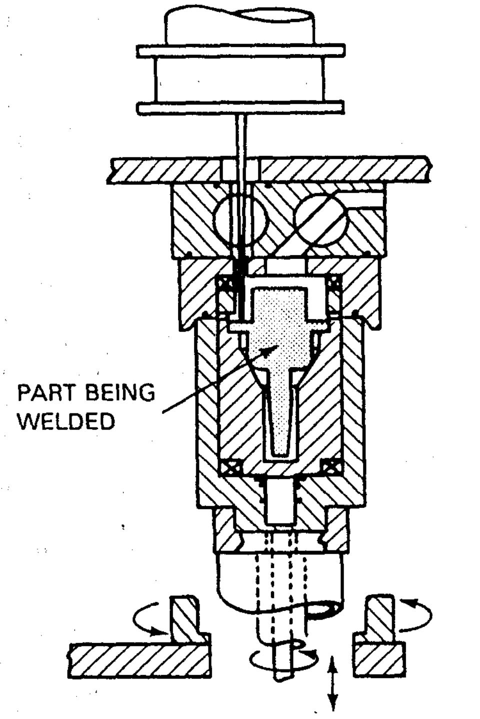
A series of chambers operating at successively higher pressures is obtained by staging; i.e., differentially pumping a number of chambers. A series of apertures is provided to permit the electron beam to pass through the wall of one chamber into the next, while restricting the gas flow in the opposite direction. This orifice and pumping system must be designed to maintain the atmospheric- to-high-vacuum gradient required. The electron beam must be accelerated through a high voltage. If the last stage is in air, this voltage must be a minimum of 150 kV in order to provide a practical working distance between the final orifice and the workpiece. The beam power level used, and the gas comprising the atmosphere through which the beam eventually passes, can greatly influence the useful working distance.

Figure 21.19 shows a conventional nonvacuum electron beam gun/column assembly, complete with orifice system. The electron gun shown is typical of those used with the other modes of electron beam welding, and is capable of operating at accelerating voltages in the range of 150 to 200 kV. Beam current, and thus the power, is controlled by the voltage on the bias electrode of the gun. The beam is focused by an electromagnetic lens to the minimum diameter of the orifice system shown at the bottom of Figure 21.19. It emerges from the vacuum environment, into air at atmospheric pressure, through the lower orifice. Inert gas shielding can be added, if desired. The workpiece is placed near the lower orifice.

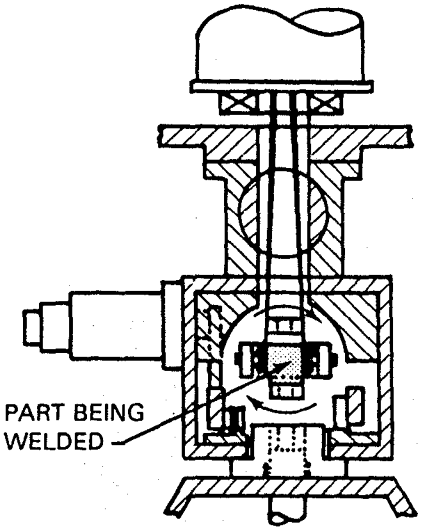
During operation, a high vacuum is continuously maintained in the upper gun area by using an oil diffusion or turbomolecular pump on this region. Lesser vacuum levels are maintained in the interim pressure stages by mechanical pumps. In most cases, the work is moved horizontally in front of the gun column, but the entire gun column can be moved if desired. As with the high-vacuum and medium-vacuum modes, the gun can be placed in either a vertical or a horizontal position, and the welding area must be shielded to protect personnel from the X-radiation produced during welding. Health hazards from this radiation are discussed at the end of this chapter under "Safety Precautions".

Another type of nonvacuum electron beam welding gun unit features a gas-filled, high-voltage power supply that can be mounted directly on the gun/column assembly during operation, both of which can then be traversed along a weld joint during operation.

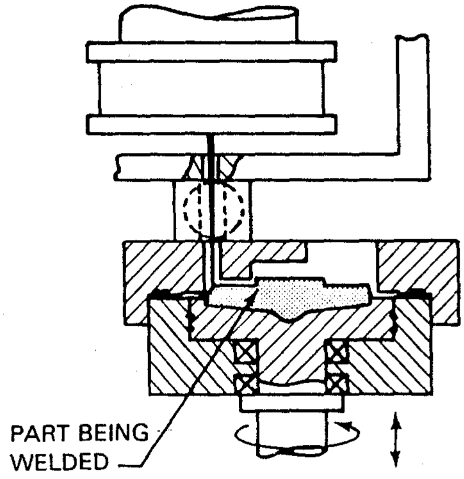
As with sliding-seal style medium-vacuum equipment, the time for evacuation of the work area is eliminated, and thus production rates in excess of 500 parts per hour are readily attainable with the nonvacuum EBW mode. In addition, since the workpiece need not be enclosed in a chamber to be evacuated, part size and part condition requirements are greatly alleviated.



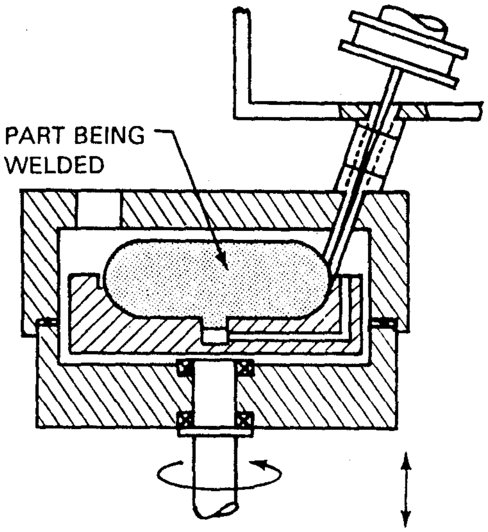
(A) BALL JOINT ASSEMBLY



(C) CARRIAGE ASSEMBLY



(B) DIAPHRAGM ASSEMBLY



(D) HOUSING ASSEMBLY

Figure 21.17–Typical Tooling Concepts in Special Purpose Medium Vacuum Electron Beam Welding Machines

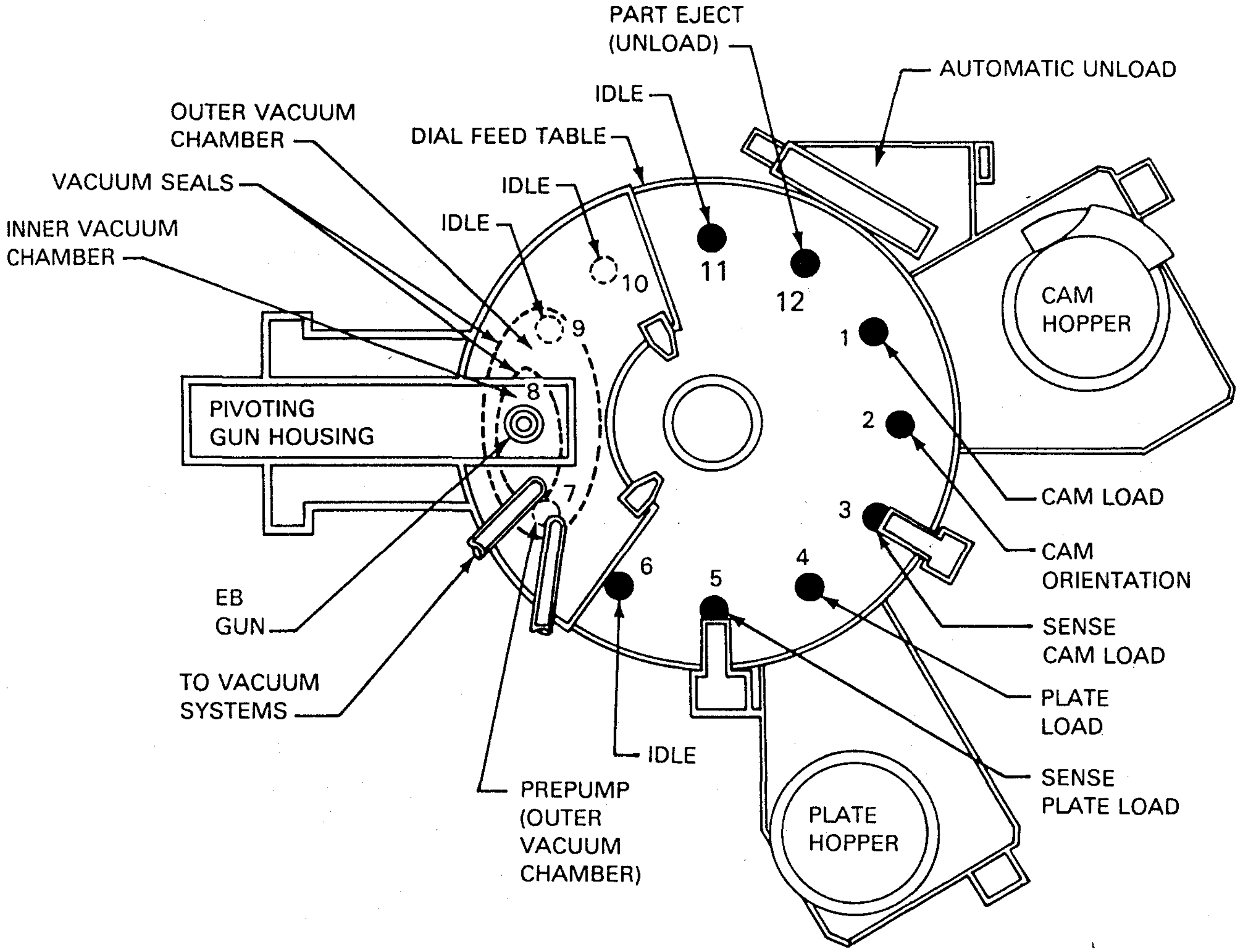


Figure 21.18–A Medium Vacuum Electron Beam Welding System with a Prepumping Zone for Continuous Part Feed Capability

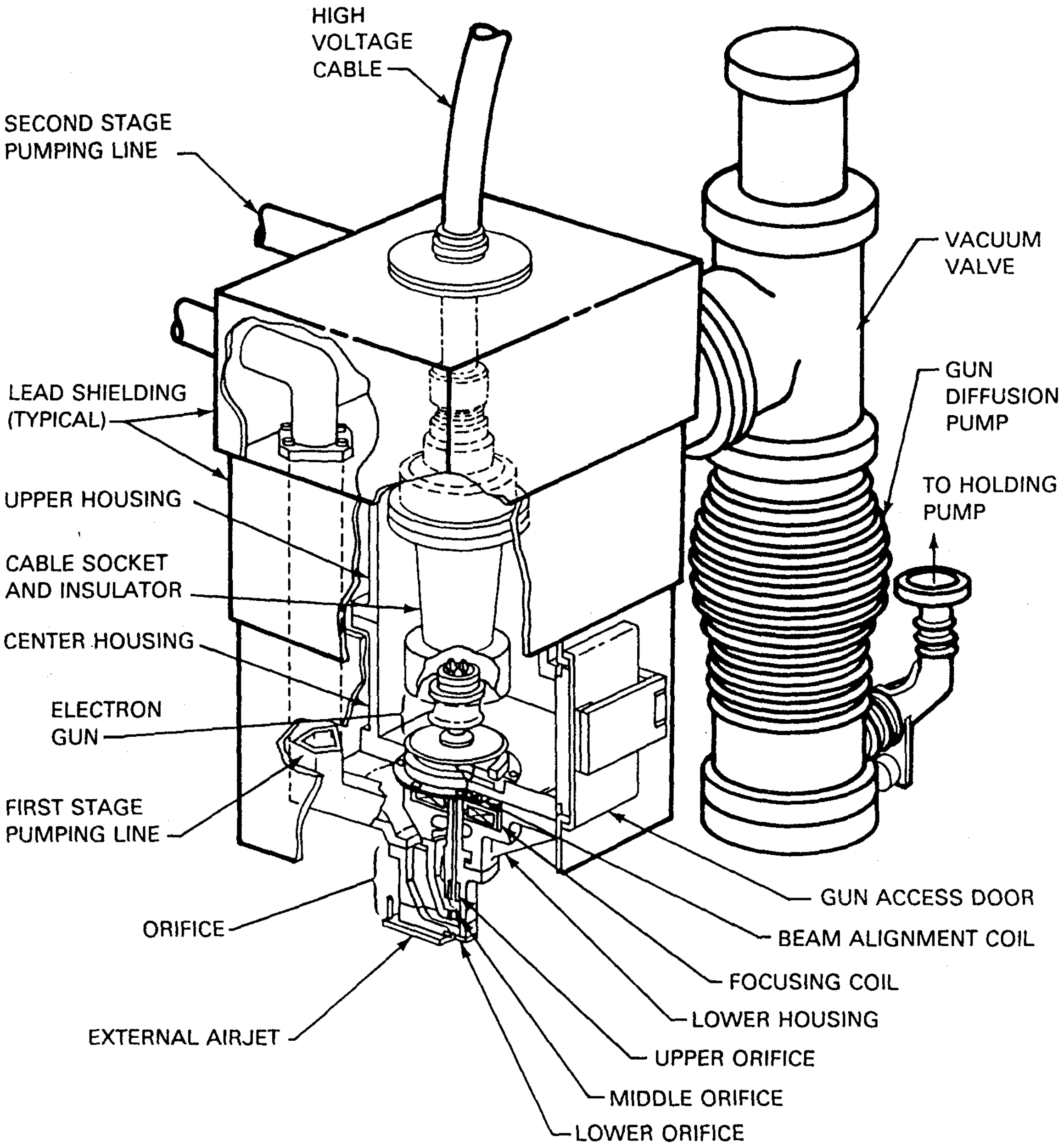


Figure 21.19–A Nonvacuum Electron Beam Gun Column Assembly

CHARACTERISTICS OF WELDS

THE ELECTRON BEAM welding process produces weld metal geometries that differ significantly from those made by conventional arc welding processes. Typical transverse cross sections through electron beam and gas tungsten arc welds are compared in Figure 21.20. The geometry of a typical electron beam weld exhibits a weld depth-to-width ratio that is very large in comparison to that of an arc weld. This feature results from the high-power density of the electron beam. The beam is concentrated in a small area, and the beam power density can exceed the power densities available in arc welding by several orders of magnitude.

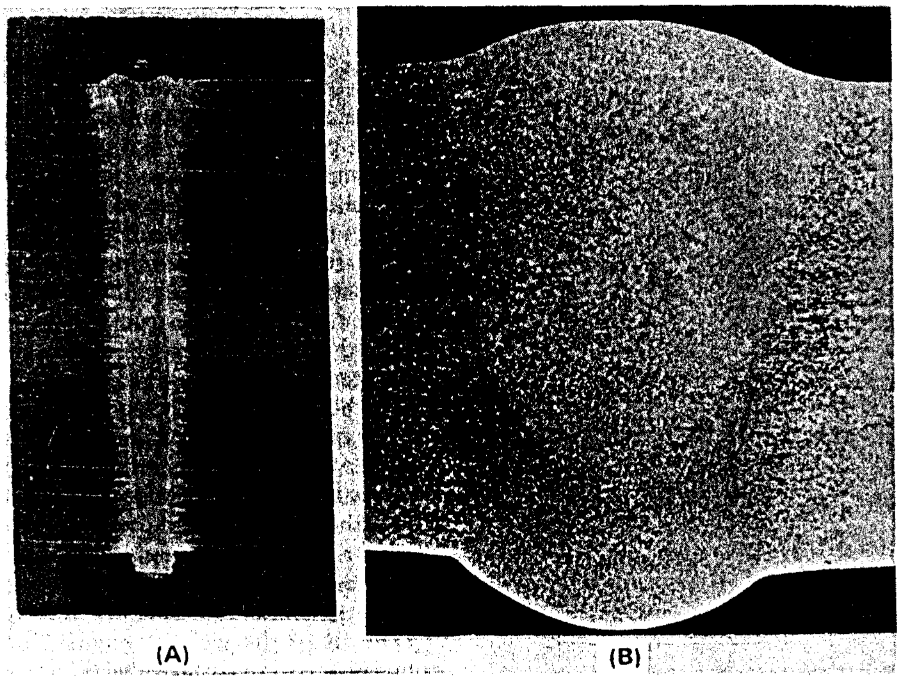


Figure 21.20–Comparison of Electron Beam (left) and Gas Tungsten Arc (right) Welds in 1/2 in. Thick Type 2219 Aluminum Alloy Plate

The high depth-to-width ratios of electron beam welds account for two important advantages of the process. First, relatively thick joints can be welded in a single pass. Thick weld joints, which require multiple-pass arc welding procedures, can be welded in a single pass by electron beam welding procedures, in considerably less time. An example of this is illustrated by Figure 21.21, which shows the cross section of a single-pass electron beam weld made in 4-in. thick carbon steel with a beam power of 33 kW and a travel speed of about 5 in./min (2 mm/sec). Second, for a given thickness, the rate (travel speed) at which welding can be accomplished is much greater than can be attained with arc welding. In turn, the electron beam welding process introduces less distortion and fewer thermal effects than arc welding.

High-vacuum welds with depth-to-width ratios of 50:1 are possible in a number of alloys. The welding of heavy sections in a single pass is practical using a square-groove butt joint. In aluminum, plates up to 18 in. (460 mm) thick have been welded in this manner.

Some problems remain with joining thick sections, but production applications in steel extend to over 6 in. (152 mm). The medium-vacuum mode sacrifices some of the penetration capability achievable in the high-vacuum mode, and in the partial (soft)-vacuum region of the medium-vacuum mode approximately five percent less penetration can be experienced. In the nonvacuum mode, the maximum penetration attainable in steel is presently under 2 in. (51 mm).

The ability to produce welds with these characteristics depends upon the process mode, whether high, medium, or nonvacuum. In all cases, it is highly dependent upon the beam spot size and the total beam power. Figure 21.22 is a representative plot showing how penetration decreases with increasing ambient pressure, due to the beam spreading brought about by increased pressure. (NOTE: The data are normalized relative to data achievable under high-vacuum conditions). The spread shown in this data plot is indicative of the fact that operating variables other than pressure (such as beam voltage, distance traveled, etc.) will also affect the penetration achieved at any given ambient pressure. The final depth-to width ratio achieved is also critically dependent upon base metal physical properties, especially melting point, heat capacity, thermal diffusivity, and vapor pressure.

EB welding, particularly in its high-vacuum mode, is an excellent tool for welding dissimilar metals and different masses, and for repair welding components impossible to salvage with other processes. Depending on the joint thickness and material being welded, the low total heat input to the workpiece can noticeably minimize weld joint distortion. In general, the high- and medium- vacuum modes are the most advantageous, although the nonvacuum mode offers some notable advantages over conventional arc welding processes.

Because a high-power density beam produces welds that are not controlled by thermal conduction, metals of significantly different thermal conductivities can be welded together. A joint between two pieces of different thickness has unequal heat losses into the thinner and thicker parts, but that is not a significant problem. In thin metals or low-

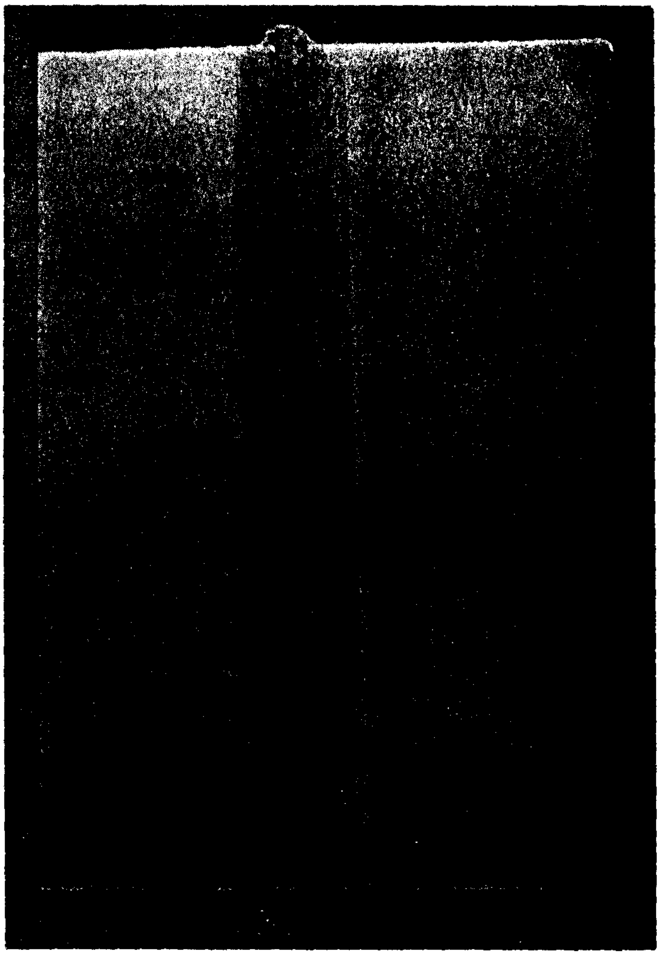


Figure 21.21–Single-Pass Electron Beam Weld in a 4 in. Thick Carbon Steel Section

melting metals, fusion can be accomplished without significant need for backup heat sinks that would be required for arc welding. For unequal masses, the beam energy is usually concentrated on the thicker section, and the power is adjusted for penetration through the thin section.

Arc welding procedures often require preheating thick sections of a metal having high thermal conductivity, such as aluminum or copper. Little or no preheat is required for electron beam welding those metals, because of the high-power density available.

Reactive and refractory metals are detrimentally affected by very small amounts of atmospheric contaminants, such as oxygen, nitrogen, and hydrogen. These metals may be electron beam welded without introducing these contaminants. Such metals include tungsten, molybdenum, columbium, tantalum, zirconium, and titanium. The high-vacuum mode is most suitable for joining these metals. The other two modes have decreasing weld performance capabilities, although they still may be satisfactorily applied in select cases.

Although electron beam welding is a high-power density process, it is also a low-energy process. The total energy input needed to weld a joint of a given thickness is considerably less than that required by more conventional arc welding processes. Two advantages result from the low-energy input: first, it minimizes distortion and reduces the size of the weld heat-affected zone; second, the high cooling rates of narrow electron beam welds can avoid metallurgical reactions, such as phase changes. However, the fundamental rules of metallurgy regarding cooling rates and the resulting microstructure still apply. Nevertheless, the weld metal will have mechanical properties normally associated with the bulk properties of the base metal.

Another aspect of electron beam welding involves the control of the process. As the process is pushed to the limit of its capabilities, the operating variables that influence the final results require much greater control. Accurate control of the electron beam process has permitted a high degree of reliability. At present, incorporation of minicomputers and microprocessors offers additional control capability over the welding conditions.

Control of the welding environment can control the composition of the weld metal. Electron beam welding in a high vacuum permits gases to escape and high vapor pressure metals to evaporate. This produces a more refined melt zone material, but may also cause the loss of certain alloying elements. At the other pressure extreme, nonvacuum electron beam welding in air may increase the nitrogen and oxygen content of the weld metal.

The narrow weld metal shape produced by this process results in less distortion in weldments. In this type of weld, the weld metal is essentially parallel-sided except where the electron beam first impinges on the top surface of the abutted members. See Figure 21.20(A). Contraction of the metal during cooling is fairly uniform through the joint. When weld metal has a characteristic V-shape, as in arc welding, there is significant warpage from the unequal thermal contraction at top and bottom of the joint.

Since the electron beam can penetrate through extremely thick sections, beveling or chamfering one or both edges of abutting members is not necessary. However, for such welds, tighter machining tolerances are normally required for high vacuum electron beam welding than for arc welding.

In medium vacuum welding, weld metal cross sections are similar to those of high vacuum welding, but the depth-to-width ratios are somewhat smaller.

With nonvacuum electron beam welding, the weld bead produced may be nearly as wide as a typical gas tungsten arc weld. That weld metal may possess all the characteristics produced by the more conventional welding processes, because insufficient power or large gun-to-work distances were employed. However, at high power and speed, depth-to-width ratios on the order of 5 to 1 are feasible with the nonvacuum welding mode.

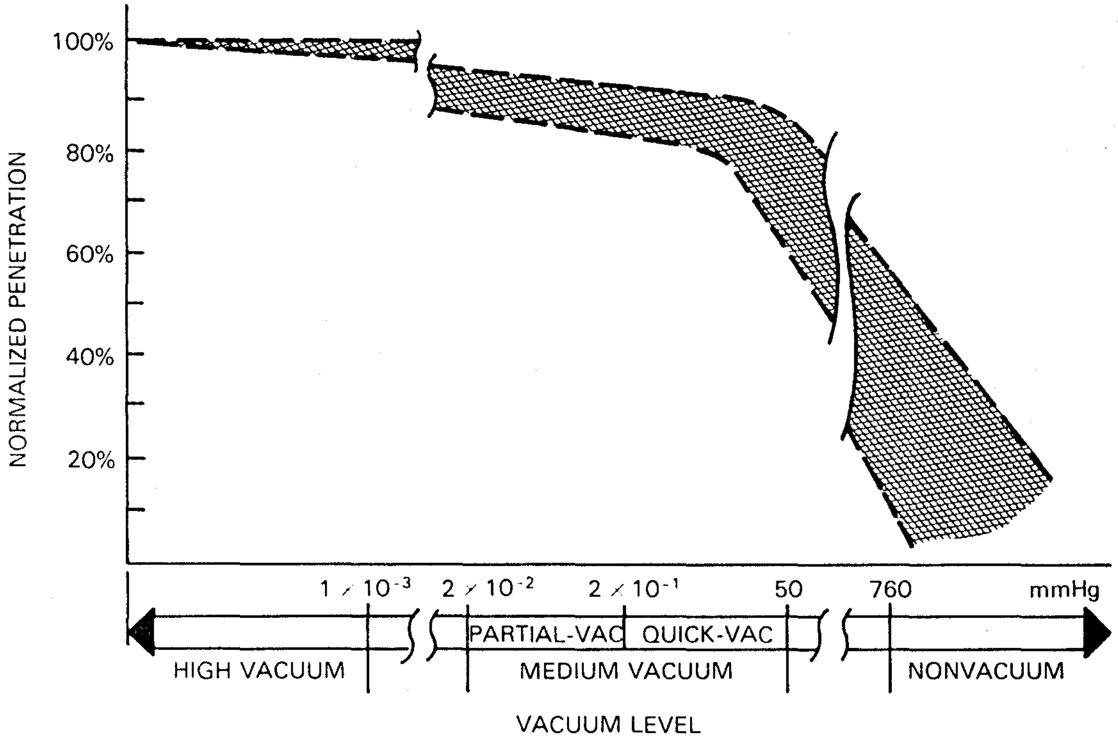


Figure 21.22–Penetration as a Function of Operating Pressure

WELDING PROCEDURES

JOINT DESIGNS

BUTT, CORNER, LAP, edge, and T-joints can be made by electron beam welding using square-butt joints or seam welds. Fillet welds are difficult to make and are not generally attempted. Typical electron beam weld joint designs are shown in Figure 21.23. Modifications of these designs are frequently made for particular applications.

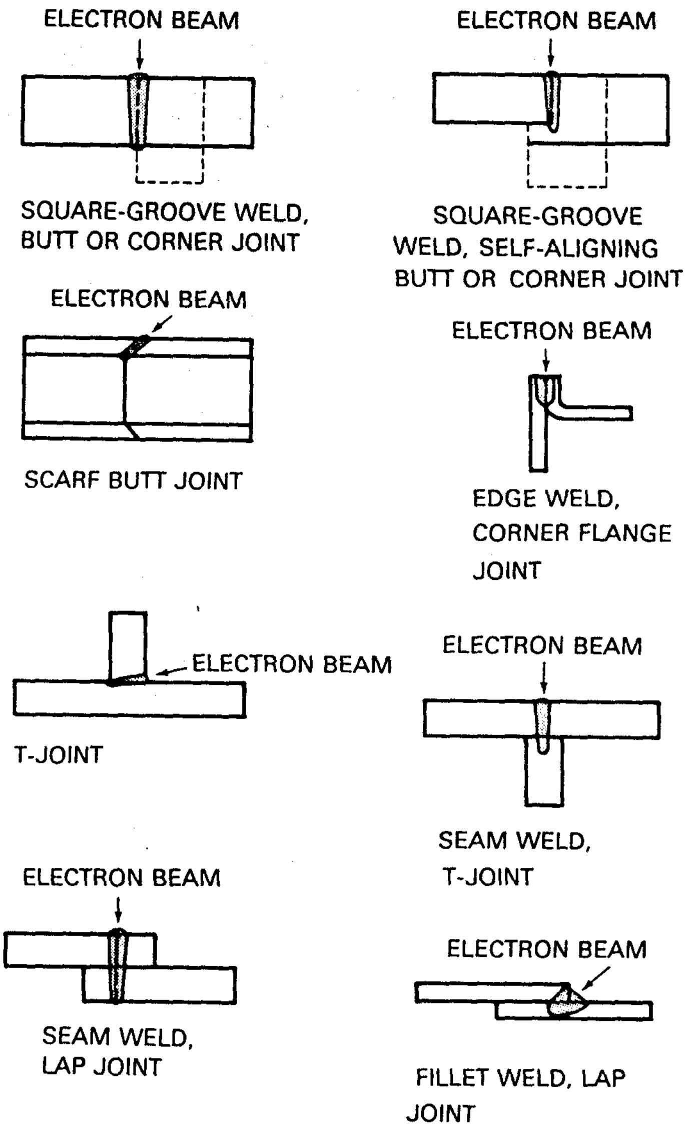
Square butt joint welds require fixturing to maintain fit-up and alignment of the joint. They can be self-aligning if a rabbet joint design is used. The weld metal area can be increased using a scarf joint, but fit-up and alignment of the joint are more difficult than with a square butt joint weld. Edge, seam, and lap fillet welds are primarily used to join sheet gage thicknesses.

JOINT PREPARATION AND FIT-UP

WHEN NO FILLER wire is added, the fit-up of parts must be more precise than for arc welding processes, because poor fit up would result in a lack of fill of the weld joint. The beam must impinge on and melt both members simultaneously, except for seam welds where the beam penetrates through the top sheet. Underfill or incomplete fusion will result from poor fit-up, and lap joints which are not clamped sufficiently will burn through.

A metal-to-metal fit between parts is desirable but difficult to obtain. The acceptable gap for a particular application will depend upon the process mode employed, the type of base metal, the thickness and configuration of the joint, and the required weld quality. Thus, while sheet sections being welded with the vacuum mode may require a fit-up of less than 0.004 in. (0.1 mm), plate sections being welded with the nonvacuum mode may tolerate a fit-up more than five times greater. Aluminum alloys can tolerate somewhat larger gaps than steel. Beam deflection or oscillation with high and medium vacuum welding, to widen the fusion zone, and with nonvacuum welding, may permit larger gaps. Consequently, the maximum acceptable joint gap and the tolerance for each particular application should be determined and qualified in order to avoid unnecessary joint preparation costs.

In general, roughness of the faying surfaces is not critical so long as the surfaces can be properly cleaned to remove



SQUARE-GROOVE WELD, BUTT OR CORNER JOINT

SQUARE-GROOVE WELD, SELF-ALIGNING BUTT OR CORNER JOINT

SCARF BUTT JOINT

EDGE WELD, CORNER FLANGE JOINT

T-JOINT

SEAM WELD, T-JOINT

SEAM WELD, LAP JOINT

FILLET WELD, LAP JOINT

Figure 21.23–Typical Joint Designs for Electron Beam Welds

any contamination. Burrs on the sheared edges of sheet are not detrimental unless they separate the faying surfaces of lap joints.

CLEANING

CLEANLINESS IS A prime requisite for high-quality welding. The cleanliness level will depend upon the end use of the welded product. Contamination of the weld metal may cause porosity or cracking, or both, as well as a deterioration of mechanical properties. Improper cleaning of the components to be welded may lengthen chamber evacuation time excessively, depending on the vacuum mode being employed.

Acetone and methylethylketone were, for many years, considered to be excellent solvents for cleaning electron gun components and workpiece parts. However, these chemicals are now considered possible toxic substances, and many facilities are presently using pure alcohol instead. Chlorinated hydrocarbon solvents should definitely not be used because of their detrimental effect on the operation of high-voltage equipment. If a vapor degreaser must contain a chlorinated hydrocarbon solvent for heavy degreasing tasks, the parts must be thoroughly washed in pure alcohol afterward. An alternative would be to degrease in a fluorocarbon type solvent. After final cleaning, the joint area should not be touched by hand or tools.

Surface oxides and other forms of contamination that solvents will not dissolve should be removed by mechanical or chemical means. Flat surfaces of soft metals, such as magnesium, aluminum, and copper, can be scraped by hand. Machining without coolant is preferred for all but very hard metals, where grinding must be used. Surfaces that are not prepared by machining should be chemically cleaned. Grit blasting and grinding are not recommended for soft metals, including soft steels, because the grit may be embedded in the surfaces. Wire brushing is not generally recommended, because it also tends to embed contaminants in the metal surface.

Nonvacuum welding will generally require less stringent precleaning than vacuum welding.

FIXTURING

ELECTRON BEAM WELDING can be accomplished by manually or automatically controlling the system's functional operation. The parts must be fixtured to align the joint, unless the design is self-fixturing, and then either the assembly or the electron beam gun column must be moved to accomplish the weld.

Where practical, self-fixturing joints should be used. A pressed or shrink fit can position circular parts for welding. However, these methods require close tolerance machining, which may not be economical for high-production welding.

Fixturing for electron beam welding need not be as strong and rigid as that required for automatic arc welding. The reason is that electron beam welds are generally made with much lower power than arc welds. Therefore, stresses in the weldment caused by thermal gradients extend over a smaller volume of metal. However, fixturing used for EBW must not introduce magnetic effects that adversely affect the beam.

The close joint fit-up and alignment required for electron beam welds generally call for fixturing made to the same tolerances. Copper chill blocks plated with nickel to avoid contamination can be used to remove heat from the joint.

Work tables and rotating positioners should have smooth and accurate motion at the required travel speeds. All fixturing and tooling should be made of nonmagnetic metals to prevent magnetic deflection of the beam. All magnetic metals should be demagnetized before welding them.

The entry and exit of the electron beam tends to produce underfill at both ends of the welded joint. To minimize or eliminate this defect, tabs of the same metal as the workpieces should be fitted tightly against both ends of the joint so that the beam can be initiated on the starting tab, traversed along the weld joint, and terminated on the runoff tab. These tabs can later be removed flush with the ends of the workpiece.

FILLER METAL ADDITIONS

WHEN FAYING SURFACES of butt joints are fitted together with acceptable tolerances, filler metal is not normally needed to obtain a full thickness weld. As welding progresses along the joint, weld metal flows from the leading edge to the trailing edge of the vapor hole. Thermal contraction, as the weld progressively freezes, usually produces a welded joint free of underfill, when proper welding procedures are used. Certain joint designs use the thermal contraction of the weldment to produce an autogenous weld from multiple weld passes; such weld procedures use a narrow tapered joint gap and a lower power density beam to produce full penetration welds. Such welds tend to exhibit few of the defects sometimes encountered with single-pass autogenous welds.

However, for some applications it is desirable or necessary to add filler metal to obtain an acceptable welded joint. Filler metal may be needed to obtain certain physical or metallurgical characteristics in the weld metal. Weld metal characteristics that may be altered or improved by filler metal addition include ductility, tensile strength, hardness, and crack resistance. For example, preplacing a thin aluminum shim in the joint can produce a deoxidizing action in mild steel, which will reduce porosity.

When filler metal is added to the joint for metallurgical purposes, wire feed is not employed exclusively. The dilution obtained from a dissimilar filler metal added as wire at the joint surface does not occur uniformly from top to bottom of the weld. For a single pass weld in heavy plate, filler metal may take the form of a thin shim. The presence of the filler shim requires that beam oscillation or a large diameter spot be used to melt the shim and the base metal on both sides of the joint. This is not the case with thin metal weldments, where filler wire can be added at the surface and dilution will occur throughout the entire joint. Typical examples of filler metal additions for metallurgical reasons are the welding of Type 6061 aluminum alloy using Type 4043 aluminum filler metal, and the welding of beryllium using aluminum or silver filler metal.

Filler metal may be added at the surface to fill the joint during a second pass after the penetration pass has been made. This is done to obtain a full thickness weld in thick plate.

Filler wire feeding equipment is usually either a modified version of that used for gas tungsten arc welding, or a unit specially designed for use in a vacuum chamber. Filler wire diameters are generally small, 0.030 in. (0.8 mm) and under, because the wire feeder must uniformly feed the wire into the leading edge of a small molten weld pool. The wire feeding nozzle should be made of a heat-resistant metal.

For welding in a vacuum chamber, the filler wire drive motor must be sealed in a vacuum-tight enclosure or otherwise designed for use in a vacuum. Outgassing from an open motor will greatly increase the work chamber evacuation time. Provisions must be made for adjusting the wire feed nozzle to position the wire with respect to the electron beam and to the weld joint over the entire length of the joint.

SELECTION OF WELDING VARIABLES

THE RATE OF energy input to the workpiece during EBW is commonly express in joules per inch, or joules per second.[4] The formula for this expression is:

$$\text{Energy input, J/in. (J/mm)} = \frac{E \times I}{S} = \frac{P}{S} \qquad (21.1)$$

where:

E = beam accelerating voltage, V
I = beam current, A
P = beam power, W or J/s
S = travel speed, in./s (mm/s)

Data for welding various thicknesses of a specific material can be plotted to permit interpolation of welding variables for that material over the range of values covered by the data. A curve relating energy input with thickness for a particular family of alloys can be determined from a few tests to establish the welding conditions for untested metal thicknesses. Figure 21.24 shows several such curves. These graphs are particularly useful to determine starting point conditions. Three factors make this possible: (1) electron beam welding machine settings are usually regulated by closed-loop servocontrols that ensure stability and reproducibility; (2) the adjustment of each variable is independently controlled, to permit flexibility in selection; (3) assuming the vacuum level and work distance being used are

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[4] Energy input to the weld from a heat source is discussed in Chapter 2, *Welding Handbook*, Vol. 1, 8th Ed., p. 33.

held constant, there are only four basic variables to adjust: accelerating voltage, beam current, travel speed, and beam focus. Beam deflection may constitute a fifth variable, if an oscillatory beam motion is employed. These variables combine to make the process of establishing the welding schedule relatively simple.

Once the required energy input per unit length is determined for a given metal thickness, the travel speed can be selected and the required welding power defined, or vice versa. The beam voltage and current can now be selected to produce the required power.

The beam size selected will be dependent upon the desired weld bead geometry. To maintain a selected beam spot diameter at the surface of the workpiece, it is necessary to correspondingly increase the focus coil current as the accelerating voltage is increased, since the beam spot size is a dependent function of the accelerating voltage. Many electron beam welding units automatically perform this compensation task. If the accelerating voltage is maintained constant but the gun-to-work distance is increased, a corresponding decrease in focus coil current is necessary to maintain a selected beam spot diameter at the surface of the workpiece.

Changes in individual welding variables will affect the penetration and bead geometry in the following manner:

(1) Accelerating voltage: as the accelerating voltage is increased, the depth of penetration achievable will also increase. For long gun-to-work distances or the production of narrow, parallel-sided welds, the accelerating voltage should be increased and the beam current decreased to obtain maximum focal range (see Figure 21.1).

(2) Beam current: for any given accelerating voltage, the penetration achievable will increase with beam current.

(3) Travel speed: for any given beam power level, the weld bead will become narrower and the penetration will decrease as the travel speed is increased.

(4) Beam spot size: sharp focus of the beam will produce a narrow, parallel-sided weld geometry because the effective beam power density will be maximum. Defocusing the beam, either by overfocusing or by underfocusing, will increase the effective beam diameter and reduce beam power density This, in turn, will tend to produce a shallow or V-shaped weld bead. These effects are shown in Figure 21.25.

Underfocusing is often used for heavy section welding in order to produce the highest possible effective aspect ratio. However, care should be taken to ensure that the depressed beam focal point does not produce a weldment having a large "nail head" or a bottle shape, since both conditions lead to weld cracking.

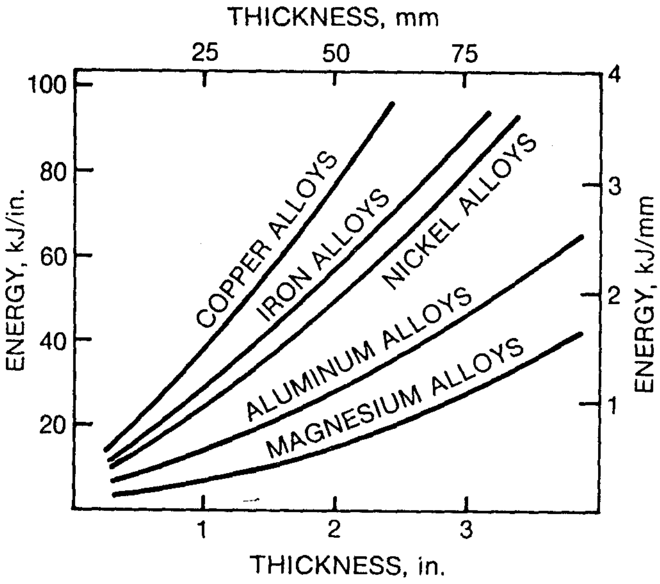
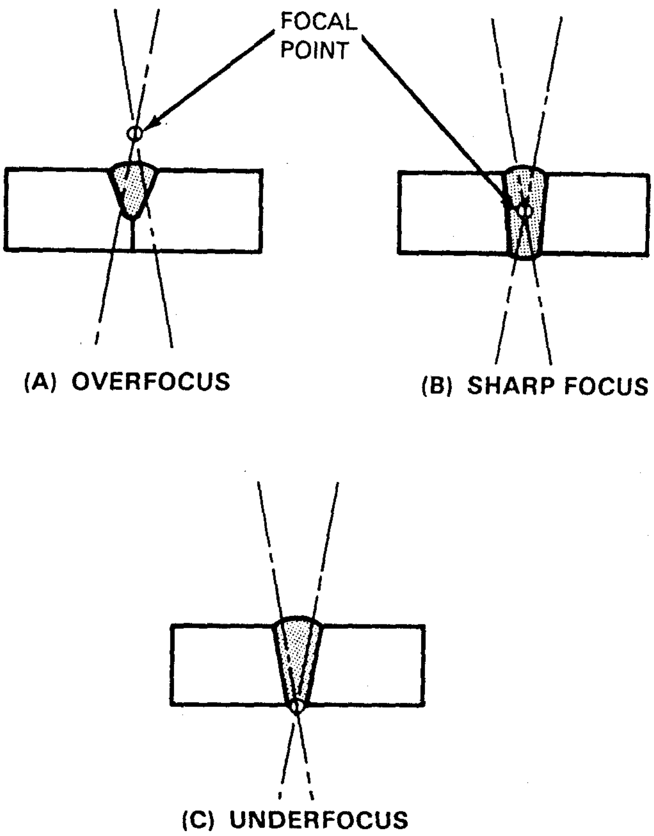


Figure 21.24—High Vacuum Electron Beam Welding Energy Requirements for Complete Penetration Welds in Several Metals as a Function of Joint Thickness



(A) OVERFOCUS

(B) SHARP FOCUS

(C) UNDERFOCUS

Figure 21.25—Effect of Electron Beam Focusing on Weld Bead Geometry and Penetration

METALS WELDED

IN GENERAL, METALS and alloys that can be fusion welded by other welding processes can also be joined by electron beam welding.[5] This includes similar and dissimilar metal combinations that are metallurgically compatible. The narrow weld metal geometry and thin heat-affected zones, especially in the high-vacuum mode, produce joints with better mechanical properties and fewer discontinuities than arc welded joints. However, electron beam welds in alloys that are subject to hot cracking or porosity will often contain such discontinuities. The weldability of a particular alloy or combination of alloys will depend upon the metallurgical characteristics of that alloy or combination, and the part configurations, joint design, process variation, and chosen welding procedure.

STEELS

Rimmed and Killed Steels

IN INGOT-CUT RIMMED steel, the chemical reaction that occurs between carbon and oxygen to form carbon monoxide gas (CO) will occur in the molten weld pool. As a result, violent weld pool action, spatter, and porosity in the solidified weld metal are expected with this type of steel.

Electron beam welds in rimmed steel can be improved if deoxidizers, such as manganese, silicon, or aluminum, are incorporated through filler metal additions. Deoxidizers can also be added locally to the joint area by painting, spraying, and shim inserts.

Running a low-power (low penetration) weld pass, before doing a required high-power (high penetration) pass, can often reduce the violence of the weld puddle action. Welding of rimmed steel can be improved by the careful selection of electron beam welding conditions, such as slow travel speed, to produce a wide and shallow weld cross section. The gases need time to escape from the molten weld metal. Then a weld of reasonable quality can be obtained. Various beam deflection patterns may help encourage gas escapement, and thus be effective in reducing weld porosity.

Continuous cast mild steels are silicon-aluminum killed, and therefore porosity is not a problem.

Hardenable Steels

THICK SECTIONS OF hardenable steels may crack when electron beam welded without preheat. Very rapid cooling in the fusion and heat-affected zones will result in the formation of brittle martensite. The combination of a hard, brittle microstructure and residual stresses can create cracks. Cracking can be prevented by preheating. Preheat can be supplied with a defocused electron beam in many applications, relying on careful programming and monitoring to achieve the proper preheat temperature.

Stainless Steels

Austenitic Stainless Steels. The high cooling rates typical of electron beam welds help to inhibit carbide precipitation in stainless steels because of the short time that the weld zone is in the sensitizing temperature range. However, the high cooling rate may cause cracking in highly constrained, low ferrite grades of material.

Martensitic Stainless Steels. Although these steels can be welded in almost any heat-treated condition, a hard martensitic heat-affected zone will result. Hardness and susceptibility to cracking increase with increasing carbon content and cooling rate. Rapid cooling can be prevented by preheating the base materials before welding.

Precipitation-Hardening Stainless Steels. These steels can, in general, be electron beam welded to produce good mechanical properties in the joint. The semiaustenitic types, such as 17-7PH[6] and PH14-8 Mo[6], can be welded as readily as the 18-8 types of austenitic stainless steel. The weld metal becomes austenitic during welding and remains austenitic during cooling. In the more martensitic types, such as 17-4 PH[6] and 15-5 PH[6], the low carbon content precludes formation of hard martensite in the weld metal and heat-affected zone. However, not all combinations of PH alloys can be welded without some cracking. Some precipitation-hardening stainless steels, such as 17-10P and HNM,[6] have poor weldability because of their high phosphorus content.

ALUMINUM ALLOYS

IN GENERAL, ALUMINUM alloys that can be readily welded by gas tungsten arc and gas metal arc welding can be electron beam welded. Two problems that may be encountered in some alloys are hot cracking and porosity.

The nonheat treatable series of aluminum alloy (1xxx, 3xxx, and 5xxx) can be electron beam welded without difficulty. Welded joints will possess mechanical properties similar to annealed base metal.

The heat treatable alloys (2xxx, 6xxx, and 7xxx) are crack sensitive to varying degrees when electron beam welded. Some may also be prone to weld porosity. Alumi-

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[5] The weldability of various metals is covered in Volume 4, *Welding Handbook*, 7th Ed.

[6] Trademarks

num alloy Types 6061-T6 and 6066-T6, which are difficult alloys to join by other processes, can be successfully welded by the electron beam process. Best results with these alloys are obtained by incorporating small amounts of Type 4043 aluminum filler metal or 718 aluminum brazing foil in the weld.

As-welded joints in 1.5 in. (38 mm) thick Type 7075-T651 aluminum alloy exhibit lower mechanical properties than unwelded plate. The low weld properties are caused by overaging in the heat-affected zone. Postweld solution treating and aging will produce heat-treated properties in the welded joint. At high travel speeds, weld porosity may result from vaporization of certain elements in this alloy, the loss of which may change the weld metal properties. This effect should be taken into consideration before welding 7075. The high zinc content of Type 7075 aluminum alloy is responsible for vapor formation. At low travel speed, the vapor escapes to the surface before the weld metal solidifies.

Zinc-free aluminum alloys can be welded at higher speeds without developing severe porosity. It is advantageous to weld thermally hardened aluminum alloys at high travel speed to minimize the width of the softer weld and heat-affected zones.

TITANIUM AND ZIRCONIUM

TITANIUM AND ZIRCONIUM absorb oxygen and nitrogen rapidly at welding temperatures, and this reduces their ductility. Acceptable levels of oxygen and nitrogen are quite low. Therefore, these materials and their alloys must be welded in an inert environment. High vacuum electron beam welding is best for both metals, but medium vacuum and nonvacuum welding with inert gas shielding may be acceptable for some titanium applications. Most zirconium applications require that welding be performed in a vacuum or an inert gas environment, to preserve the corrosion resistance of the metal.

REFRACTORY METALS

ELECTRON BEAM WELDING is an excellent process for joining the refractory metals, because the high-power density allows the joint to be welded with minimum heat input. This is especially important with molybdenum and tungsten, because fusion and recrystallization raise the ductile-to-brittle transition temperatures of these metals above room temperature. The short time at temperature associated with electron beam welding minimizes grain growth and other reactions that raise transition temperatures.

The refractory metals rhenium, tantalum, vanadium, and niobium are readily welded. Molybdenum and tungsten are difficult to weld.

Electron beam welding joins molybdenum and tungsten successfully provided the joints are not restrained during welding. Thin sections are easy to handle, and it may be better to fabricate a composite structure by joining thin welded sections rather than to weld a single thick section. Freedom from impurities such as oxygen, nitrogen, and carbon is important. Alloys of metals containing rhenium are better suited for welding than the pure metals because they remain more ductile at lower temperatures.

DISSIMILAR METALS

WHETHER TWO DISSIMILAR metals or alloys can be welded together successfully depends upon their physical properties, such as melting points, thermal conductivities, atomic sizes, and thermal expansions. Weldability is usually predicted by empirical experience in this area. A generalization about weldability can be made by examining the alloy phase diagram of the metals to be joined. If intermetallic compounds are formed by the metals to be joined, the weld will be brittle.

Information on the relative weldability of some dissimilar metals is given elsewhere in the Handbook.[7] However, the available information about each particular application must be reviewed with regard to joint restraint and service environment. The problem of metallurgical incompatibility can sometimes be solved by the use of a filler metal shim or by welding each of the materials to a compatible transition piece. Examples are given in Table 21.2. Table 21.3 presents a summary of the weldability of various metal combinations derived from phase diagram information and accumulated practical experience.

Often the electrical couple formed at the interface produced when two dissimilar materials are being welded can induce an electromagnetic force (EMF) at elevated temperatures. If large circulating currents and magnetic fields are produced, they may cause the electron beam to be deflected from the joint centerline in medium to heavy section weldments. This undesirable effect may be corrected by broadening the beam spot, by providing a slight bias to the beam's angle of impingement, or by both techniques.

Table 21.2
Examples of Filler Metal Shims for Electron Beam Welding

Metal A	Metal B	Filler Shim
Tough pitch copper	Tough pitch copper	Nickel
Tough pitch copper	Mild steel	Nickel
Hastelloy X [a]	SAE 8620 steel	321 stainless steel
304 stainless steel	Monel [a]	Hastelloy B *
Inconel 713 [a]	Inconel 713 [a]	Udimet 500 *
Rimmed steel	Rimmed steel	Aluminum

* Tradenames

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[7] *Welding Handbook*, Vol. 4, 7th Ed.

Table 21.3
Weldability of Dissimilar Metal Combinations

	Silver	Aluminum	Gold	Beryllium	Cobalt	Copper	Iron	Magnesium	Molybdenum	Columbium	Nickel	Platinum	Rhenium	Tin	Tantalum	Titanium	Tungsten
Aluminum	2																
Gold	1	5															
Beryllium	5	2	5														
Cobalt	3	5	2	5													
Copper	2	2	1	5	2												
Iron	3	5	2	5	2	2											
Magnesium	5	2	5	5	5	5	3										
Molybdenum	3	5	2	5	5	3	2	3									
Columbium	4	5	4	5	5	2	5	4	1								
Nickel	2	5	1	5	1	1	2	5	5	5							
Platinum	1	5	1	5	1	1	1	5	2	5	1						
Rhenium	3	4	4	5	1	3	5	4	5	5	3	2					
Tin	2	2	5	3	5	2	5	5	3	5	5	5	3				
Tantalum	5	5	4	5	5	3	5	4	1	1	5	5	5	5			
Titanium	2	5	5	5	5	5	5	3	1	1	5	5	5	5	1		
Tungsten	3	5	4	5	5	3	5	3	1	1	5	1	5	3	1	2	
Zirconium	5	5	5	5	5	5	5	3	5	1	5	5	5	5	2	1	5

1. Very desirable
   (solid solubility in all combinations)
2. Probably acceptable
   (Complex structures may exist)
3. Use with caution
   (Insufficient data for proper evaluation)
4. Use with extreme caution
   (No data available)
5. Undesirable combinations
   (Intermediate compounds formed)

APPLICATIONS

ELECTRON BEAM WELDING is primarily used for two distinctly different types of applications: high precision and high production.

High-precision applications require that the welding be accomplished in a high-purity environment (high vacuum) to avoid contamination by oxygen, nitrogen, or both, and with minimum heat effects and maximum reproducibility. These types of applications are mainly in the nuclear, aircraft, aerospace, and electronic industries. Typical products include nuclear fuel elements, special alloy jet engine components, pressure vessels for rocket propulsion systems, and hermetically sealed vacuum devices.

High-production applications take advantage of the low-heat input and the high reproducibility and reliability of electron beam welding if a high-purity environment is not required. These relaxed conditions permit welding of components in the semifinished or finished condition using both medium and nonvacuum equipment. Typical examples are gears, frames, steering columns, and transmission and drive-train parts for automobiles; thin-wall tubing; bandsaw and hacksaw blades; and other bimetal strip applications. Figure 21.26 shows a bimetallic strip welding machine where individual strips are fed continuously into and out of the weld chamber through a series of pressure zones.

Nonvacuum electron beam welding has found its major application in high-volume production of parts whose size or composition precludes their effectively being welded in a vacuum. One example of this is the automotive industry, where nonvacuum welding is employed for many applications. A nonvacuum electron beam welded torque converter assembly is shown in Figure 21.27. The manufacture of welded tubing is another example. Integrated EB welding machine/tube mill units have been built to weld copper or steel tubing continuously at speeds up to 100 ft/min. (500 mm/s).

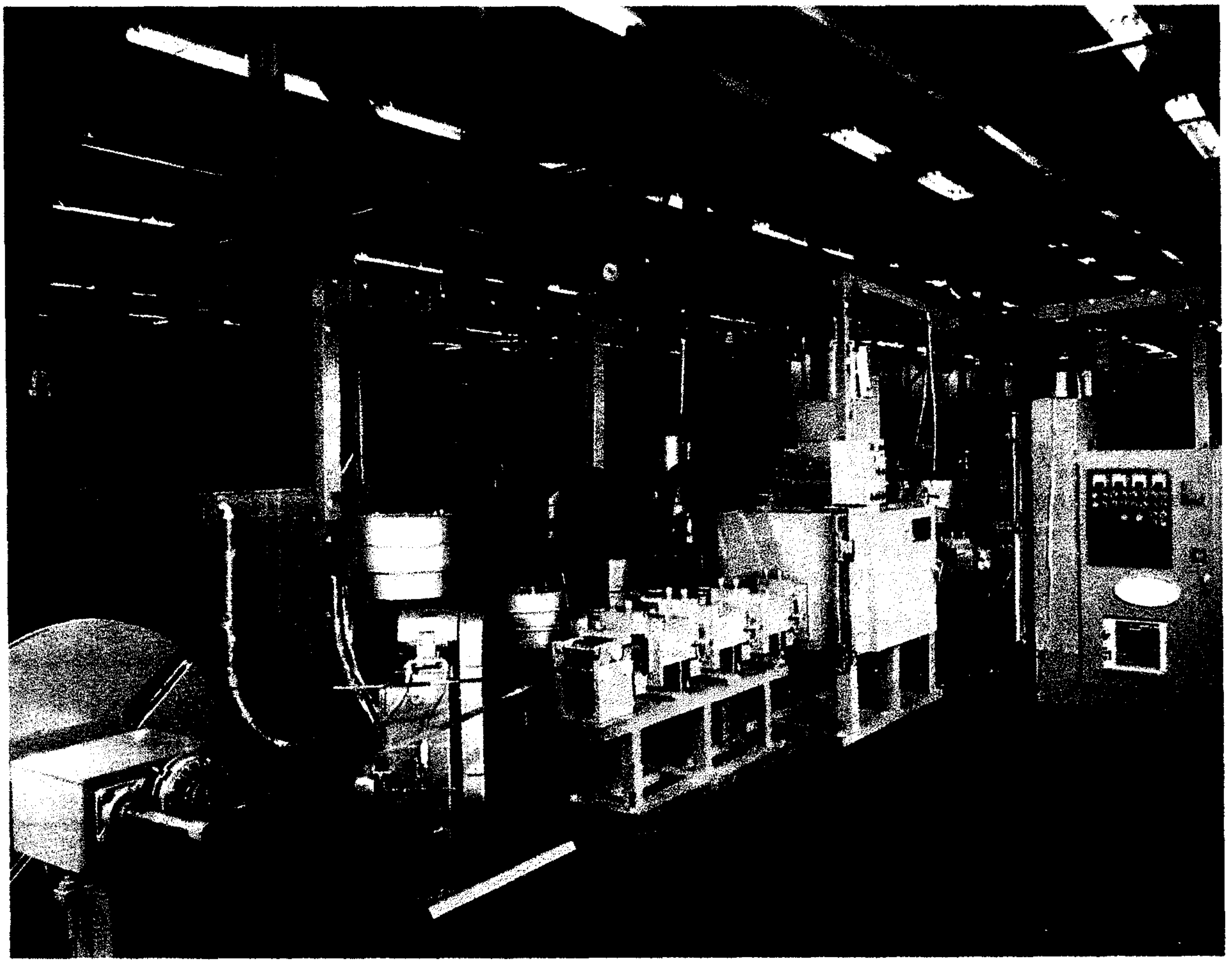

Figure 21.26–Electron Beam Welding Machine Designed for Joining Bimetallic Strip

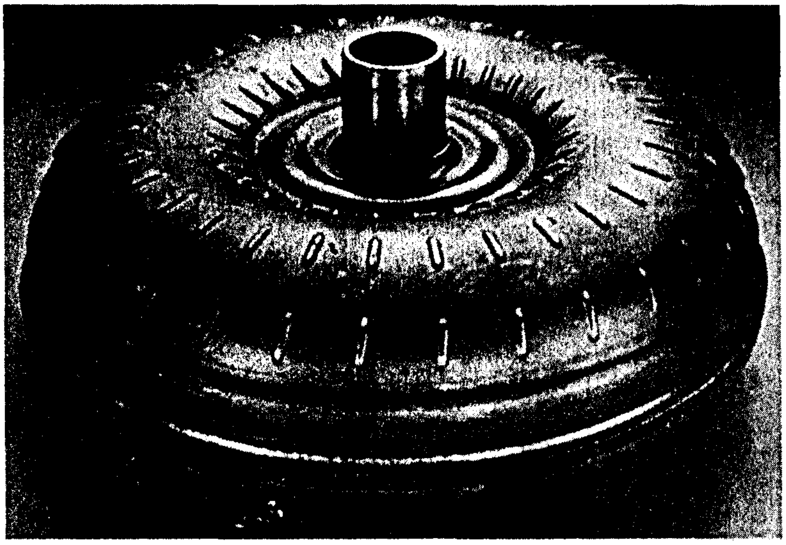

Figure 21.27–Torque Converter Assembly Welded with a Nonvacuum Electron Beam Welding Machine (Welds Made to Hold Vanes in Place)

WELD QUALITY

TO PRODUCE WELDS that meet the requirements of specifications set forth in the welding industry, it is necessary to control three factors that are primarily responsible for electron beam weld quality: (1) joint preparation, (2) welding procedure, including provisions for keeping the beam on the seam, and (3) characteristics of the metals being welded. The first two of these are covered in other sections of this chapter.

The third factor relates to the physical and mechanical properties of the metals being welded, as well as to their metallurgical characteristics. Weld discontinuities of metallurgical origin include cracking and porosity.

Weld zones constitute regions of different microstructures within the base metal structure. Unlike a cast ingot, weld metal grains usually grow from partially melted grains at the fusion line. The phenomenon is called *epitaxial solidification*. The nature of the weld metal structure is controlled by the size and orientation of the base metal grains, and by the thermal gradients in and the shape of the weld pool.

The nature of the stress resulting from fusion welding is also important. Metal immediately adjacent to the moving weld pool is first heated; it expands against the restraining forces of the surrounding cold base metal; then it cools and contracts. In the process, that metal is plastically deformed (upset) during the heating cycle and restrained in tension during cooling. Residual tensile and compressive stresses surround the weld zone, often resulting in warpage of the welded assembly.

In considering these factors, it would appear that electron beam welding offers the following unique characteristics for controlling the weld joint properties.

(1) Base metal recrystallization and grain growth can be minimized.

(2) Beam oscillation and travel speed can be used to control the shape of temperature gradients in the weld pool.

(3) Low-heat inputs result in low thermal stresses in the base metal and, hence, low distortion.

Residual stresses are symmetrically distributed due to the characteristic two-dimensional symmetry (parallel sides) of the electron beam weld zone.

Unfortunately, it is not always possible to realize the full potential of the process, since the weldability of a metal is ultimately controlled by metallurgical factors. For this reason, electron beam welds may exhibit most of the common discontinuities associated with fusion welding. A possible exception is hydrogen-induced cold cracking of carbon steel weldments because normally there is no source of hydrogen in an autogenous high vacuum electron beam setup.

One type of discontinuity sometimes found in partial joint penetration welds is large voids at the bottom of the weld metal. Typically, a large number of these voids will be aligned and will appear as linear porosity rather than scattered porosity. When the weld barely penetrates through the joint, root porosity will appear as a lack of fill, accompanied by spatter on the back side of the weld.

Another occurrence peculiar to the vacuum mode of welding is the release of trapped air through the molten weld metal. This sometimes creates a defect. It happens during an attempt to weld a gas-filled container that is not properly vented to vacuum.

Other discontinuities are generally the same as those found in other types of fusion welds. Electron beam weld discontinuities include the following:

(1) Porosity
(2) Shrinkage voids
(3) Cracking
(4) Undercutting
(5) Underfill
(6) Missed joints
(7) Lack of fusion

The probability of encountering these discontinuities is more pronounced when welding thick sections. Knowledge of the causes of the discontinuities and means for avoiding them are essential for the production of high-quality welds. As an example, in welding thick sections in the horizontal position, holes and porosity can be avoided by tilting the beam axis a few degrees out of the plane of welding. Equally important is a reliable nondestructive testing method, such as ultrasonic inspection, to determine the presence of certain types of defects that are not detectable by radiography.

The narrow weld beads created by electron beam welding make radiographic inspection difficult. Certain joint designs incorporate a feature called a *radiographic window*. As shown in Figure 21.28, this provides a void within the joint that is easily resolved by radiographic technique, when not completely consumed by the weld. This window can be located at any position in the joint, and its absence in the radiograph after welding assures that penetration to that depth has been achieved.

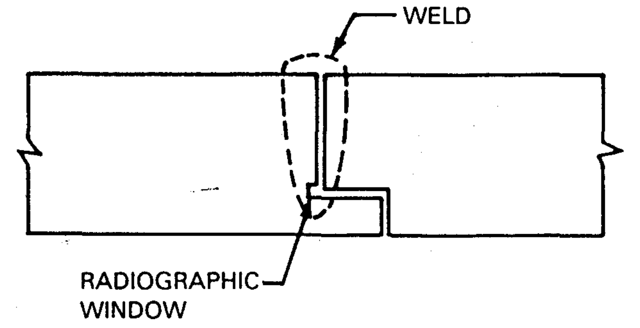

Figure 21.28–Radiographic Window Feature Often Used to Simplify Reading of Weld Joint Radiographs

POROSITY AND SPATTER

POROSITY IN ELECTRON beam welds is caused by the evolution of gas as the metal is melted by the beam. The gas may form as a result of (1) the volatilization of high vapor pressure elements in the alloy, (2) the escape of dissolved gases, or (3) the decomposition of compounds such as oxides and nitrides. Copper-zinc alloys (brasses) and aluminum-magnesium alloys are difficult to electron beam weld because metal vapors evolve. Both zinc and magnesium have low boiling points. Dissolved gases and compounds are likely to be present in alloys originally melted in air or under protective gas atmospheres.

Spatter is caused by the same factors as porosity. The rapid evolution of gas or metal vapor causes the ejection of drops of molten weld metal that scatter over the work surface and within the chamber. Spatter and porosity can even occur in vacuum remelted alloys when a residual phase volatilizes under the intense heat of the electron beam.

An effective means of preventing porosity and spatter is to weld only vacuum melted or fully deoxidized metals. When gas-emitting metals or high vapor pressure alloys must be welded, special techniques are required to minimize porosity. Filler metal containing a deoxidizer may be added when welding metals that are not completely deoxidized. Slow welding speed will provide time for gas bubbles to escape from the molten metal.

An oscillatory beam deflection may be effective in reducing porosity. In extreme cases, remelting the joint a second or third time will reduce it. However, these techniques reduce joint strength in age-hardening alloys that are heat-treated prior to welding.

SHRINKAGE VOIDS

SHRINKAGE VOIDS MAY occur between dendrites near the center of the weld metal. These voids are characterized by irregular outlines of porosity. Shrinkage voids usually occur in alloys having high volumetric shrinkage on solidification. In electron beam welds where the bond lines are essentially parallel, solidification proceeds uniformly from the base metal to the center of the weld. When solidification shrinkage of the metal is great, voids will form if the face and root surfaces freeze before the center of the weld. An example of shrinkage voids in an electron beam weld in 15-7Mo PH stainless steel is shown in Figure 21.29. Low travel speed or beam oscillation may minimize or eliminate shrinkage voids by increasing the volume of molten metal and decreasing the solidification rate. However, these conditions will generally widen the fusion zone.

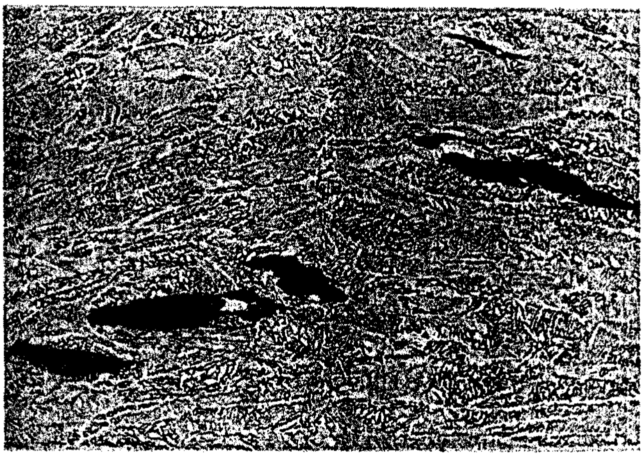

Figure 21.29–Shrinkage Voids in an Electron Beam Weld

CRACKING

HOT OR COLD cracks may form in electron beam welds in alloys that are subject to these types of cracking. Hot cracking is generally intergranular and cold cracking is transgranular. Hot cracks form in a low-melting grain boundary phase during solidification of the weld metal. Cold cracks form after solidification as a result of high internal stresses produced by thermal contraction of the metal during cooling. A crack originates at some imperfection or point of stress concentration in the metal and propagates through the grains by cleavage.

Hot cracking may be minimized by welding at high travel speeds with minimum beam energy. Cold cracking may be overcome by redesigning the joint to eliminate points of stress concentration. Quench-hardenable steels should be preheated to a suitable temperature to control the formation of martensite in the weld zone.

UNDERCUTTING

ELECTRON BEAM WELDS with good bead geometry have essentially parallel bond lines with a uniform crown or buildup of weld metal on the top surface, as shown in Figure 21.30(A). Undercutting refers to grooves produced in the base metal at the edges of the weld bead, as shown in Figure 21.30(B). Undercut occurs when the weld metal does not wet the base metal. Undercutting is promoted by very high travel speeds, improper cleaning procedures, or beam asymmetry (it usually occurs on one side only). Alloy additions that reduce surface tension or increase fluidity, such as aluminum additions to carbon steel welds, have a beneficial effect.

Undercutting on the top surface of the weld can sometimes be filled by making a "cosmetic pass". This is usually performed at lower power levels relative to the penetration pass, and can be made more effective by beam deflection or a "defocused" beam to widen the top of the bead. Certain joint designs provide extra metal above the desired "finished surface" of the weldment which is machined off after the weld. Undercut is removed during the machining operation.

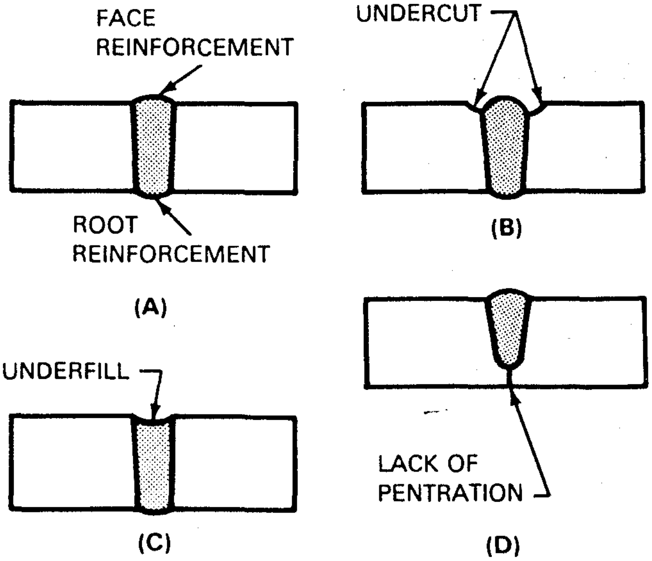

Figure 21.30–Correct (A) and Incorrect (B, C, and D) Electron Beam Weld Geometries

UNDERFILL

FULL PENETRATION WELDS can develop either a uniform or irregular root surface, depending on the weld variables and material. The width of the root surface is dependent upon the welding conditions. In thick sections of metal, such as 3-in. (76 mm) stainless steel, the face and root surface shapes are dependent upon the surface tension supporting the column of molten metal as it is being transported along the weld joint. At low welding speeds there will be a relatively large mass of molten weld metal, and the bead will tend to sag due to insufficient surface tension and the force of gravity. This will form an extremely heavy root reinforcement and the weld face may show severe underfill (concavity), as shown in Figure 21.30(C). Various techniques can eliminate this condition. These include the use of a backing strip, a step joint, or welding in the horizontal or the vertical position.

Excessive sagging of the root surface usually results when the beam energy is too high or the molten weld metal is too wide. This can be reduced by proper adjustment of the welding variables. If underfilling persists at the best beam operating conditions, filler metal must be added to fill the groove. A number of techniques are effective in providing the required filler metal. One is to place a narrow strip over the face of the joint and then weld through it. The thickness of the strip must be slightly greater than the depth of any undercut, so that the undercut will be entirely in the strip. Filler metal wire may similarly be added to the leading edge of the weld as it is being made, or during a subsequent smoothing pass made with a defocused beam. On circular welds, beam power ramping (upslope and downslope) may be used to minimize defects in the overlap area.

LACK OF PENETRATION

THERE ARE NUMEROUS applications of electron beam welding in which full penetration of the joint is not required. These applications generally involve seal welds or welds subjected to shearing forces only. In these cases, the sharp notch at the root of the weld is acceptable. However, when a welded joint must support a transverse tensile stress at the root of the weld, full joint penetration is required. Lack of penetration may be caused by low beam power, high travel speed, or improper focusing of the beam. This condition is shown in Figure 21.30(D).

MISSED JOINTS

WHEN A SMALL diameter electron beam is used to make a long joint in a thick section, the beam axis must be in the same plane as the joint faces and remain aligned with the joint along its entire length of travel. Otherwise, the possibility of missing the joint at some location is great. Even when the beam is properly aligned with the joint, electrostatic or magnetic forces can cause beam deflection, resulting in portions of the joint being missed. An electrostatic field can be generated by the accumulation of an electrical charge on an insulated surface, such as the glass in the vacuum chamber windows. The electron beam will be deflected away from or toward the charged surface if the beam passes close to it.

Residual magnetism in a ferromagnetic base metal or in the fixturing can cause unexpected beam deflection. For example, a steel part may be magnetized during grinding if it is held by a magnetic chuck, and the residual magnetism in the part will cause the beam to deflect and miss the joint. This can be avoided by demagnetizing all ferromagnetic parts before welding, and by using nonmagnetic materials for fixturing.

Unexpected beam deflection can occur when welding dissimilar metals, especially when one is ferromagnetic. An example of this is shown in Figure 21.31, a weld between a nonmagnetic nickel-base alloy and a magnetic maraging steel. Residual or induced magnetism in the steel deflected the electron beam and caused lack of fusion at the root of the joint. If dissimilar materials are to be welded in production, it is important that test welds be made and examined to determine whether beam deflection will occur.

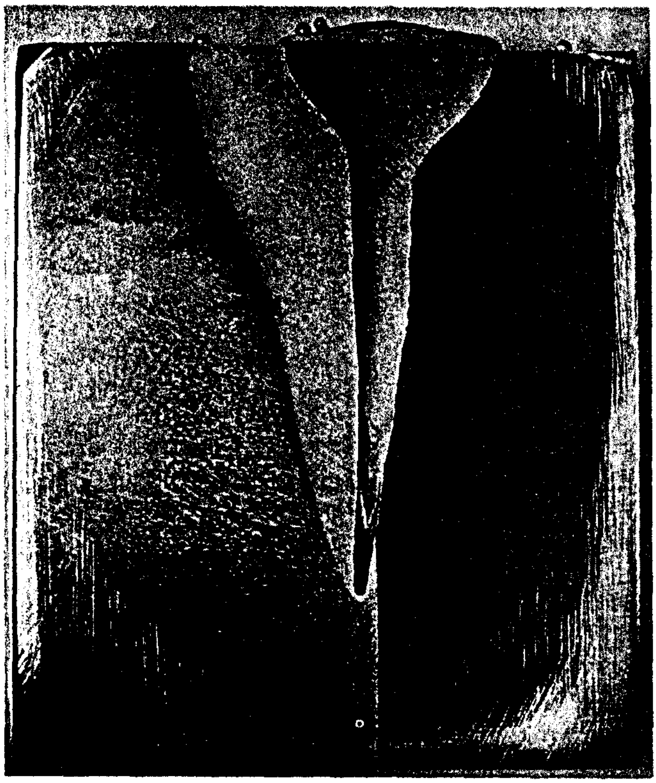

Figure 21.31–Beam Deflection When Welding Dissimilar Metals

The occurrence of missed joints can be verified by using joint designs which include witness lines and radiographic windows. Witness lines are scribed parallel to the joint on the face or root side of the joint, or both. The weld lies between these lines, and its position relative to the joint can be determined by postweld examination. See Figure 21.32.

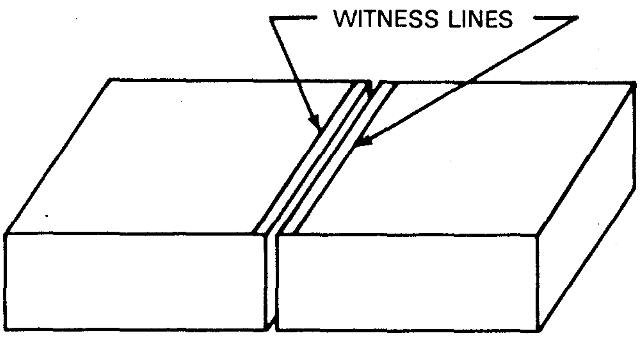

Figure 21.32–Witness Lines Scribed Parallel to Joint

LACK OF FUSION

LACK OF FUSION occurs mostly in partial penetration welds. However, it can also occur near the root of full penetration welds made with insufficient beam power. Figure 21.33 shows an example of this in an electron beam weld in a titanium alloy.

Lack of fusion generally can be avoided by using properly adjusted welding variables. There are circumstances, however, where partial penetration welding is required. One example is the welding of circular joints where the beam power and penetration must be decreased as the end of the weld overlaps the start, to avoid crater formation. A partial penetration weld is formed in the overlap and lack of fusion can occur. Another example is the welding of thick sections. Two partial penetration weld passes, one from each side of the joint, may be required when the metal thickness is too great to be penetrated in a single pass. The second pass must reach the root of the first pass.

Welding with a slightly defocused beam and low travel speed (to compensate for the lower energy density) is effective in eliminating lack of fusion. Beam oscillation, either circular or transverse, is sometimes effective. Preheating is helpful because it reduces the thermal gradients at the root of the weld. Lack of fusion is difficult to locate nondestructively because it is similar to fine cracks and usually can not be detected with x-ray inspection. Penetrant tests are ineffective because the unfused area does not usually extend to the surface.

Ultrasonic testing is the only nondestructive test method that can detect lack of fusion in electron beam welds. Experienced nondestructive test personnel are required to perform the test and interpret the results. Even then, the test method is not suitable for many applications. Since certain joint designs can be easier to inspect ultrasonically, NDT personnel should be consulted prior to designing the joint on critical assemblies.

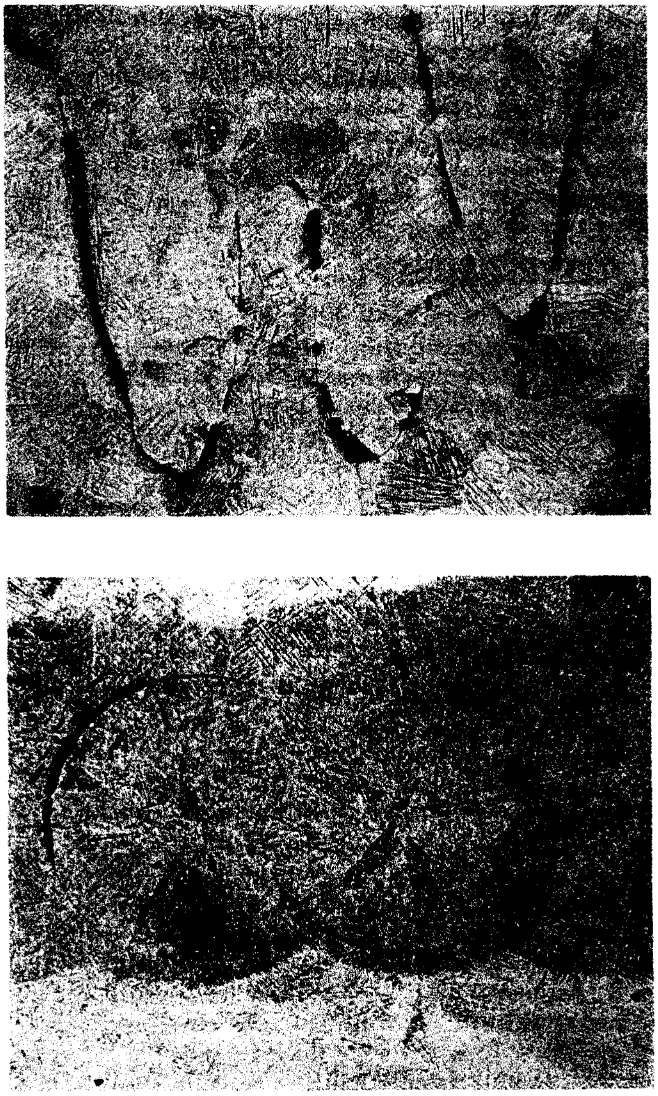

Figure 21.33–Lack of Fusion or Spiking in Vertical (top) and Horizontal (bottom) Sections Through an Electron Beam Weld in a Titanium Alloy

SAFETY PRECAUTIONS

SINCE ELECTRON BEAM welding machines employ a high-energy beam of electrons, the process requires users to observe several safety precautions not normally necessary with other types of fusion welding equipment. The four primary potential dangers associated with electron beam equipment are electric shock, x-radiation, fumes and gases, and damaging visible radiation. In addition to the potential dangers associated with welding specific materials (beryllium, etc.), there may also be a potential danger associated with collateral materials (solvents, greases, etc.) used in operating the equipment. Precautionary measures should be taken to assure that all required safety procedures are strictly observed. ANSI/AWS F2.1, *Recommended Safe Practices for Electron Beam Welding and Cutting*, and ANSI/ASC Z49.1, *Safety in Welding and Cutting* (latest editions) give the general safety precautions that must be taken.

ELECTRIC SHOCK

EVERY ELECTRON BEAM welding system operates with a voltage level high enough to cause fatal injury, regardless of whether the system is referred to as being a "low voltage" or a "high voltage" unit. Manufacturers of electron beam equipment, by meeting various underwriter requirements, attempt to ensure that their machines are well-insulated against the dangers of contact with the high voltage. However, all precautions required when working around high voltages should still be observed when working with EBW machines.

X-RADIATION

THE X-RAYS GENERATED by an electron beam welding machine are produced when electrons, traveling at a high velocity, collide with matter. The majority of these x-rays are produced when the electron beam impinges upon the workpiece. Substantial amounts are also produced when the beam strikes gas molecules or metal vapor in both the gun column and work chamber. Underwriters Laboratories and Federal regulations have established firm rules for permissible x-radiation exposure levels, and producers and users of equipment must observe these rules.

Approximately 1 in. (25 mm) thick steel, when used for manufacturing the work part vacuum enclosure, will be sufficient to satisfy the x-ray shielding required for beam systems using accelerating voltages of up to 60 kV, assuming proper design. For units with higher beam accelerating voltages, either a much thicker steel or use of a lead covering on top of steel is needed to satisfy the x-ray shielding requirements for these units. Leaded glass windows are employed in both high and low voltage electron beam systems. In general, commercial shielded vacuum chamber walls and leaded glass windows provide sufficient radiation protection for operators.

In the case of nonvacuum systems, some type of radiation enclosure must be provided to assure the safety of the operator. Thick walls of high-density concrete (or some other similar material) may be selected instead of steel and lead, especially if a large radiation enclosure is required. Special safety precautions should be imposed to prevent personnel from accidently entering or being trapped inside these enclosures when equipment is in operation.

A complete x-ray radiation survey of the electron beam equipment should always be made at the time of installation and at regular intervals thereafter. These surveys should be performed by personnel trained in the proper procedures for doing a radiation survey, and knowledgeable about the use of radiation survey equipment, in order to assure initial and continued compliance with all radiation regulations and standards applicable to the site where the equipment is installed.

FUMES AND GASES

IT IS UNLIKELY that the very small amount of air left in a high vacuum electron beam chamber would be sufficient to produce ozone and oxides of nitrogen in harmful concentrations. However, nonvacuum and medium vacuum electron beam systems are capable of producing these byproducts, as well as other types of airborne contaminants, in concentrations well above acceptable levels.

Adequate area ventilation should be employed to reduce concentrations of any airborne contaminants around the equipment below the maximum allowable exposure levels. Proper exhausting techniques should be employed to maintain residual concentrations in the chamber or enclosure below these same limits.

VISIBLE RADIATION

DIRECT VIEWING OF visible radiation emitted by the molten weld metal can be harmful to eyesight. In the presence of intense light sources, proper eye protection is necessary. Optical viewing should be done through filters in accordance with ANSI Z87.1, *Occupational and Educational Eye and Face Protection* (latest edition).

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CHAPTER 22

LASER BEAM WELDING

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CHAPTER 22

LASER BEAM WELDING

FUNDAMENTALS OF THE PROCESS

DEFINITION AND GENERAL DESCRIPTION

A LASER IS a device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for light amplification by stimulated emission of radiation. Coherent means that all the light waves are in phase.

In practice, a laser device consists of a medium placed between the end mirrors of an optical resonator cavity. When this medium is "pumped" (i.e., excited) to the point where a population inversion occurs, a condition wherein the majority of active atoms (or molecules) in this medium are put into a higher-than-normal energy state, a source of coherent light that can then reflect back and forth between the end mirrors of the cavity will be provided. This results in a cascade effect being induced which will cause the level of this coherent light to reach a threshold point (i.e., the point at which the gain in light amplification being produced begins to exceed any losses in light that might simultaneously be occurring), thereby allowing the device to start to emit a beam of laser light.

From an engineering standpoint, a laser is an energy conversion device that simply transforms energy from a primary source (electrical, chemical, thermal, optical, or nuclear) into a beam of electromagnetic radiation at some specific frequency (ultraviolet, visible, or infrared). This transformation is facilitated by certain solid, liquid, or gaseous mediums which, when excited on either a molecular or atomic scale (by various techniques), will produce a very coherent and relatively monochromatic (i.e., exhibiting a fairly singular frequency) form of light — a beam of laser light. Because they are coherent and monochromatic, both low-power and high-power laser light beams have a very low divergence angle. Thus they can be transported over relatively large distances before being highly concentrated (through the use of either transmissive or reflective-type focusing optics) to provide the level of beam power density needed to do a variety of material processing tasks such as welding, cutting, and heat treating.

The first laser beam was produced in 1960 using a ruby crystal pumped by a flash lamp. Solid-state lasers of this type produce only short pulses of light energy, and at repetition frequencies limited by heat capacity of the crystal. Consequently, even though individual pulses do exhibit instantaneous peak power levels in the megawatt range, pulsed ruby lasers are limited to low average power output levels. Both pulsed and continuously operating solid-state lasers, capable of welding and cutting thin sheet metal, are currently commercially available. Many of the latter utilize neodymium-doped, yttrium aluminum garnet (Nd-YAG) crystal rods to produce a continuous, monochromatic beam output in the 1 to 2 kW power range.

Electrically pumped, pulsed and continuous wave (CW) gas lasers of the ac, dc and rf excited variety have also been developed. Thus carbon dioxide (CO_2) lasers, with beam power outputs of up to 25 kW, are commercially available today, and are in use for a wide variety of industrial material processing tasks. Such lasers are capable of providing full penetration, single-pass welds in steel up to 1-1/4 in. (32 mm) thick.

PRINCIPLES OF OPERATION

LASER BEAM WELDING (LBW) is a fusion joining process that produces coalescence of materials with the heat obtained from a concentrated beam of coherent, monochromatic light impinging on the joint to be welded. In the LBW process, the laser beam is directed by flat optical elements, such as mirrors, and then focused to a small spot (for high-power density) at the workpiece using either reflective focusing elements or lenses. LBW is a noncontact process, and thus requires that no pressure be applied. Inert gas shielding is generally employed to prevent oxidation of the molten puddle, and filler metal may occasionally be used.

As described above, the lasers predominantly being used for industrial material processing and welding tasks are the 1.06 μm wavelength YAG laser and the 10.6 μm wavelength CO_2 laser, with the active element most commonly employed in these two varieties of lasers being the neodymium (Nd) ion, and the CO_2 molecule (respectively).

Solid-State Lasers

SOLID-STATE LASERS utilize an impurity in a host material as the active medium. Thus the neodymium ion (Nd^{+++}) is used as a "dopant", or purposely added impurity in either a glass or YAG crystal, and the 1.06 μm output wavelength is dictated by the neodymium ion. The lasing material, or host, is in the form of a cylinder about 6 in. (150 mm) long by 0.375 in. (9 mm) in diameter. Both ends of the cylinder are made flat and parallel to very close tolerances, then polished to a good optical finish and silvered to make a reflective surface. The crystal is excited by means of an intense krypton or xenon lamp. A simplified schematic arrangement of the rod, lamp, and mirrors is shown in Figure 22.1.

The selection of the host material for the neodymium ion depends on several factors. These include the ability to produce large quantities of good optical quality rods (i.e., having an acceptable hardness and polishability factor), with acceptable levels of thermal conductivity, fluorescent lifetime, efficiency, and optical absorption bands. All of these factors influence the ability of the system to emit reasonable amounts of energy in a single pulse, and successful materials are those from which large amounts of energy can be extracted. Since the YAG crystal possesses all of the ideal characteristics outlined, it makes an excellent host material.

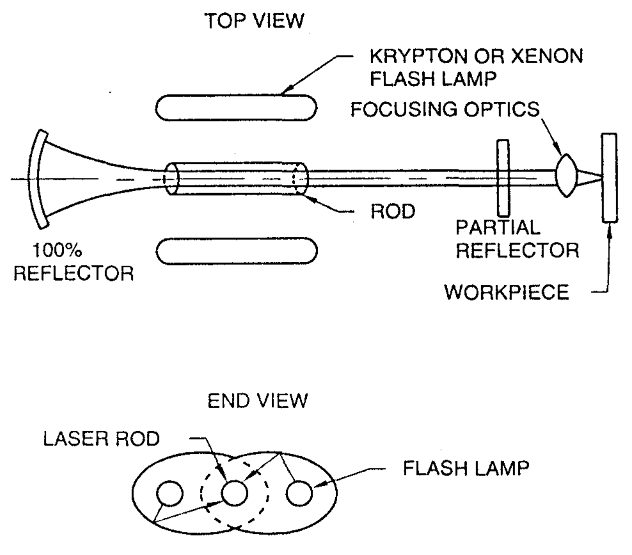

Figure 22.1–Schematic View of a Solid-State Laser

The output characteristics of Nd:YAG lasers depend on the excitation method, which may be either continuous or repetitively pulsed in nature. In continuous operation, the laser is excited with either xenon lamps for power levels up to 10 W or krypton lamps for power levels in the range of 100 W and greater. For repetitively pulsed lasers, the output characteristics depend on lamp configuration. The most common configuration is shown in Figure 22.1. Table 22.1 gives the characteristics of Nd:YAG lasers and offers some idea of the capability for trade-offs between the average power, pulse energy, pulse duration, and pulse repetition rates for such lasers.

The relatively narrow frequency band exhibited by Nd:YAG lasers facilitates continuous wave operation at room temperature, making the continuous wave Nd:YAG laser second only to the CW gas lasers in terms of continuous wave power generation. However, its considerably lower overall efficiency capability (i.e., typically two percent versus ten percent for gas lasers) results in a lower power output.

In the pulsed mode, the active medium of a YAG laser is pumped intermittently, instead of continuously, by employing a pulsed power supply to drive the flashlamp.

Figure 22.2 shows the time relationship of the flashlamp and laser output pulses of a typical pulsed solid-state laser. The beginning of the flashlamp pulse establishes a population inversion in the active medium. When the loop gain reaches 1.0, lasing begins and continues as a series of closely spaced spikes for the duration of the flashlamp pulse. These spikes are produced by gain switching in the

Table 22.1
Output of a Nd: YAG Laser

Continuous wave operation	
Average power	<1000 W (multimode) <20 W (TEM_{00})
Divergence	1-20 mrad
Beam diameter	0.04-0.4 in.
Pulse Length of 0.1 TO 20 ms	
Output energy	<500 J/pulse (multimode) 5J/pulse (TEM_{00})
Repetition rate	200 Hz
Divergence	10 mrad (multimode) 3 mrad (TEM_{00})
Beam diameter	0.2-0.4 in.
Pulse length of 0.1 to 1 μs (repetitive switch)	
Output energy	1 mJ/pulse
Repetition rate	50-100 kHz
Average power	10-100 W
Peak power	10-50 kW

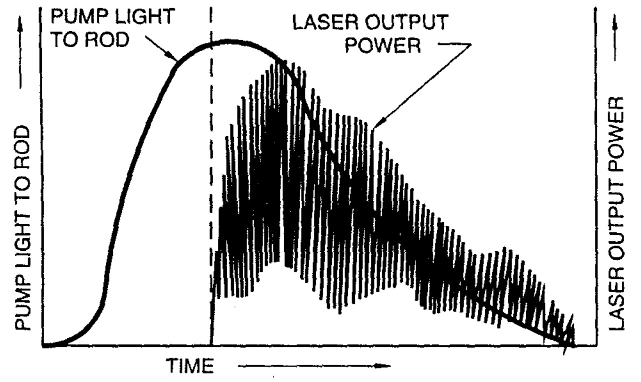

Figure 22.2–Output of a Typical Pulsed Solid-State Laser Compared to Pump Light Input to Rod as a Function of Time

active medium. The gain rises quickly to a high value because of the intense pumping level. This results in a high loop gain and a high-intensity standing wave in the optical cavity. This quickly depletes the population inversion for that particular wavelength, and lasing stops. Thus, the laser switches itself off momentarily by using up all of its gain.

Because of the spiking in the output, the peak power of a pulsed solid state laser tends to be difficult to determine, and tends to vary from pulse to pulse, even though the overall energy and duration of each pulse may remain constant.

For these reasons, specifications of pulsed solid state lasers usually do not include the maximum output power. Instead, pulse energy and pulse duration are specified. Peak output power may be approximated by dividing the energy of the output pulse by pulse duration as with other pulsed lasers.

Solid-state laser pulse durations vary from as short as 50 µs to as long as 50 ms, with the usual pulse duration employed being about 1 ms. Only Nd:YAG systems are capable of pulse durations much greater than 2 ms, and some Nd:YAG laser drillers use pulse durations of 5 to 8 ms.

Glass also has certain desirable characteristics as a laser host material. One is that large pieces of high optical quality can be fabricated into a variety of sizes and shapes, ranging from fibers with diameters of a few microns to rods with diameters on the order of 4 in. (100 mm) and lengths of up to 6 1/2 ft (2 m). However, since the thermal conductivity of glass is lower than that of most crystalline hosts, cooling it will present a problem that can limit the maximum repetition rate at any given pulse energy level. Also, the emission lines of ions in glass are broader than those in crystalline materials. This raises the threshold of the glass for laser action, because a higher population inversion is required to achieve the same gain. The output characteristics of Nd-glass lasers suitable for laser welding are given in Table 22.2.

Table 22.2
Output of a Nd-Glass Laser (for a Pulse Length of 1 to 10 ms)

Output energy	20 J/pulse (multimode)
Repetition rate	10 Hz
Divergence	5-10 mrad
Beam diameter	0.2-0.4 in.

Gas Lasers

THE ELECTRIC DISCHARGE style CO_2 gas lasers are the most efficient type currently available for high power LB material processing. These lasers employ a gas mixture of primarily nitrogen and helium containing a small percentage of carbon dioxide, and an electric glow discharge is used to pump this laser medium (i.e., to excite the CO_2 molecule). Gas heating produced in this fashion is controlled by continuously flowing the gas mixture through the optical cavity area, and thus CO_2 lasers are usually categorized according to the type of gas flow system they employ: slow axial, fast axial, or transverse.

Slow Axial Flow. The slow axial flow (SAF) is the simplest CO_2 gas laser. Gas flow is in the same direction as the laser resonator's optical axis and electric excitation field, or gas discharge path, as shown in Figure 22.3. The axial flow of gas is maintained through the tube to replenish molecules depleted from the effects of the gas discharge being used for excitation, which causes the CO_2 to be reduced to $CO + O$ by electron bombardment. Catalytic devices are employed in the recycling gas flow path to help accomplish a recombination effect.

Cooling of the laser gas is achieved by conduction through the walls of the discharge tubes to a liquid coolant in the cooling mantle, and some form of external heat exchanger system is then used to dissipate the heat being continuously extracted in this manner.

A mirror is located at each end of the discharge tubes to complete the resonator cavity. Typically, one mirror is totally reflective (rear mirror) and the other is partially reflective and partially transmissive (output coupler). Slow axial flow resonators are capable of generating laser beams with a continuous power rating of approximately 80 watts for every meter of discharge length. A folded tube configuration is used for achieving output power levels of 50 to 1000 watts, maximum, rather than simply extending the length of the resonator cavity to attain these power levels.

Fast Axial Flow. Fast axial flow (FAF) lasers have a similar arrangement of components to that of the slow axial flow laser described above except that, in the case of the FAF laser, a Roots blower or turbo pump is used to circulate the laser gas at high speed through the discharge region and corresponding heat exchangers. See Figure 22.4.

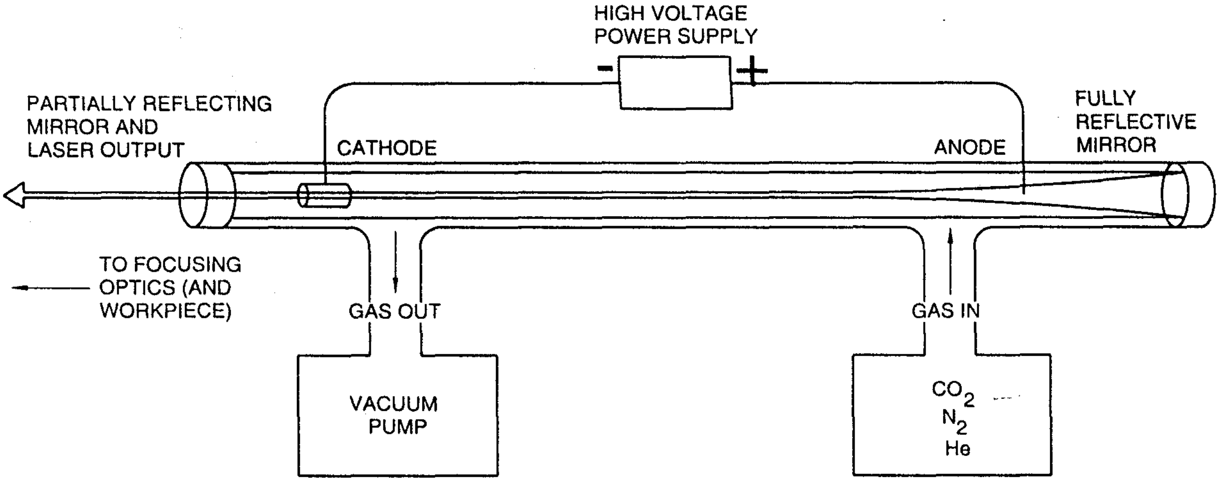

Figure 22.3–Schematic Diagram of a Slow Axial Flow Laser

Within the confines of the laser itself, cooling is enhanced by forcing the hot laser gas through gas-to-liquid heat exchangers. This gives a much higher rate of heat extraction than is available with slow-axial flow lasers, and provides the capacity for achieving output power levels of greater than 2 kW per meter of discharge length. Fast axial flow (FAF) lasers with CW output power levels of between 500 and 6000 watts are currently available. As with SAF lasers, most FAF lasers can readily be pulsed.

Transverse Flow. Transverse flow lasers operate by continuously circulating gas across the resonator cavity axis by means of a high speed fan-type blower, while maintaining an electric discharge perpendicular to both the gas flow direction and the laser beam's optical axis. Because the volume of the resonator is large relative to its length, mirrors can be placed at each end to reflect the beam several times through the discharge region before transmission through an output coupler. A transverse flow laser is shown in Figure 22.5. The ability to achieve a long optical path within a short resonator structure allows transverse flow lasers to be both compact and capable of generating high output powers. Transverse flow lasers with CW output power levels of between 1 and 25 kW are currently available.

BEAM DELIVERY AND FOCUSING OPTICS

LASER BEAMS MUST be focused to a small diameter to produce the high-power density required for welding. This focusing is accomplished with transmitting optics (lenses) or reflective optics (mirrors). See Figures 22.6 and 22.7. Minimum spot size can be varied by optics design and choice of focal length. For a given laser beam, the final focused spot size attainable will be directly proportional to the focal length employed. Thus the resultant power density achieved will vary inversely proportional to the square of the focal length, while the depth of focus attained will vary directly with focal length. Therefore, laser beams being focused with short focal length optics require that greater precision be observed (in maintaining the lens-to-workpiece distance) than when longer focal length optics are employed.

The shortest practical focal length to use for CO_2 laser welding is approximately 5 in. (125 mm). This is because of

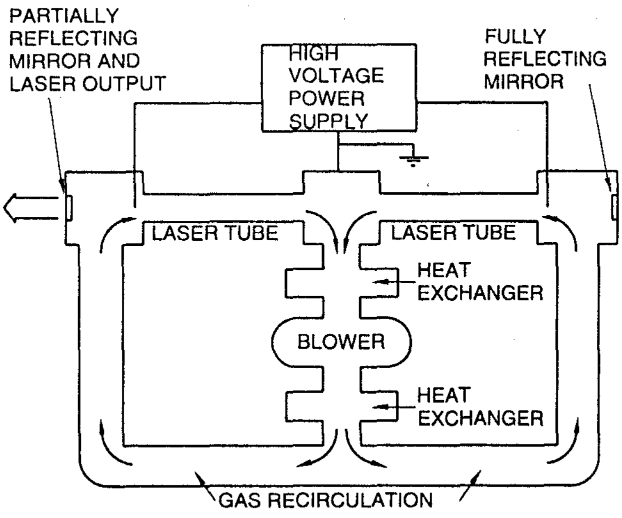

Figure 22.4–Schematic View of a Fast Axial Flow Laser

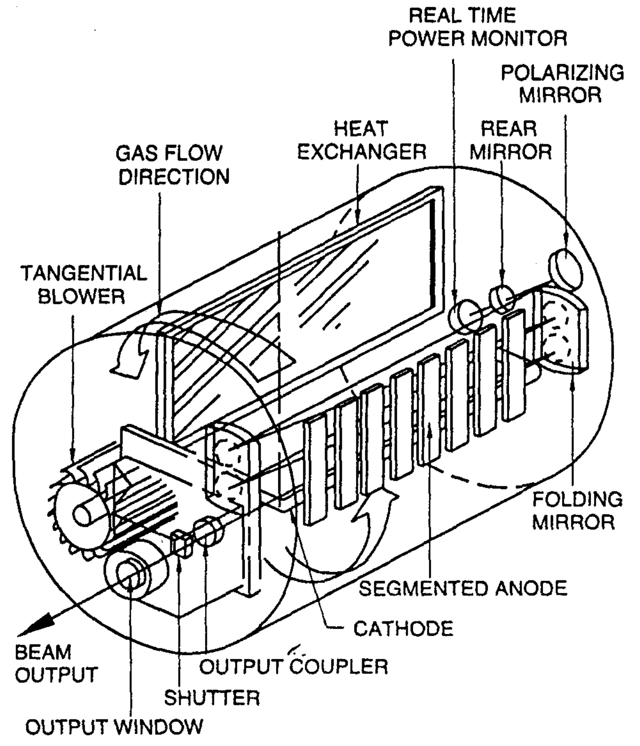

Figure 22.5–Schematic Diagram of a Transverse Flow Laser

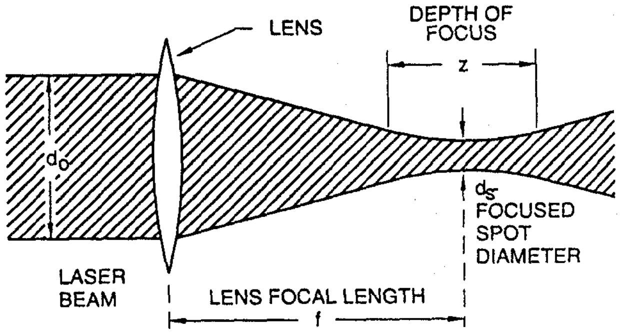

Figure 22.6–Focusing a Gaussian Beam With a Simple Lens

the adverse effects which the weld spatter and vapor produced during processing can have on the focusing optics. Since the spot size at the focal plane varies inversely with the diameter of the beam incident upon the focusing optic element, a beam expander may be used to increase the beam's diameter prior to focusing, thus allowing longer focal lengths to be employed, without having to sacrifice power density.

Referring to Figure 22.6, the ratio of the focal length of the optics to the beam diameter (f/d_O) is referred to as the F number (F#). The focused laser beam's spot size (i.e., the focused beam spot diameter d_s) will vary directly proportional to the laser beam's wavelength and the F# of the focusing system, as shown in equation 22.1.

$$d_s = K(F\#)\lambda = K\,(f/d_O)\lambda \tag{22.1}$$

where d_s is the focused spot diameter, K is a quality measure which specifies the focusability of the laser beam (a factor discussed later under the beam quality section) and λ is the laser beam wavelength. The power density of the laser beam at focus is inversely proportional to the beam diameter squared. The smaller the F# used for a particular system, the smaller the focused spot diameter and the greater the power density.

Focusing Systems

LOW-POWER SOLID-STATE LASER systems usually employ transmissive style optics (lenses) to focus the beam on the workpiece, while higher power gas lasers generally employ reflective style optics (mirrors) for this purpose. These mirrors are usually made of metal, and are water cooled to withstand high incident powers. They may be either bare or coated. In comparison to transmissive optics, these mirrors are less sensitive to soiling from weld spatter and fumes and are easier to maintain in production. Highly polished, bare copper mirrors are commonly employed, but gold-coated mirrors will provide the highest reflectivity and thus the least amount of beam attenuation. However, they are expensive and susceptible to surface damage.

Molybdenum-coated mirrors, while still expensive, have good reflectivity and are less susceptible to fume and spatter damage. Thus, a laser system may use gold-coated mirrors to transmit the laser beam to the work station, but then employ molybdenum-coated mirrors within the work station. Several different types of reflective style focus heads used for high-power laser welding are shown in Figure 22.7.

The primary advantage of metal mirror-type optics is that they may be water cooled by flowing liquid through passages beneath the reflecting surface or around the periphery. Thus, in comparison to transmissive-type optics, reflective optics allow a more efficient cooling capability and thereby provide more repeatable results with time.

In recent years the number of vendors of optics systems has increased because of the increased demand for this product. Mirrors and mirror focusing systems can be purchased in the many different configurations needed to satisfy most manufacturing requirements. Many of these can be purchased directly off the shelf, while special orders require a modest lead time. In addition, there are many facilities available to repolish or refurbish mirrors at reasonable prices.

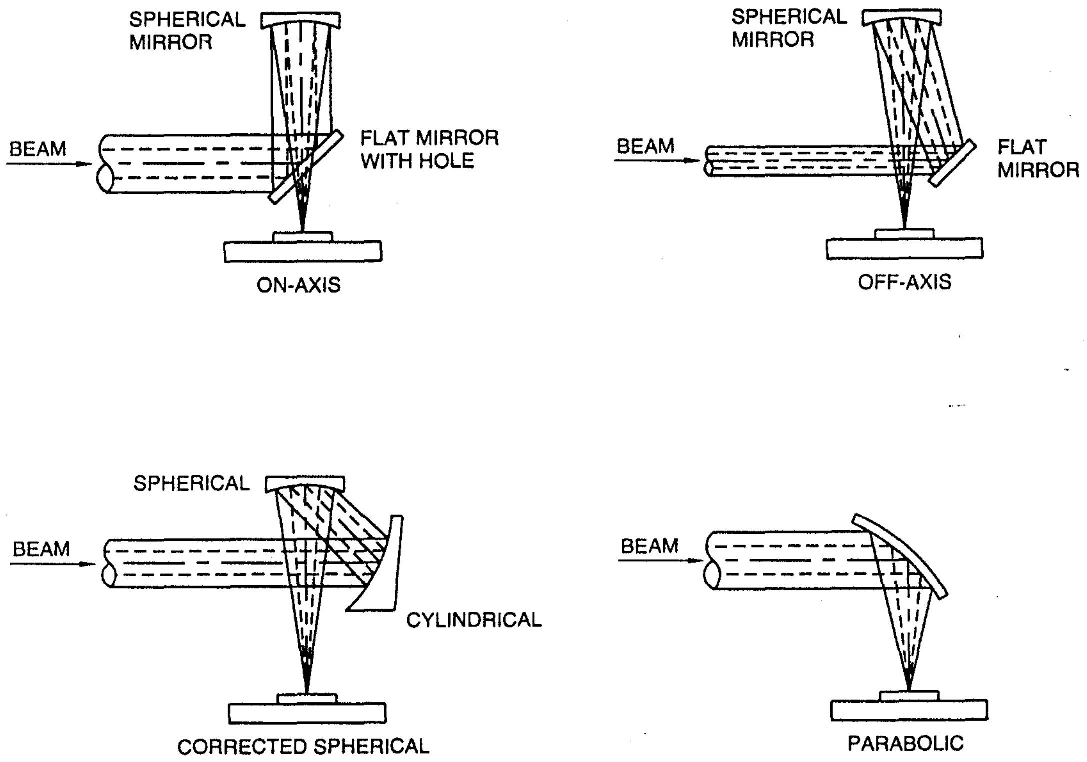

Figure 22.7–Multikilowatt Laser Beam Focusing Heads

Beam Quality

LASER BEAM QUALITY is a measure of focusability. It is a function of the beam's transverse mode, and the extent of aberrations and divergence introduced by the optics. The radiant energy oscillating from one end of the laser resonant cavity to the other forms an intense electromagnetic field. This field can assume many different cross-sectional shapes called *transverse electromagnetic* (TEM) *modes*, which establish the laser beam's radial energy distribution. This TEM mode is expressed as TEM_{mn}, where the subscripts "m" and "n" specify the transverse modal lines across the emerging beam's cross-section. Thus the beam, in cross-section, is segmented into two distinct planes (at right angles to each other) as illustrated in Figure 22.8, and then the number of energy density modes (or "valleys") in each of these directions is expressed as a subscript. The notation TEM_{00} is, therefore, representative of the lowest order mode (or purest beam), and the power distribution across this beam is Gaussian. A pure TEM_{00} beam is the highest "absolute quality" beam attainable, and thus is the most focusable. Although the TEM_{00} mode is indicative of the highest quality beam obtainable, it may not be the most ideal mode to employ for welding — depending on the specific weld task to be performed.

At laser output powers in the multikilowatt range, the ability to generate a high-quality output beam can be limited by several factors. Non-uniformities in the lasing media, a phenomena which is more prevalent in transverse flow units than in axial flow designs, will affect beam quality. Thermally induced changes of diffraction in materials used as output couplers and windows can also significantly affect the output beam's quality and result in a degradation of weld performance. This phenomenon is commonly referred to as "thermal focusing" or "thermal lensing". This phenomenon can also be produced by the presence of freon or some other heavy molecular element somewhere along the beam's transmission path. In an effort to preserve process consistency and maintain a reasonable lifetime of laser optics, which are consumable items, many laser manufacturers resort to using either a higher order mode beam than TEM_{00}, thus inducing less thermal distortion due to the refractive index of transmissive components, or employ a laser design that has no transmissive components at all. Figure 22.8 illustrates a variety of different type modes that can be generated by the CO_2 lasers being employed in industry today.

The TEM_{00} mode and some of the higher order modes are usually produced using a stable oscillator configuration similar to that depicted in Figure 22.3. The unstable oscil-

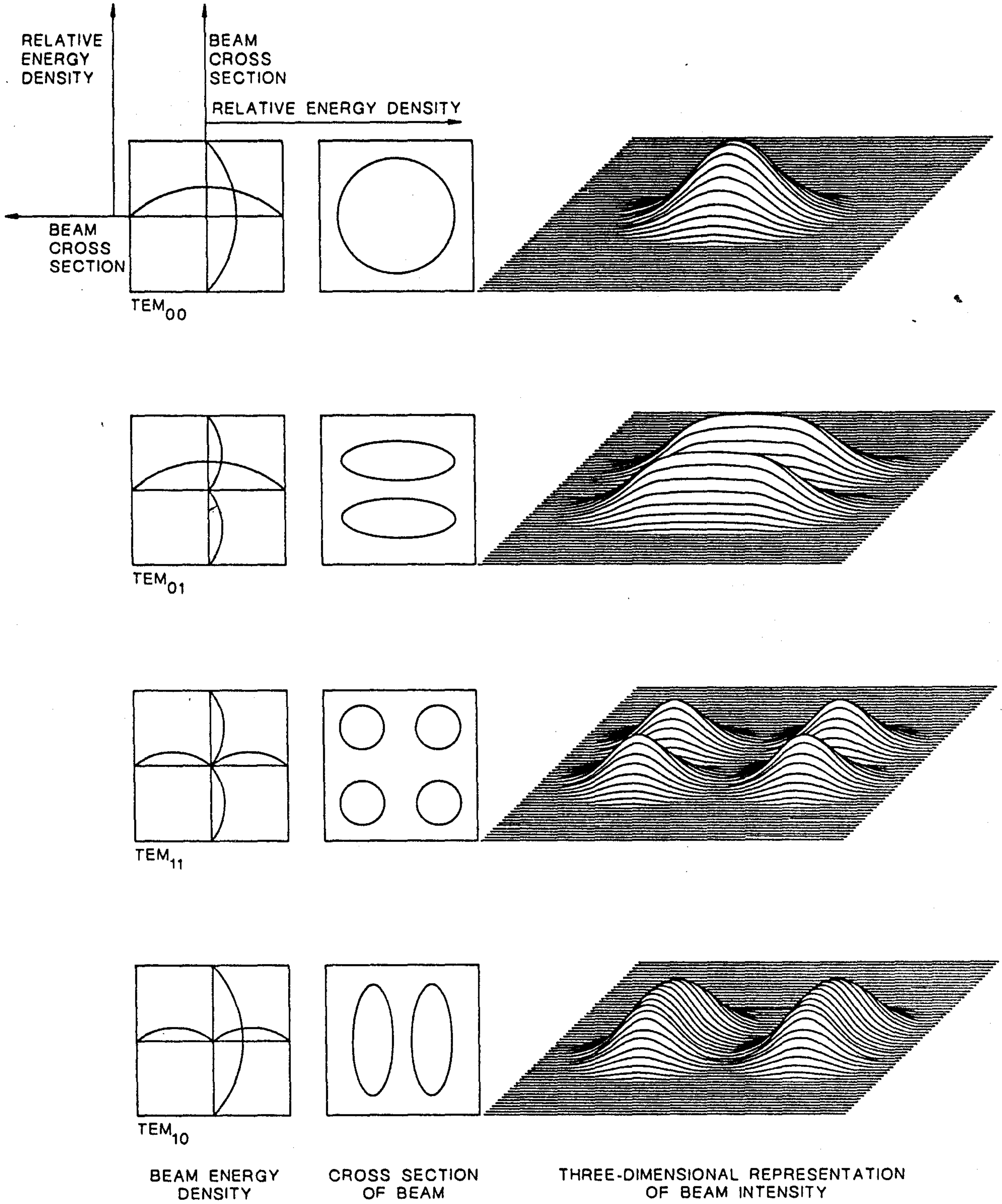

Figure 22.8–Beam Cross Sections for Four Different TEM Modes

lator configuration depicted in Figure 22.9, on the other hand, illustrates another means for generating the multikilowatt level laser beams which are focusable to power densities sufficiently high enough to produce deep penetration welding. The intensity profile of the laser beam produced with the unstable oscillator configuration shown will be annular. Multikilowatt lasers employing this method, for use in production welding at power levels up to 25 kW, are readily available. Some of these lasers use no transmissive elements and, instead, employ an aerodynamic window to transmit the beam from the reduced pressure environment in the laser cavity to atmospheric pressure. Above 6 kilowatts, aerodynamic windows are almost mandatory for production usage because solid windows have too short an operating life.

The most significant unstable oscillator parameter affecting beam quality (i.e., focusability) is its magnification M, which is defined as the ratio of the near field annular output beam's outer diameter, (OD) to inner diameter, (ID). This is illustrated in Figure 22.9. As this magnification increases, both focusability and welding performance improve. Improved welding performance of M = 4 versus M = 2 laser cavity optics is shown in Figure 22.10. This effect is also illustrated in Figure 22.11, where fusion zone cross sections of welds made with M = 2, M = 3, and M = 4 laser cavity optics are compared.

Beam Polarization

LASER WELDING SPEED has been proven to be dependent on the alignment of the plane of the polarization of the incident laser beam on the workpiece relative to the direction of motion of the welding beam. Highest welding speeds with the narrowest weld bead geometries result when the polarization plane is coincident with the direction of welding. Conversely, welding in a direction perpendicular to the plane of polarization results in the lowest welding speed. Due to this effect, "circular polarization" (i.e., equal in all directions) of the laser beam is often employed to give consistent results regardless of the orientation of the welding direction with respect to the polarization plane of the laser output.

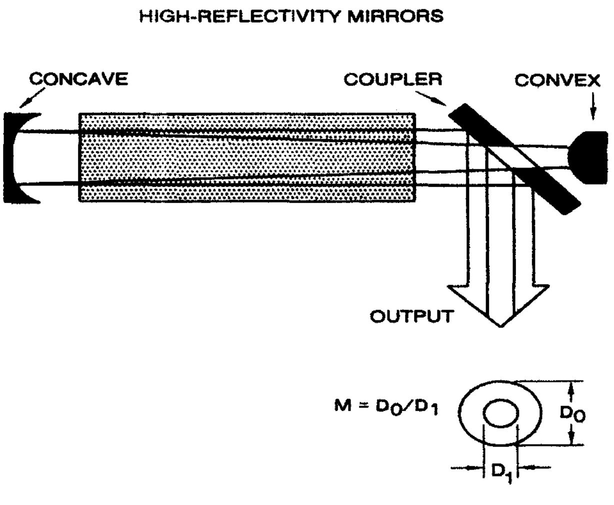

Figure 22.9—Unstable Oscillator Laser Cavity Optics

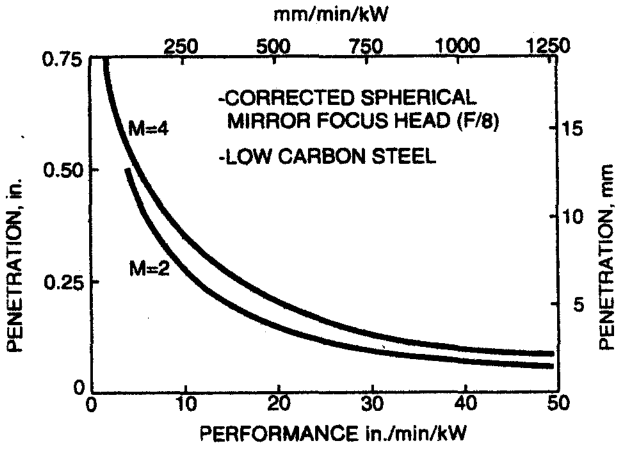

Figure 22.10—Welding Performance Comparison for M=2 and M=4 Laser Cavity Optics

The output of a laser is frequently characterized as being either "randomly polarized" or "linearly polarized". In the case of the former, the design of the resonator in the laser allows the polarization plane to "drift" in a random fashion. This often happens at relatively high speed. Welds made with such lasers generally do not exhibit any polarization effects.

Linearly polarized output beams are produced by laser resonator designs where the plane of polarization is "locked" and cannot rotate. This characteristic must be noted in the design of welding systems and a choice made whether to employ circular polarization optics in the beam delivery system. In typical production welding systems, where the beam delivery optics are fixed and the workpiece is manipulated under the focused beam, the orientation of the plane of polarization of the incident beam in relationship to the direction of welding must be maintained constant in order to guarantee repeatable results.

Beam Switching

THE ABILITY TO transmit the laser beam directly through the atmosphere, over distances of up to several meters in air, makes it feasible to use a single laser source for servicing several different work stations. In production, a single

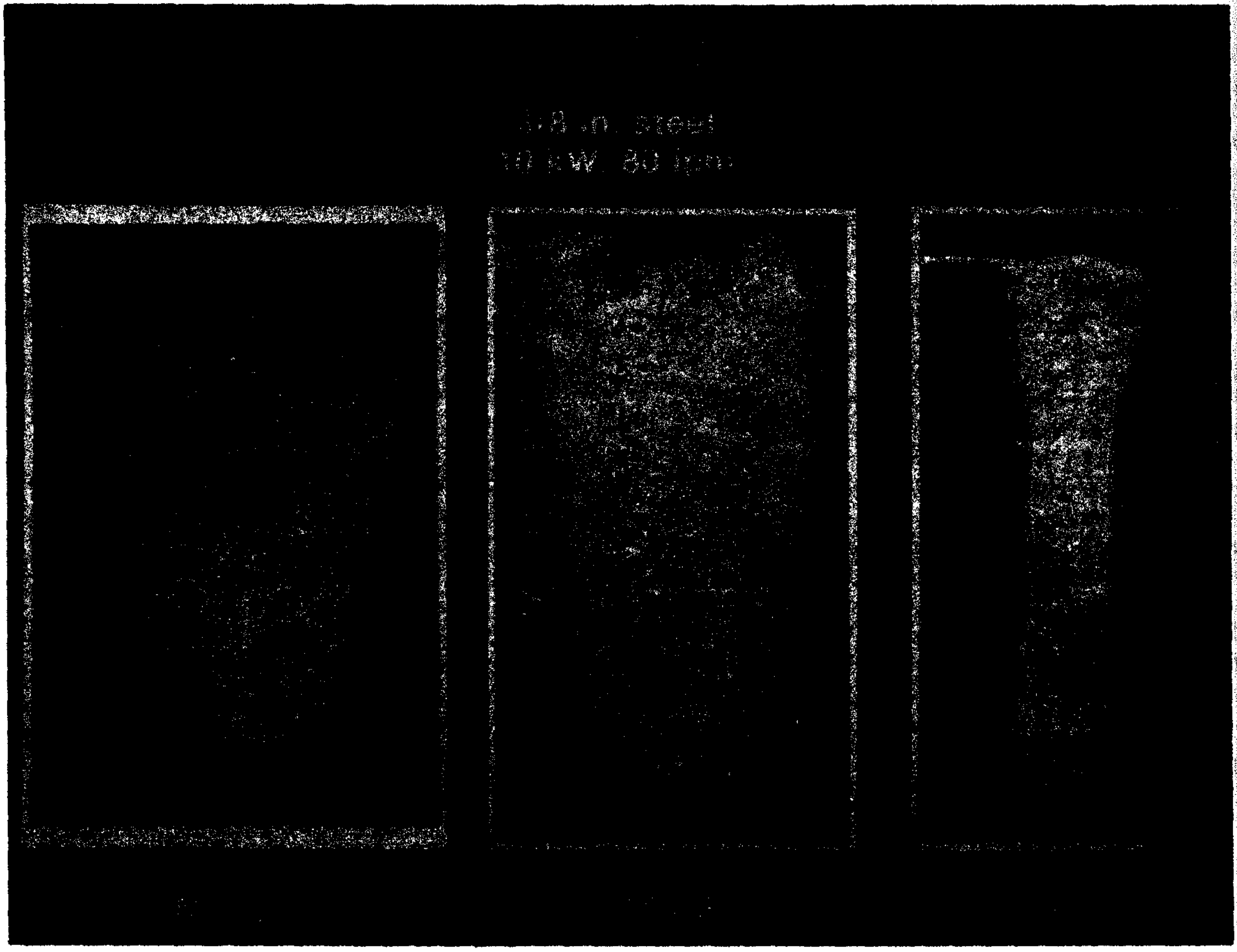

Figure 22.11–Comparison of Bead-on-Plate Weld Profiles in 3/8 in. Thick Carbon Steel Using M=2, M=3, and M=4. Welding Conditions: 10 KW, 80 in./min.

laser may often be used to service several work stations by employing beam switching mirrors.

The primary advantage of operating in this manner is that it helps increase the laser beam's usage factor. While the laser beam is processing material in one station, parts can be prepared for processing in another. Then, when the processing task in the first station is completed, the beam can immediately be switched to the second station.

Robotic Style Beam Delivery

WHILE LASER WELDING was initially performed in much the same manner as electron beam welding, by manipulating the joint to be welded under a stationary beam, it is currently quite common to use robotic style devices to manipulate the laser beams over stationary joints. Consequently, highly flexible laser beam motion systems having the capability to perform three-dimensional welding tasks are readily available today.

Two different concepts are currently employed to provide this robotic style of LBW capability. The first involves mounting beam-focusing optics on the end of an articulated mechanical arm, and using a series of beam-directing mirror combinations (situated in the various joints of the arm) to direct the beam to these optics. The other is to mount the beam-focusing optics on a Z-travel axis, suspended from an X-Y gantry style motion system, and then use a series of singular beam-directing mirrors to direct the beam to them.

Both these robotic style laser concepts are presently employed in industry to accomplish a variety of welding tasks.

EQUIPMENT

High-Power Lasers

HIGH-POWER (I.E., 6 kW and greater) electric discharge gas lasers generally employ three basic sub-assemblies: the optical cavity, the gas flow loop, and the electric discharge system, which includes the power supply and electrodes. The optical cavity is usually formed by precise location of water-cooled metal mirrors of specific radius of curvature and spacing which determines the beam mode. The mirrors are mounted on a truss or similar structure which is designed to have minimum distortion due to temperature variations. The volume encompassed within the optical cavity is normally maintained at reduced pressure.

A typical system might operate at one tenth of an atmosphere. The gas flow loop contains the laser gas, comprised of approximately 95 percent helium and nitrogen and the remainder carbon dioxide. The gas is driven around an enclosed loop by a large axial vane or similar pump. The gas is electrically excited in the laser cavity where the optical power is produced; unused power in the form of heat is removed by a gas-to-water heat exchanger located just downstream of the laser cavity, and the gas is recirculated to be electrically excited again. The electric discharge system contains a high voltage dc, ac, or rf (radio frequency) power supply which is connected to an electrode array to provide excitation to the gas throughout the laser cavity volume. Sometimes ballast resistors are placed in series with the electrodes to provide a smoother electrical discharge for the CW laser beam.

In addition to the above, high-power industrial lasers utilize many ancillary systems, all usually controlled by a CNC, so that the laser may be operated quickly and easily. Control systems automate start up and laser operation with a minimum of operator induced functions so that operator skill may be minimized.

Some of the ancillary systems that may be found in an industrial laser include: a gas supply system where either premixed gas or separate bulk gases are supplied to the laser; a vacuum system to maintain the laser pressure at its operating level or to evacuate the laser cavity when a fresh mixture of gas is required; a bulk water supply for heat exchanger and mirror cooling; a solid or aerodynamic window to transport the high power beam from the reduced pressure laser cavity to the work environment at atmospheric pressure; power meters to monitor beam power; and a beam shuttering system which delivers the beam to the workstation on demand via operator or workstation CNC controls.

Industrial carbon dioxide lasers are available with up to 25 kW of focusable power which can produce penetrations of up to 1.25 in. (32 mm) in low carbon steel. Deep penetration laser welds can have depth to width ratios in the ten to one range, similar to those formed with electron beams. Laser welds, however, are formed without the need of vacuum chambers or protection from x-rays (see Figure 22.12). Welding is normally done inside an enclosure which protects the operator from stray (reflected laser beam) radiation. High-power industrial lasers occupy a reasonable size floor space on the shop floor, have a relatively high "availability" time, and are not excessively expensive to operate. They normally use all reflective, water-cooled optic elements (requiring a minimum of periodic maintenance) and are ruggedly built to withstand the rigors of the manufacturing environment. An artist's rendition of a typical 25 kilowatt laser is shown in Figure 22.13, and Figure 22.14 shows a laser similar to this integrated into a finished production system.

The beam quality of high-power industrial lasers, although not as good or as focusable as near-Gaussian low power lasers, provides the focusing capability needed for "keyhole" welding. High-power industrial lasers, however, do not normally have the pulsing capability desirable for some applications. Cathode maintenance may be periodically required in some high power lasers. When solid windows are used to transmit the beam from the laser cavity to the ambient environment, limited life and cost of this consumable item also must be considered.

PROCESS ADVANTAGES

MAJOR ADVANTAGES OF laser beam welding include the following:

(1) Heat input is close to the minimum required to fuse the weld metal; thus, metallurgical effects in heat-affected zones are reduced, and heat-induced workpiece distortion is minimized.

(2) Single pass laser welding procedures have been qualified in materials of up to 1 1/4 in. (32 mm) thick, thus allowing the time to weld thick sections to be reduced and the need for filler wire (and elaborate joint preparation) to be eliminated.

(3) No electrodes are required; welding is performed with freedom from electrode contamination, indentation, or damage from high resistance welding currents. Because LBW is a noncontact process, distortion is minimized and tool wear essentially eliminated.

(4) Laser beams are readily focused, aligned, and directed by optical elements. Thus the laser can be located at a convenient distance from the workpiece, and redirected around tooling and obstacles in the workpiece. This permits welding in areas not easily accessible with other means of welding.

(5) The workpiece can be located and hermetically welded in an enclosure that is evacuated or that contains a controlled atmosphere.

(6) The laser beam can be focused on a small area, permitting the joining of small, closely spaced components with tiny welds.

Figure 22.12–Laser Weld Being Made on 1/8 in. (3.2 mm) Thick Type 304 Stainless Steel

(7) A wide variety of materials can be welded, including various combinations of different type materials.

(8) The laser can be readily mechanized for automated, high-speed welding, including numerical and computer control.

(9) Welds in thin material and on small diameter wires are less susceptible to burn-back than is the case with arc welding.

(10) Laser welds are not influenced by the presence of magnetic fields, as are arc and electron beam welds; they also tend to follow the weld joint through to the root of the workpiece, even when the beam and joint are not perfectly aligned.

(11) Metals with dissimilar physical properties, such as electrical resistance, can be welded.

(12) No vacuum or X-ray shielding is required.

(13) Aspect ratios (i.e., depth-to-width ratios) on the order of 10:1 are attainable when the weld is made by forming a cavity in the metal, as discussed later under the section on keyhole welding.

(14) The beam can be transmitted to more than one work station, using beam switching optics, thus allowing beam time sharing.

PROCESS LIMITATIONS

LASER BEAM WELDING has certain limitations when compared to other welding methods, among which are the following:

(1) Joints must be accurately positioned laterally under the beam and at a controlled position with respect to the beam focal point.

(2) When weld surfaces must be forced together mechanically, the clamping mechanisms must ensure that the final position of the joint is accurately aligned with the beam impingement point.

(3) The maximum joint thickness that can be laser beam welded is somewhat limited. Thus weld penetrations of

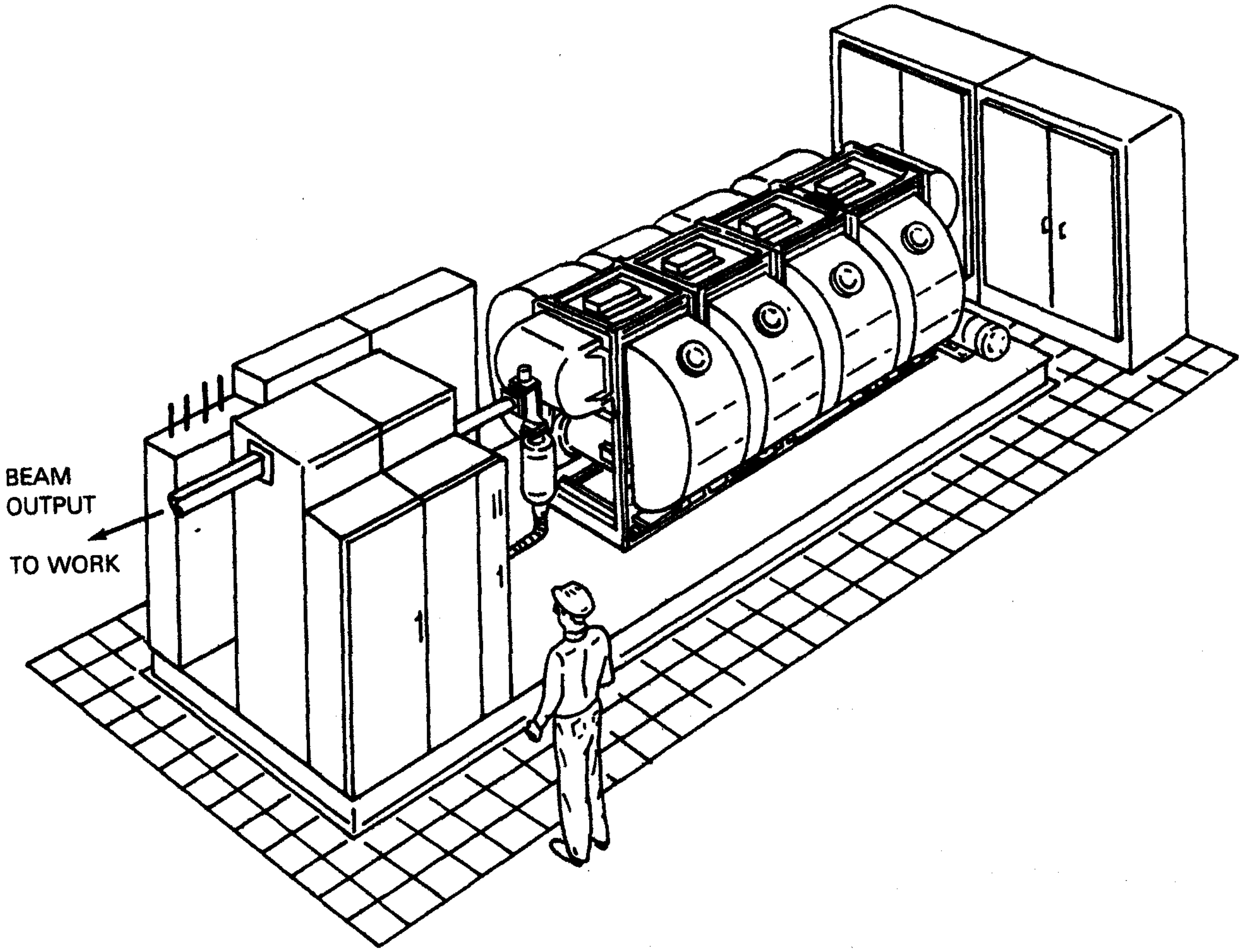

Figure 22.13–Artist's Conception of a 25 KW CO_2 Laser

much greater than 0.75 in. (19 mm) are not presently considered to be practical production LBW applications.

(4) The high reflectivity and high thermal conductivity of some materials, such as aluminum and copper alloys, can affect their weldability with lasers.

(5) When performing moderate-to-high power laser welding, an appropriate plasma control device must be employed to ensure weld reproducibility is achieved.

(6) Lasers tend to have a fairly low energy conversion efficiency, generally less than 10 percent.

(7) As a consequence of the rapid solidification characteristic of LBW, some weld porosity and brittleness can be expected.

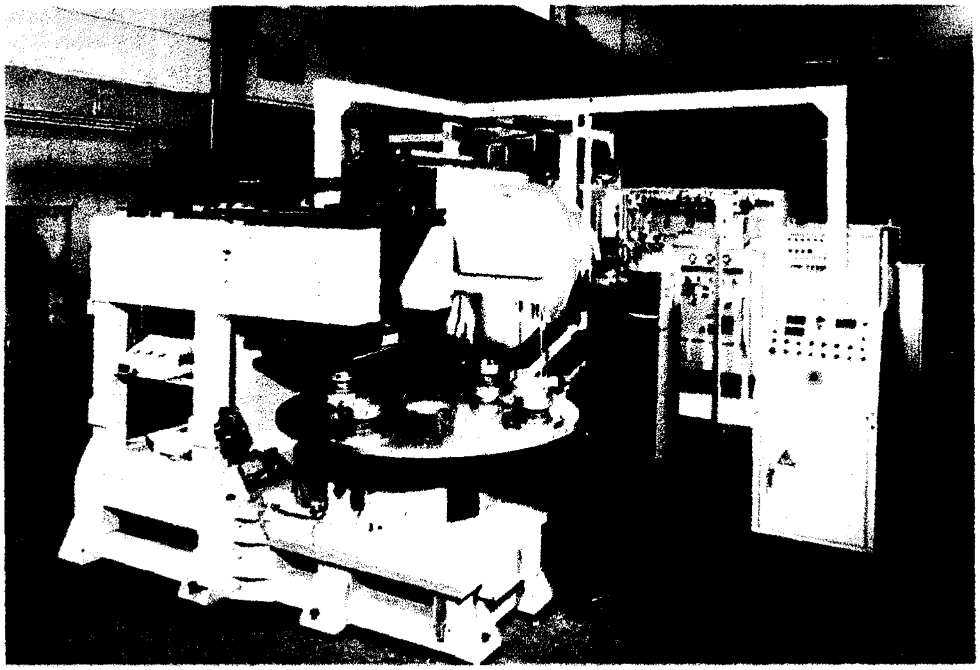

Figure 22.14–Production System Showing a CO_2 Laser Combined With a Rotary Work Table

CHARACTERISTICS OF THE WELD

KEYHOLE OR DEEP PENETRATION WELDING

WHEN BEAM POWER densities on the order of 1 x 10^6 W/in.^{2} (1.55 x 10^3 W/mm^2) or greater are achieved, deep penetration beam welding is accomplished by a keyhole energy transfer mechanism. At this power density level, the energy input of the impinging beam is so intense that it cannot be removed by the normal conduction, convection or radiation processes. Thus the area upon which the beam is being impinged melts and vaporizes. Power densities associated with the transition from conduction welding to keyhole or deep penetration beam welding are shown in Figure 22.15. This keyhole welding phenomena is common to both laser beam and electron beam welding, indicating that it is primarily a function of power density, and not dependent upon wavelength.

When the material at the interaction point melts and vaporizes, the vapor recoil pressure creates a deep cavity or "keyhole" as shown in Figure 22.16. This keyhole is a vapor column surrounded by a thin cylinder of molten metal. When the workpiece moves relative to the beam, the vapor pressure of the metal sustains the keyhole, and the molten metal surrounding the keyhole flows opposite to the weld direction where it rapidly solidifies, forming a narrow fusion zone or weld. Depth-to-width ratios in the range of ten to one can be obtained when laser welding in the keyhole mode. The narrow, high depth-to-width ratio fusion zone formed by laser welds at atmospheric pressure are similar to electron beam welds made in vacuum.

Plasma Suppression

THE INTENSE HEAT generated by the laser beam melts the workpiece, and some of the liquid metal is vaporized into a gaseous state. A fraction of this gas is ionized by the high energy beam and becomes a plasma. The presence of this plasma is detrimental because it tends to absorb and attenuate the laser beam.

Since this plasma can cause the beam to be severely attenuated, failure to control or significantly suppress it will result in reduced welding performance, diminished depth of penetration and sometimes a collapse of the keyhole. Fortunately, plasma can be suppressed by blowing it away

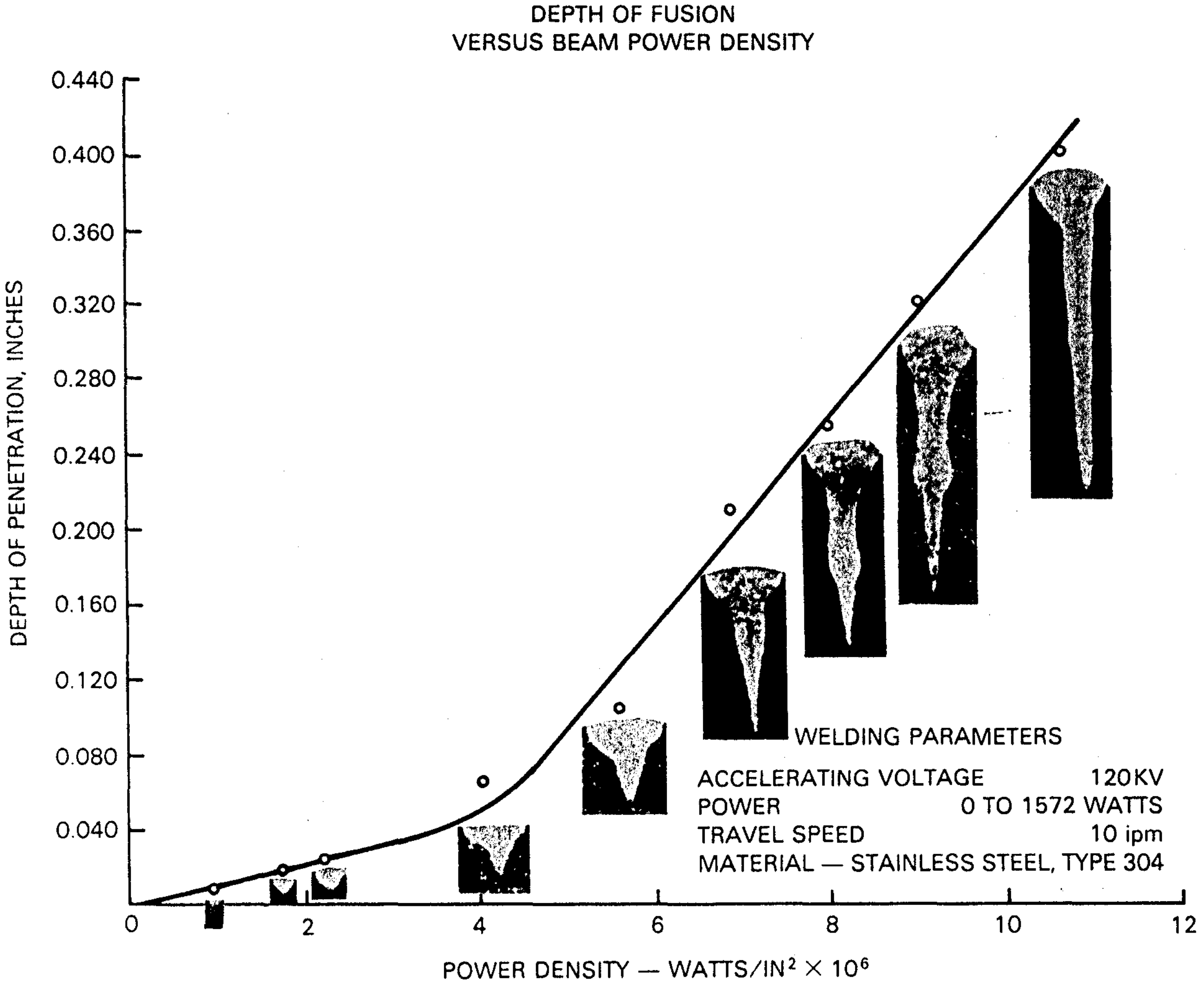
DEPTH OF FUSION
VERSUS BEAM POWER DENSITY

Figure 22.15–Depth of Weld Penetration as a Function of Laser Beam Power Density

with a stream of gas having a component of velocity transverse to the laser beam axis.

For laser power less than 5 kilowatts, helium, argon or various mixtures of the two may be effectively utilized to suppress plasma. Nitrogen and carbon dioxide may also be used effectively provided that they are compatible with the molten metal and vapor. For higher powers, however, helium is preferred because it is less likely to break down under the influence of the high energy density laser beam.

Flow rates or flow velocities must be adjusted to suppress the plasma but should not be so great as to disturb the molten pool. Many plasma suppression jet designs have been used effectively. One of the simplest techniques is simply to flow the gas across the beam impingement point as shown in Figure 22.17. For production welding, the size of the plasma suppression jet can be minimized and precisely aligned to reduce volume flow. For experimental and development work, a larger plasma suppression jet may be useful, because small changes in process parameters such as work distance can be evaluated independent of precise plasma suppression jet location.

Auxiliary Gas Shielding

WHEN THE WELD metal must be shielded until it cools below the oxidation temperature, auxiliary inert gas shielding can be provided using shielding hardware compatible with the laser welding process. As with more conventional welding processes, the main objective is to provide an inert environment over that length of the workpiece which is at or above the oxidation temperature without disturbing the molten weld puddle. In some cases it is also necessary to

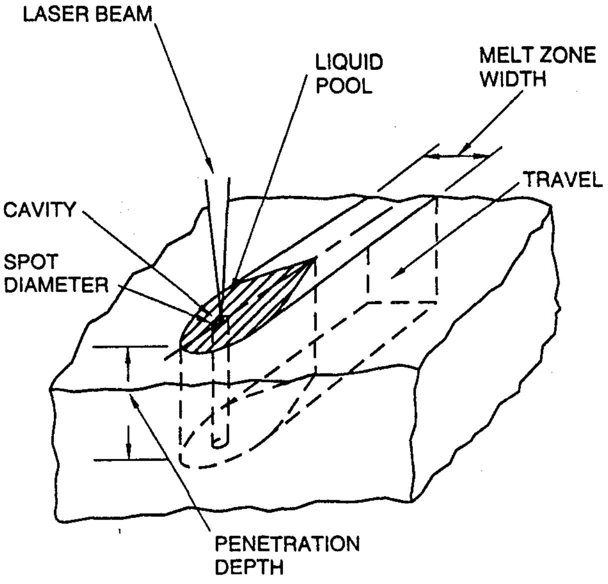

Figure 22.16–Schematic View of Keyhole Welding

provide underbead shielding. Inert shielding also can be obtained by placing the workpiece in a dry box which can be purged and backfilled with inert gas.

Energy Absorption

EFFECTIVE LASER BEAM welding depends upon absorption of beam energy by the workpiece. However, shiny metal surfaces at room temperature have high reflectivity for laser light, particularly at a wavelength of 10.6 µm. For example, absorption of low intensity 10.6 µm CO_2 laser beam light is as low as forty percent for stainless steel and one percent for polished aluminum or copper. Absorption levels are higher for Nd:YAG and ruby laser beams. Fortunately, the absorption in most metals increases with temperature, and surface temperature increases rapidly at the beam impingement point when the metal is exposed to high-power density laser radiation. At power densities on the order of $10^6 W/in.^2$ ($1.55 \times 10^3 W/mm^2$), a threshold value of absorption is experienced for most steels and superalloys where the absorption level is approximately 90 percent. For aluminum and copper, this threshold occurs at intensities of approximately $1 \times 10^7 W/in.^2$ ($1.55 \times 10^4 W/mm^2$) and for tungsten at $1 \times 10^8 W/in.^2$ ($1.55 \times 10^5 W/mm^2$).

SHALLOW PENETRATION WELDING AND CONDUCTION EFFECTS

WHEN SUBKILOWATT LASER output power levels and welding speeds approach the limit of penetration dictated by the lower laser output power being employed, the effects of thermal conduction become more prevelant than the deep welding effects described above.

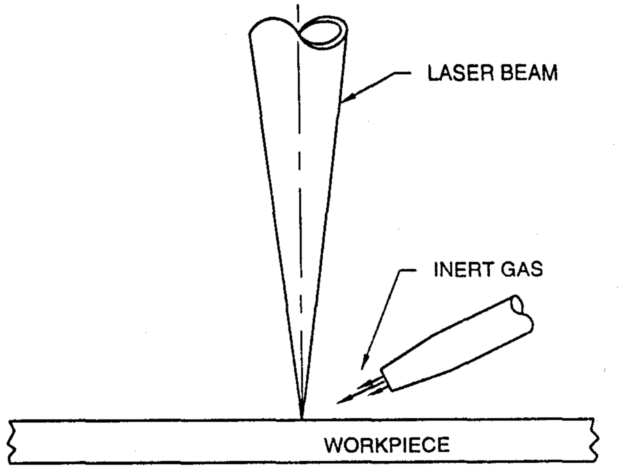

Figure 22.17–Plasma Suppression Using a Transverse Jet of Inert Gas

The result of this transition is generally seen as a broadening of the weld bead, from the deep keyhole, high aspect ratio weld shape to the characteristic "wineglass" shape. See Figure 22.18.

Shallow penetration welds performed with a pulsed laser such as closure welds for hermetic sealing in electronic enclosures, batteries, etc., are typically conduction welds, with limited keyhole formation. Surface plasma generation aids in transferring the energy of the laser beam into the workpiece, giving the desired melt zone required to form the closure weld.

THIN SECTION WELDING

IN SOME APPLICATIONS, the welding speed may be reduced in order to obtain a wider weld through conduction effects. This method is commonly applied in sheet metal butt welding applications where fit-up tolerance forces the laser into accepting lower welding speeds to ensure the reliability and repeatability of the process.

Laser welding is an excellent process for welding thin sections. Stainless steel as thin as 0.0001 in. (0.0025 mm) has been successfully welded by pulsed lasers. Pulsed Nd:YAG and pulsed CO_2 laser welding machines are especially suited for most thin section welds. As with other processes, full penetration welds are preferable to partial penetration welds. Distinct advantages and disadvantages of pulsed welding include:

Advantages:

(1) Small fusion and heat-affected zones
(2) Low heat input

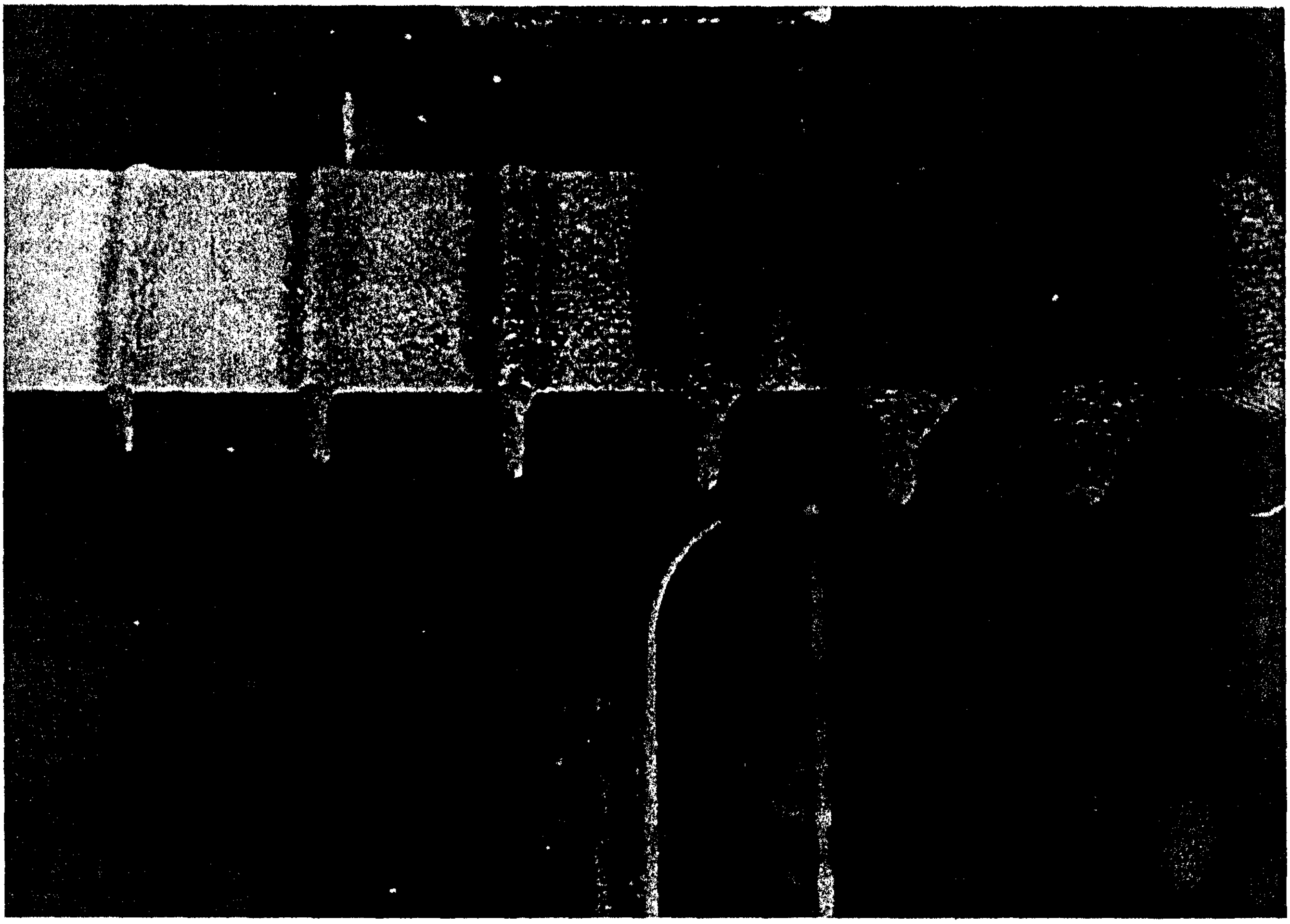

Figure 22.18–Variation of Weld Penetration as Travel Speed Changes Using a Constant Output Power

(3) Ability to precision tack weld a joint
(4) Unique properties of heat transfer with lasers

Disadvantages:

(1) Extremely high cooling rates
(2) Sensitivity to material chemistry
(3) Problems coupling with high reflectivity materials

The first two advantages of laser welding are fairly self-explanatory. The ability to precision tack weld a joint is aided by the pulsed mode of welding. A single pulse may be used to tack the joint before the final weld is made. The heat-transfer properties during laser welding differ dramatically from welding processes that depend on electrical conductivity to make welds. These properties allow laser welding of many materials which are not electrically conducting. Materials transparent to light of a specific wavelength can, on the other hand, be used for hold-down fixturing during laser welding. See Figure 22.19.

Fixturing

FIXTURING IS EXTREMELY important for thin section laser welding. Tolerances must be held closely to maintain joint fitups without allowing either mismatch or gaps. Standing-edge joints are preferable for thin section welds since the actual weld joint cross section is enlarged. Butt joints are difficult to design for welding, and distortion during welding may cause joint mismatching or gaps.

The disadvantages of laser welding for thin sections are generally related to material cracking or laser coupling problems. Cracking is typically caused by high cooling rates, which may lead to undesirable brittle phases in some

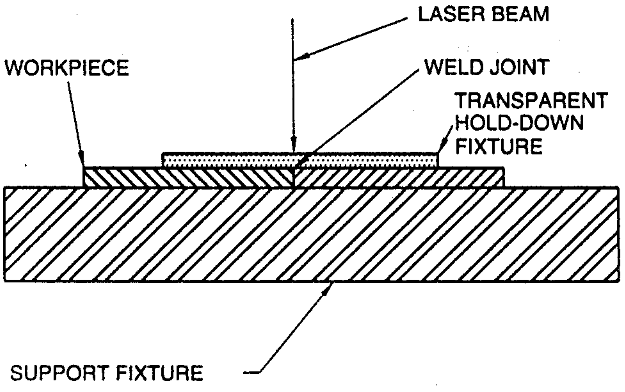

Figure 22.19–Use of Transparent Hold-Down Fixturing For Flat Thin Section Welding

materials, or by material chemistry problems, which may lead to hot cracking. These may be solved, in most cases, by either preheating or using a different laser wavelength to reduce high cooling rates, or by changing to a more suitable material in the case of hot cracking.

Coupling problems occur when materials (such as copper, aluminum, and silver) are highly reflective to the laser wavelength. The problem is usually solved in one of three ways: changing to a different wave length laser, etching or painting the surface to reduce reflectivity, or using a keyhole mode weld in which the energy density is great enough to overcome reflectivity.

APPLICATIONS

LASER BEAM WELDING is being used for an extensive variety of applications such as in the production of automotive transmissions and air conditioner clutch assemblies. In the latter application, laser welding permits the use of a design that could not otherwise be manufactured. The process is also being used in the production of relays and relay containers and for sealing electronic devices and heart pacemaker cases. Other applications include the continuous welding of aluminum tubing for thermal windows and for refrigerator doors.

Successful laser welding applications include welding transmission components (such as synchro gears, drive gears and clutch housings) for the auto industry. These annular and circumferential-type rotary welds need from 3 to 6 KW of beam power, depending on the weld speed being employed, and require penetrations which typically do not exceed .125 in. (3.2 mm). Materials welded are either carbon or alloy steels. In some cases, such as the gear teeth, they have been selectively hardened before welding. There are many advantages to laser welding such assemblies. The low heat input provided by the laser does not cause any affect to the prehardened zones adjacent to the weld. Also, this low heat input produces a minimal amount of distortion so that precision stampings can often be welded to finished dimensions. Since the ease of automation and high weld-speed capability of the laser process makes it ideal for automotive-type production, a number of these systems have recently been installed in the automotive industry.

Figure 22.20A shows a fully automated, 3 KW system employed for welding clutch assemblies. This system incorporates a beam switch to use one laser for sequentially welding at two separate but in-line work stations. While welding in one station, parts are loaded into the other station, thus helping to maximize the production capability of this dual-station system. As illustrated by Figure 22.20B, individual hub and housing components are brought to each station and then assembled, pressed to proper dimensions and welded, all under the control of a central unit. Weld speed is 90 ipm for these assemblies.

Figure 22.21 shows another transmission component weld, which involves welding a threaded annular boss onto a circular ring. Here a 2.5 kW (CO_2) laser is used to provide an 0.187 in. (4.75 mm) deep weld at 60 ipm, employing helium shield gas.

Figure 22.22(A) shows a recuperative plate pair for a heat exchanger which is joined by welds made around each of the air holes [Figure 22.22(B)] in the cutout pattern shown. The material of the these plates is 0.008 in. (0.2 mm) thick Inconel 625, and welding is done using a CO_2 laser rated for 750 W (continuous output power), operating in an enhanced pulse mode (i.e., 1.5 millisecond pulse length and 200 pulse per second repetition rate). Weld type is a lap weld, made at 120 ipm. A 5 in. (127 mm) focol length lens was used.

Figure 22.23 shows the cross section of a 416 stainless steel cap welded onto a 310 stainless steel body, using a 750 W CO_2 laser at 45 ipm weld speed. Penetration of weld into the body component is 0.050 in. (1.27 mm) deep.

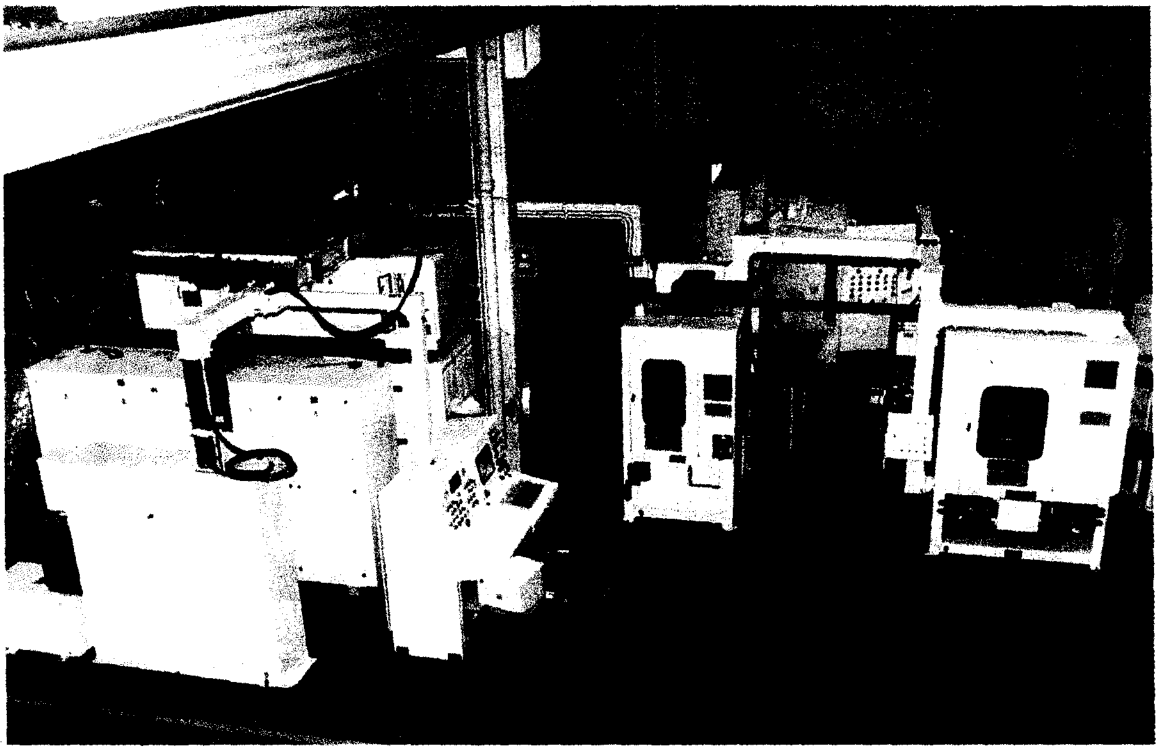

Figure 22.20A–Production Welding System for Automotive Transmission Components

METALS WELDED

LASER BEAM WELDING can be used for joining most metals to themselves as well as dissimilar metals that are metallurgically compatible. Low carbon steels are readily weldable, but when the carbon content exceeds 0.25 percent, martensitic transformation may cause brittle welds and cracking. Pulsed welding helps minimize the tendency for cracking. Fully killed or semi-killed steels are preferable, especially for structural applications, because welds in rimmed steel may have voids. Steels having high amounts of sulfur and phosphorus may be subject to hot cracking during welding. Also, porosity may occur in free machining steels containing sulfur, selenium, cadmium, or lead.

Difficulty has been encountered in welding carburized or nitrided steels. Welds in these alloys are generally porous and exhibit cracks. Occasionally nickel shims are added to these metals and some alloy steels to increase toughness. Aluminum in small quantities has also been added to joints of rimmed steel to reduce porosity caused by entrapped gases.

Many stainless steels are considered good candidates for laser welding. The low thermal conductivity of these metals permits forming narrower welds and deeper penetrations than possible with carbon steels. Stainless steel of the 300 series, with the exception of free machining Types 303 and 303Se and stabilized Types 321 and 347, are readily weldable. Welds made in some of the 400 series stainless steels can be brittle and may require post weld annealing. Many heat resistant nickel and iron based alloys are being welded successfully with laser beams. Titanium alloys and other refractory alloys can be welded in this way, but an inert atmosphere is always required to prevent oxidation.

Copper and brass are often welded to themselves and other materials with specialized joint designs used for conduction welding. Aluminum and its weldable alloys can be joined for partial penetration assembly welds and are commonly joined by pulsed conduction welds for hermetically sealed electronic packages. Joint designs must retain aluminum in tension.

Refractory metals such as tungsten are often conduction welded in electronic assemblies, but require higher power than other materials. Nickel-plated Kovar is often used in sealing welds for electronic components, but special care is required to ensure that the plating does not contain phosphorous, which is usually found in the electroless nickel

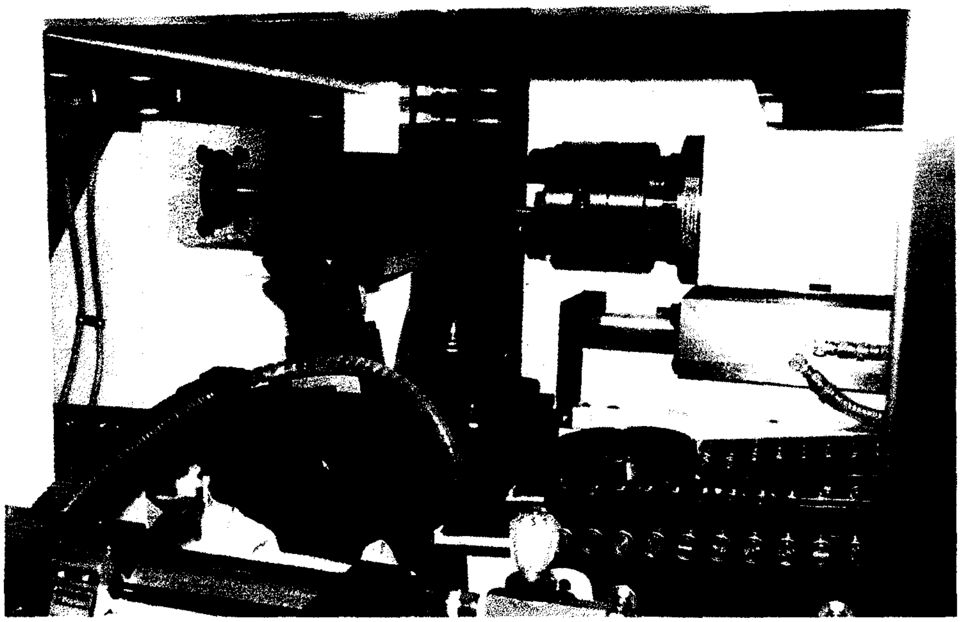

Figure 22.20B—Production Welding System for Automotive Transmission Components

plating process commonly used for Kovar parts that are to be resistance welded.

Dissimilar metal joints are commonly encountered in conduction welds where the twisting of conductors forms a mechanical support that minimizes bending of potentially brittle joints. Dissimilar metals having different physical properties (reflectivity, conductivity and melting points) are often joined in the welding of conductors. Special techniques such as adding extra turns of one material to the joint as opposed to the other may be required to balance the melting characteristics of the materials. Some of these concepts can also be applied to structural and assembly welds, but the possibilities are much more limited.

JOINT DESIGN

JOINTS DESIGNED FOR laser welding must meet the criteria of the manufacturing engineer, and strength and safety specifications must be considered. Joints must be accessible to a focused laser beam and must be economical when considering machining operations before and after welding. A good joint design can enhance a laser welding production system because tooling design, manufacture, and maintenance are affected by weld joint design. An optimum weld joint design may facilitate assembly of a part before welding. The weld joint also should be easy to inspect.

A variety of joints is applicable to the laser welding process. Joints used in laser welded construction are normally designed for structural, assembly, sealing, or similar purposes. Some types of joints used in laser welded construction are shown in Figure 22.24. Butt, corner, T-lap, as well as variations and combinations are applicable to the laser welding process.

Butt Joint

BUTT JOINT GEOMETRIES may be annular, circumferential or linear. Joint cleanliness must be maintained and as with any welding operation, rust and scale must be removed so as not to inhibit fusion zone integrity. An important consideration in laser joint preparation is fit-up. In some cases, gaps of 3 percent of metal thickness can be tolerated. However, underfill occurs if gapping is too extreme.

When employing butt joint design for laser processing, hold-down tooling should be considered, especially if the application is to be repeated in high-volume production. Butt joints are conducive to automated, high volume production welding operations, but intimate contact must be assured through fixturing design and dimensional control of the parts. In the case of annular butt joints, subassemblies can be manufactured to include an interference fit, allowing assembly to take place independent of the weld process. Preassembly can simplify the overall design of a laser welding system. A separate press or assembly station

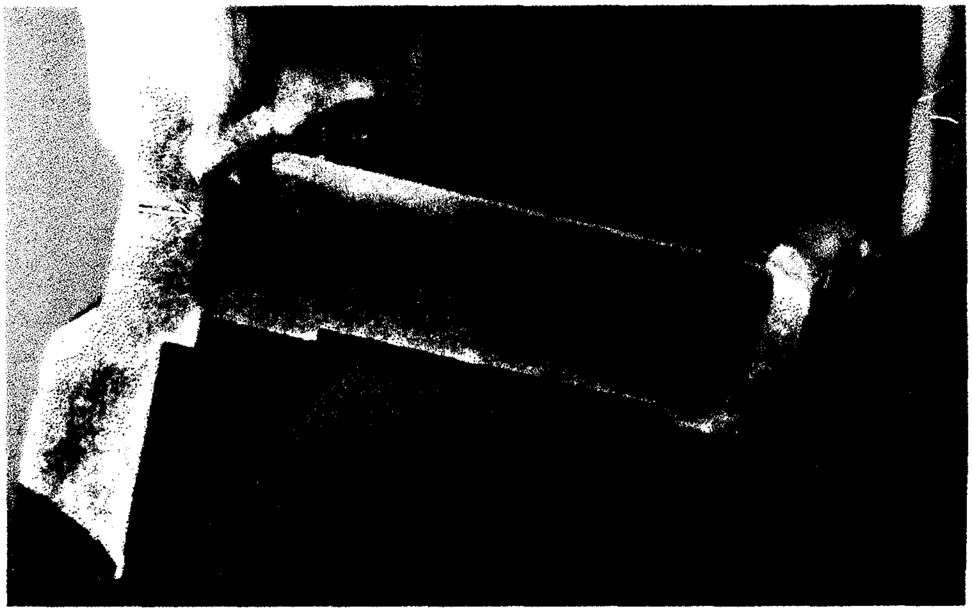

Figure 22.21–Cross Section of a Laser Beam Weld Joining a Boss to a Ring. A 2.5 KW CO_2 Laser Produced a Travel Speed of 60 in./min (25 mm/sec). Penetration was 0.187 in. (4.8 mm)

also adds another measure of quality control to the production system, as part size tolerances can be gauged before the joining process.

Butt joints [Figure 22.24(A)] are applicable in structural, assembly, and sealing applications. Single-pass penetration of 1.25 in. (31.8 mm) thick butt joints has been demonstrated with 25 kW high-power CO_2 lasers using the keyhole penetration technique. A majority of successful laser welding applications in the automotive transmission industry utilize single-pass, full penetration welds of 0.090 to 0.200 in. (2.3 to 5.1 mm) requiring 5 kW to 9 kW.

Keyhole penetration welding is easily performed with sharply focused laser beams of 1 kW or greater. Assembly or structural joints requiring limited or partial penetration also may be welded with lower powered lasers. At lower power levels, keyhole formation does not take place, but weld puddle creation is accomplished via conduction from the material surface similar to the more conventional welding processes.

T-JOINT

A LASER BEAM can be aimed at the root of an accessible T-joint [Figure 22.24(C)]. At an optimum directed angle, a focused beam may follow the gap between the intersecting workpieces. Depending upon plate thickness and laser power used, fusion takes place at the interface between workpieces. The stress load is transferred from one member to another primarily through the root. If a fillet is formed, it will act to reduce stress. However, laser formed fillets are not usually as pronounced as typical arc welding fillets.

CORNER JOINT

CORNER JOINTS [FIGURE 22.24(B)] are often used in laser welding assembly and sealing applications. The use of a corner joint design is limited by plate or sheet thickness. The thinner the material, the less the power that is required, but the greater the reliability on focused spot location that is needed.

The corner joint has the advantage of accessibility where tooling and fixturing are important to maintain fit-up integrity.

LAP JOINT

LAP JOINTS [FIGURE 22.24(D)] are typically used in sheet metal assembly applications. The focused laser beam can be impinged onto the top surface, causing a weld penetration into or through one or more material sheets in contact. This type of weld is sometimes referred to as a burn-through lap weld.

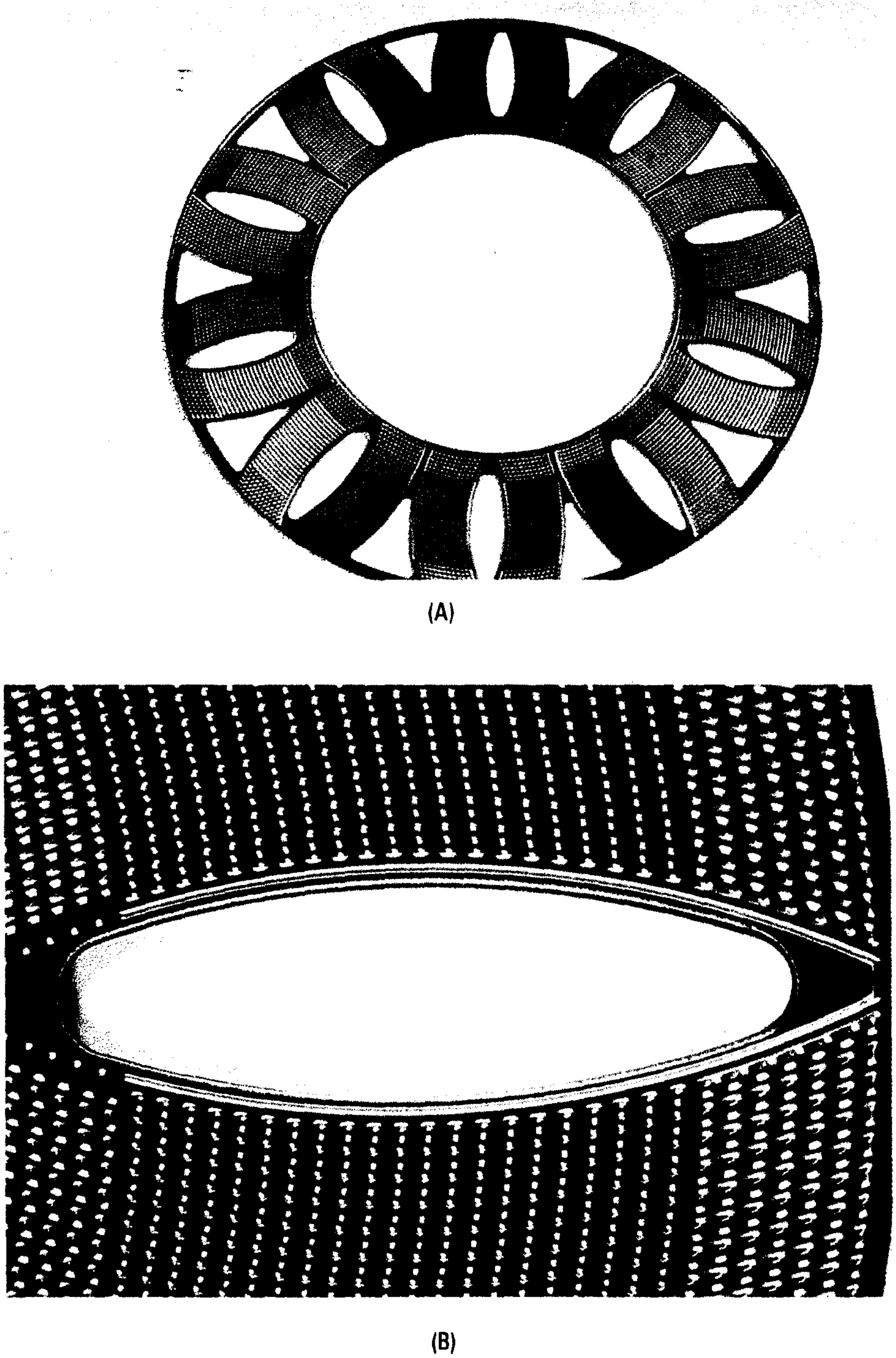

Figure 22.22–Heat Exchanger Recuperator Plate Pair Joined by Laser Beam Welds Around Each of the Air Holes. Material is 0.008 in. (0.2 mm) Thick Inconel 625

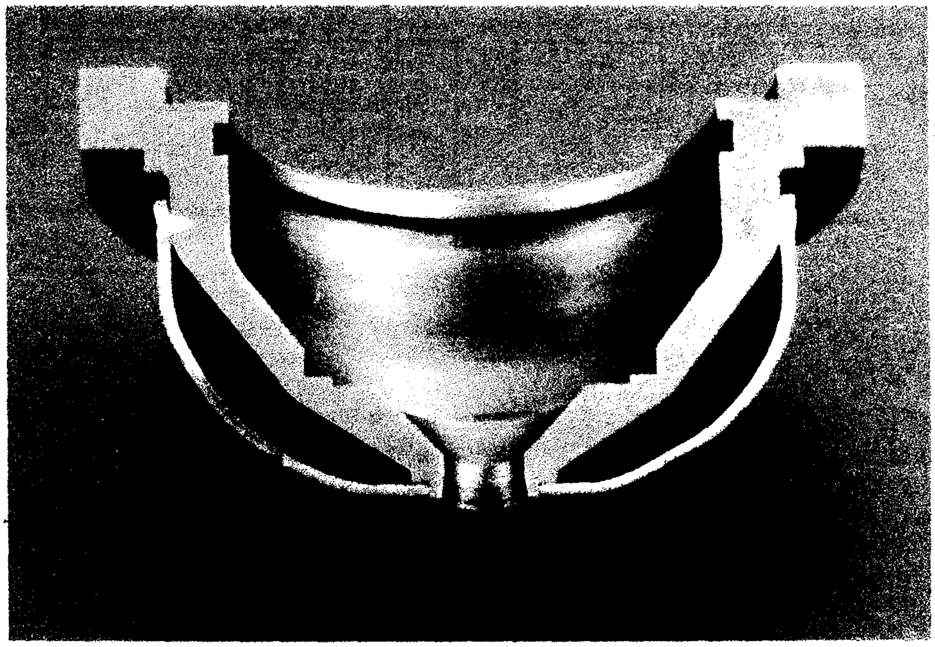

Figure 22.23–Cross Section of a Laser Beam Weld Joining a 416 Stainless Steel Cap to a 310 Stainless Steel Body

Intimate contact is not necessarily required in the burn-through lap weld because molten metal will bridge limited gaps between layers. In some applications using coated steels, a gap may be advantageous because it would avoid entrapment of outgassing products from the coating. The gap tolerance has a relatively narrow band which is related to workpiece thickness and beam spot size. For example, for 0.030 to 0.040 in. (0.8 to 1.0 mm) thick material welded with laser beam of approximately 0.020 in. (0.5 mm) diameter, a gap of approximately 0.003 in. (0.08 mm) is required to prevent porosity from outgassing. However, if the gap exceeds approximately 0.006 in. (0.15 mm), incomplete fusion of the joint may occur.

As with any lap joint weld, the fusion zone interface is the stress carrier. To increase the interface area, a laser beam may be directed in a circular or linear pattern (by moving the beam delivery optics). Although laser lap weld joints are not as sensitive to fit-up variances as other joints described above, part fit-up must generally be maintained using suitable fixtures or tooling.

Laser lap welds are usually characterized by a slight reinforcement at the fusion zone faces. For burn-through lap welds, a slight reinforcement of the root may also be achieved. When the bottom member of the assembly is not penetrated, a deformation is usually observed at the bottom surface. Finally, the lap joint is less dependent on the focused laser beam location tolerance than are butt, corner, or T-joints.

JOINT PREPARATION

Cleaning

ALL LASER WELDED joints must be free of rust, scale, lubricants, or other contaminants. Parts cleaning systems are easily integrated with laser processing production facilities via materials handling conveyors. The type of cleaning system used must comply with local and state laws.

Gap Tolerance

THE SENSITIVITY OF lap welds to gap was discussed above. Butt, T, and other similar joints also are sensitive to gaps. The gap tolerance for these joints is dependent on material thickness, weld speed, beam diameter, and beam quality. Normally, gap tolerance increases with material thickness. However, as the gap increases, the reinforcement normally associated with line-on-line fit up of laser welds decreases. When the gap is too large for weld bead reinforcement, underfill will occur. As the gap continues to increase, underfill will become more severe until complete lack of fusion occurs. This condition is characterized by the beam actually channeling through the gap without being absorbed by the workpiece at the mating surfaces.

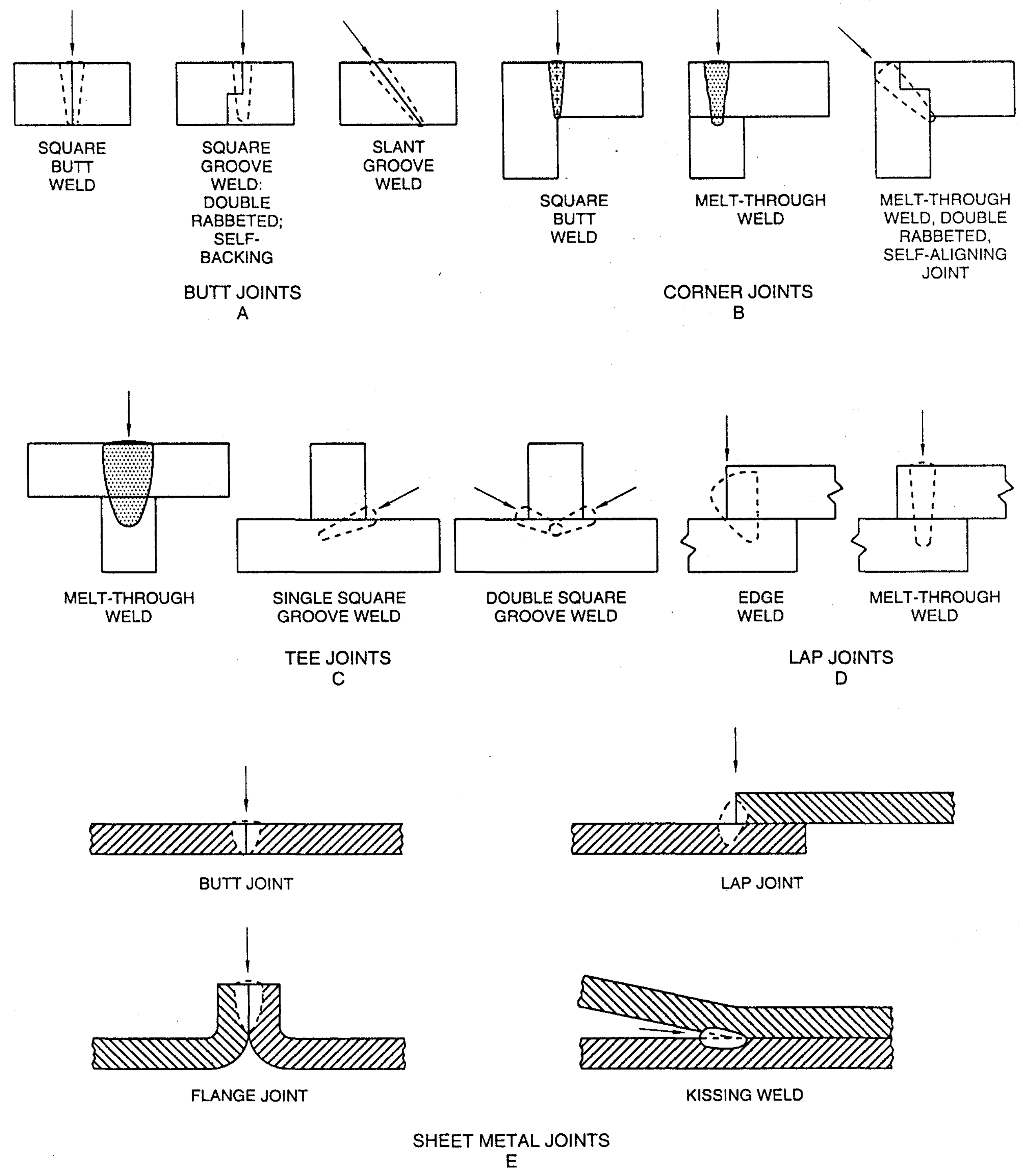

Figure 22.24—Joint Configurations for Laser Welds

For laser beams employed to weld materials up to 0.5 in. (12.7 mm) thick, a typical gap tolerance may be given as 3 percent of material thickness. However, the minimum gap specified should be based on the factors mentioned above as well as the required fusion zone geometry.

Mismatch

LASER BEAMS ARE considerably more tolerant to mismatch than gap. Mismatch as great as half the material thickness can be tolerated. However, joint specification and integrity should be used to designate the mismatch tolerance.

SAFETY

MISUSE OF LASER equipment can result in permanent damage to the eyes and skin of both operators and nearby personnel. In addition, specific precautionary measures are needed to avoid other potential hazards sometimes associated with using lasers such as dangers related to servicing high-voltage power sources, and harmful fumes that can be released when laser processing certain materials. These hazards can, in some instances, be far more significant than the beam-related hazards which are usually considered the most important.

Detailed laser safety information can be found in ANSI publication Z-136.1[1] and the Federal Performance Standard for Laser Products: FDA-Title 21, CFR, Section 1040.[2] Reference to these documents is strongly recommended.

Detailed training[3] is recommended for those working with lasers, including those on the technical support staff and technicians.

BEAM-RELATED HAZARDS

BOTH THE ANSI and FDA standards divide all lasers into four major classes with some sub classes which define the potential beam-related hazards associated with each type. These categories can be summarized as follows:

Class 1 - Denotes exempt lasers or laser systems that cannot, under normal operating conditions, produce a hazard. This would include, for example, bar code reading lasers found at grocery store check-out counters.

Class 2 - Denotes low power visible lasers or laser systems which, because of natural human aversion response to bright light, do not normally present a hazard but which may produce a hazard if viewed directly for extended periods.

Class 3A - Denotes lasers or laser systems that would not produce a hazard under normal conditions if viewed for only momentary periods with the unprotected eye, but may present a hazard if viewed using some form of light collecting optics.

Class 3B - Denotes lasers or laser systems that can produce a hazard if viewed directly, including intrabeam (i.e., direct) viewing of specular (i.e., concentrated) reflections. Except for higher power Class 3B lasers, this class will not usually produce a hazardous diffuse reflection.

Class 4 - Denotes lasers or laser systems that can produce a hazard not only if the beam or specular reflections are viewed directly, but also from direct viewing of diffuse reflections. In addition to eye damage, the beam and its reflections may also produce both skin and fire hazards.

Control Measures

CONTROL MEASURES CENTER on enclosing as much as possible of the beam path and baffling the target area to reduce the chance of hazardous reflections. Care should be taken to employ dark filters to reduce the level of visible light to a comfortable level. Robotic systems should be designed and installed to limit laser beam traverse so as not to direct the beam at personnel.[4]

NONBEAM-RELATED HAZARDS

THE POTENTIAL NONBEAM-RELATED hazards associated with using a laser include items like electrical shock, toxic gases and other occupational hazards, the proper safety precautions for which are clearly defined in ANSI/ASC Z49.1, Safety in Welding and Cutting.[5] The general safety requirements expressed therein as well as those provided by OSHA's General Industry Safety Standards,[6] should be strictly adhered to at all times.

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[1] American National Standard for the Safe Use of Lasers, ANSI Z136.1 (latest edition).

[2] Center for Devices and Radiological Health, Food and Drug Administration, Title 21, CFR-Section 1040: Federal Performance Standard for Laser Products (latest edition).

[3] R. J. Rockwell, Jr., Controlling Laser Hazards, *Laser Applications*, 5 (9); 93-99: 1986 Sept.

[4] Sliney and Wolbarsht, *Safety With Lasers and Other Optical Sources*, New York, Plenum, 1980.

[5] American National Standard for Safety in Welding and Cutting, ANSI/ASC Z49.1 (latest edition).

[6] Code of Federal Regulations, Title 29, Part 1910 (in its entirety): Occupational Safety and Health Standards (latest edition).

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CHAPTER 23

FRICTION WELDING

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CHAPTER 23

FRICTION WELDING

DEFINITION AND PROCESS VARIATIONS

FRICTION WELDING (FRW) is a solid-state welding process that produces a weld under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. While considered a solid-state welding process, under some circumstances a molten film may be produced at the interface. However, even then the final weld should not exhibit evidence of a molten state because of the extensive hot working during the final stage of the process. Filler metal, flux, and shielding gas are not required with this process. The basic steps in friction welding are shown in Figure 23.1.

First, one workpiece is rotated and the other is held stationary as shown in Figure 23.1(A). When the appropriate rotational speed is reached, the two workpieces are brought together and an axial force is applied, as in Figure 23.1(B). Rubbing at the interface heats the workpiece locally and upsetting starts, as in Figure 23.1(C). Finally, rotation of one of the workpieces stops and upsetting is completed, as in Figure 23.1(D).

The weld produced is characterized by a narrow heat-affected zone, the presence of plastically deformed material around the weld (flash), and the absence of a fusion zone.

ENERGY INPUT METHODS

THERE ARE TWO methods of supplying energy in friction welding. Direct drive friction welding, sometimes called *conventional friction welding*, uses a continuous input. Inertia friction welding, sometimes called *flywheel friction welding*, uses energy stored in a flywheel.

Direct Drive Welding

IN DIRECT DRIVE friction welding, one of the workpieces is attached to a motor driven unit, while the other is restrained from rotation. The motor driven workpiece is rotated at a predetermined constant speed. The workpieces to be welded are moved together and then a friction weld-

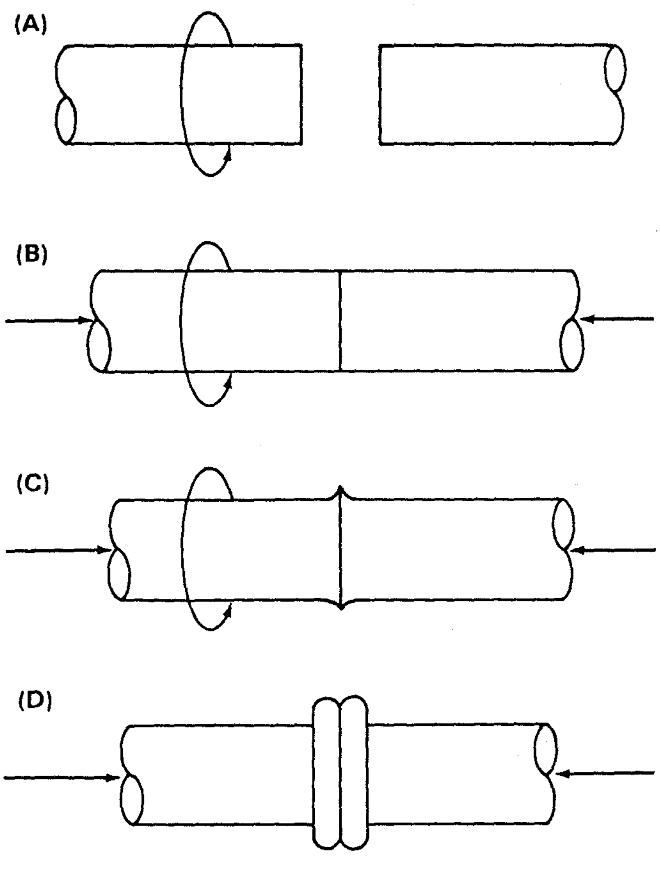


Figure 23.1–Basic Steps in Friction Welding

ing force is applied. Heat is generated as the faying surfaces (weld interface) rub together. This continues for a predetermined time, or until a preset amount of upset takes place. The rotational driving force is discontinued, and the rotating workpiece is stopped by either the application of a braking force or by its own resistance to rotation. The friction welding force is maintained or increased (forge force) for a predetermined time after rotation ceases. The relationship of direct drive friction welding parameter characteristics is shown in Figure 23.2.

Inertia Drive Welding

IN INERTIA FRICTION welding, one of the workpieces is connected to a flywheel, and the other is restrained from rotating. The flywheel is accelerated to a predetermined rotational speed, storing the required energy. The drive motor is disengaged and the workpieces are forced together by a friction welding force. This causes the faying surfaces to rub together under pressure. The kinetic energy stored in the rotating flywheel is dissipated as heat, through friction at the weld interface, as the flywheel speed decreases. An increase in friction welding force may be applied (forge force) before rotation stops. The forge force is maintained for a predetermined time after rotation ceases. The relationship of inertia friction welding parameter characteristics appears in Figure 23.3.

TYPES OF RELATIVE MOTION

WITH MOST FRICTION welding applications, one of the two workpieces is rotated about an axis of symmetry with the faying surfaces perpendicular to that axis. This means that in the normal case, one of the two workpieces must be circular or tubular in cross-section at the joint location. Typical arrangements for single and multiple welding operations are shown in Figures 23.4 (A) through (E).

Figure 23.4(A) depicts the conventional and most commonly used mode in which one workpiece rotates while the other remains stationary. Figure 23.4(B) shows another mode in which both workpieces are rotated, but in opposite directions. This procedure would be suitable for producing welds where very high relative speeds are needed. Figure 23.4(C) shows a third mode where two stationary workpieces push against a rotating piece positioned between them. This setup might be desirable if the two end parts are long or are of such an awkward shape that rotation would be difficult or impossible by the other modes.

A similar situation, shown in Figure 23.4(D), involves two rotating pieces pushing against a stationary piece at the middle. The same principle can be applied to the making of two welds back to back at the same time with one rotating spindle at the center, as shown in Figure 23.4(E), for the purpose of improving productivity.

Additional forms of friction welding are rather unique. Radial, orbital and angular reciprocating friction welding

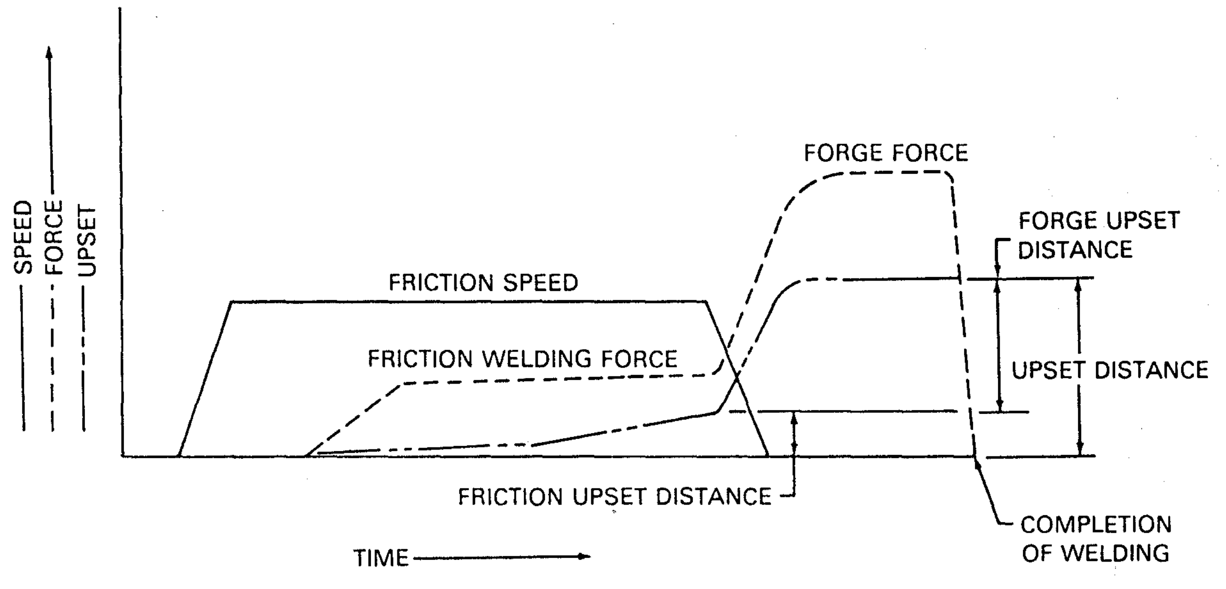


Figure 23.2–Direct Drive Friction Welding Parameter Characteristics

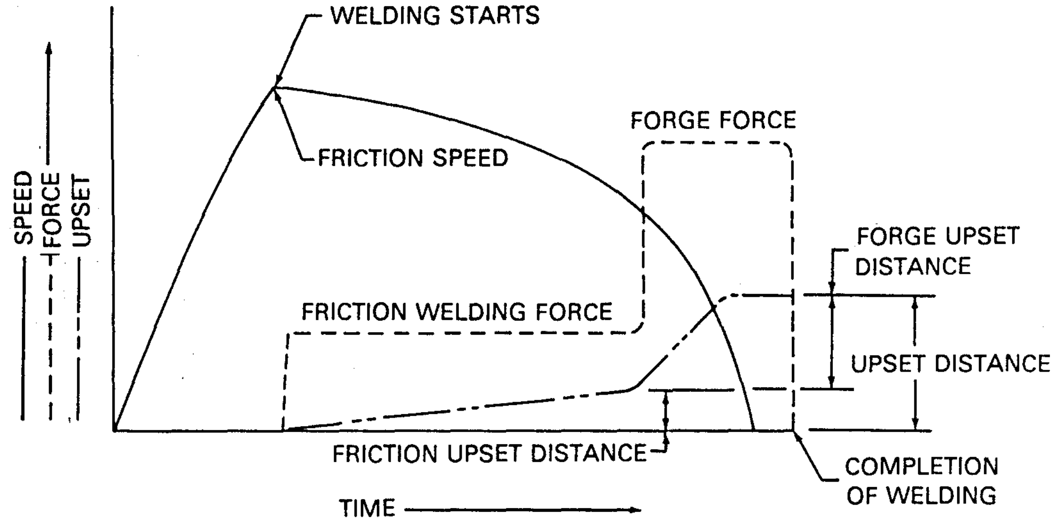


Figure 23.3–Inertia Friction Welding Parameter Characteristics

and friction surfacing are special cases using rotational motion. Linear reciprocating friction welding, as suggested by the name, uses a straight-line motion. These variations of friction welding are described below.

Radial

THIS PROCESS VARIATION can be used to join circular sections where it is undesirable to rotate the parts to be joined. It is also used to weld collars to shafts and tubes. As illustrated in Figure 23.5, the applied force on the rotating band is perpendicular to the axis of rotation. The collar is rotated and compressed as it is heated. An internal expanding mandrel supports the pipe walls and prevents penetration of upset metal into the bore of the pipe.

Orbital

IN THIS PROCESS variation, illustrated in Figure 23.6, one part rotates (or orbits) around the other. Neither part actually rotates around its axis. Consequently, the parts being joined do not need to be circular or tubular in cross-section. This variation is especially useful when part-to-part angular orientation is necessary.

Friction Surfacing

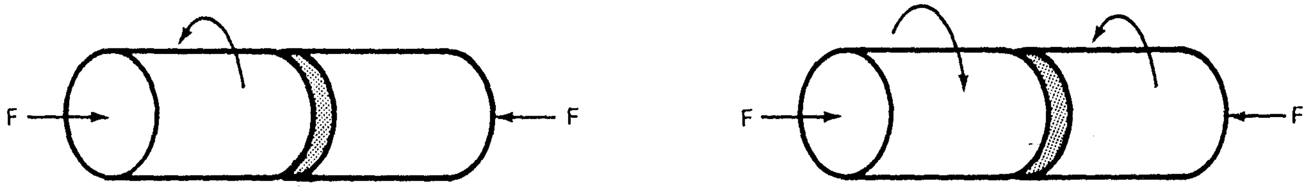
THIS PROCESS VARIATION uses rotational motion of one of the parts, but at the same time adds a relative motion in a direction perpendicular to the axis of rotation. This process is used to deposit material in a solid-state mode to a variety of configurations from flat plates to circular or cylindrical shapes. This variation is shown in Figure 23.7(A).

Angular Reciprocating

THIS PROCESS, SHOWN in Figure 23.7(B), is used primarily for joining plastics. It employs a cyclic reversing rotational motion in which the moving part is rotated through a given angle which is less than one full rotation.

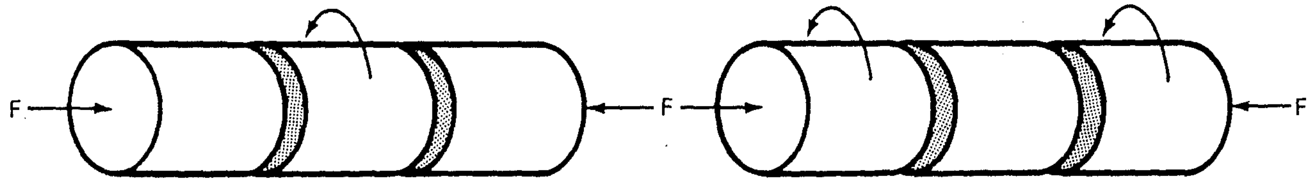
Linear Reciprocating

THIS PROCESS USES a straight-line back and forth motion between the two parts to be joined. An advantage of this variation is that rotational symmetry of the parts to be joined is not necessary. This variation is illustrated in Figure 23.7(C).



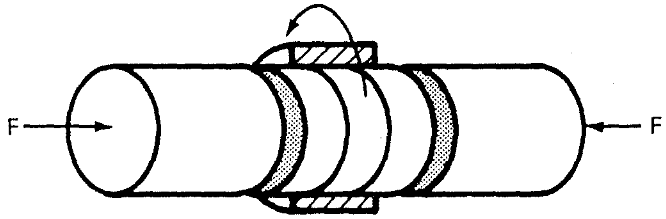
(A) BASIC

(B) COUNTER ROTATION



(C) CENTER DRIVE (SPLICING)

(D) TWIN WELDS



(E) CENTER DRIVE (DUAL PRODUCTION)

Figure 23.4—Typical Arrangements of Friction Welding

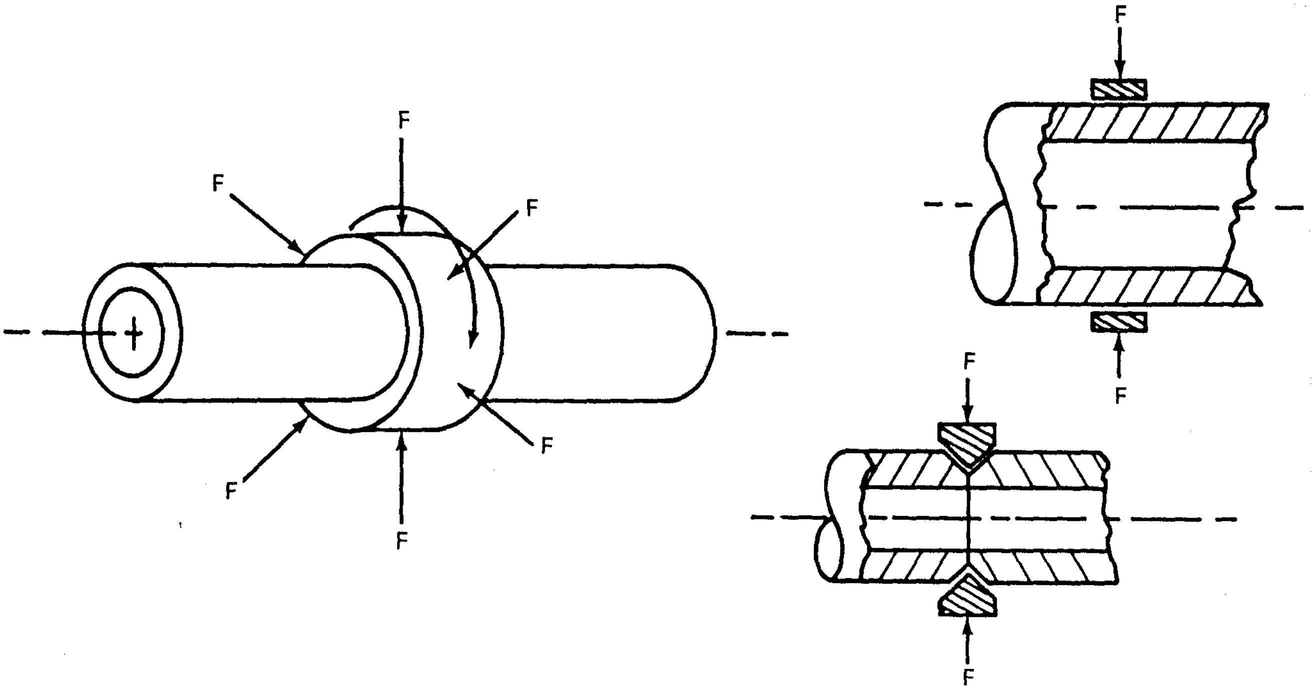


Figure 23.5–Radial Friction Welding

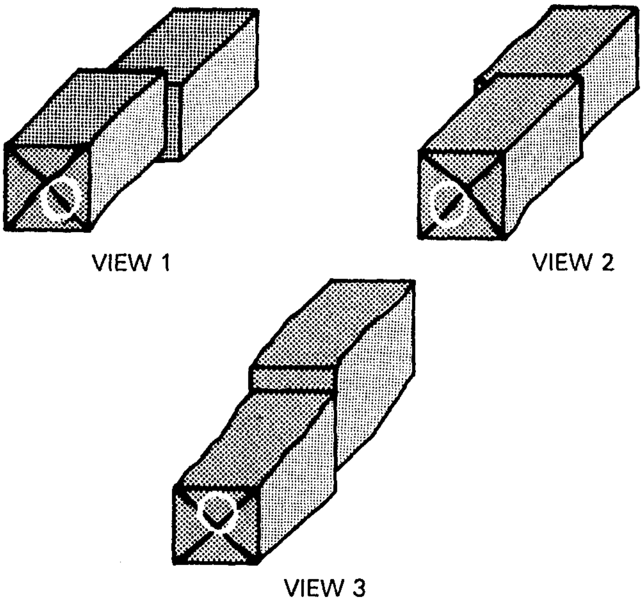


Figure 23.6–Schematic View of Orbital Friction Welding. Three Consecutive Views Taken at 120 Degree Intervals

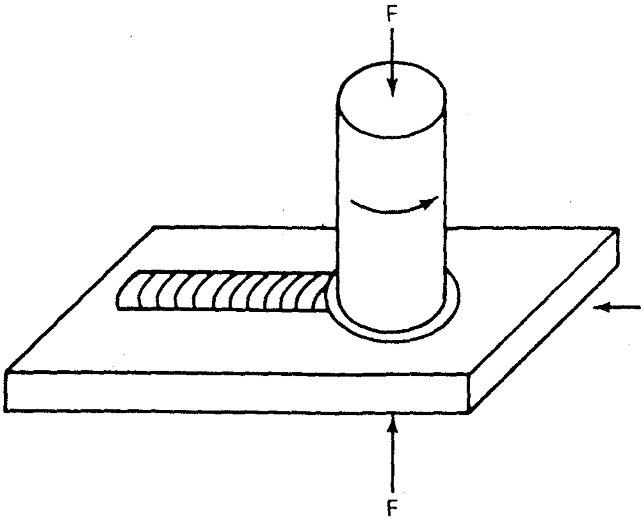


Figure 23.7A–Friction Surfacing

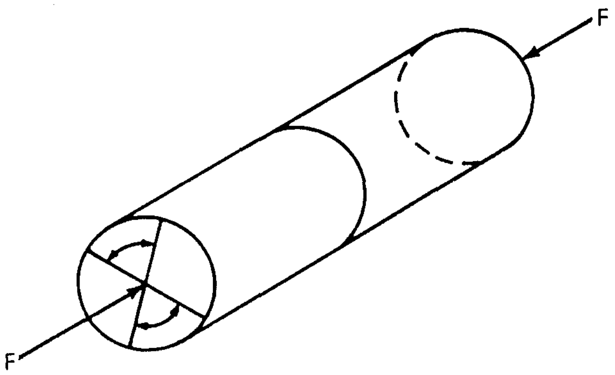


Figure 23.7B–Angular Reciprocating Friction Welding

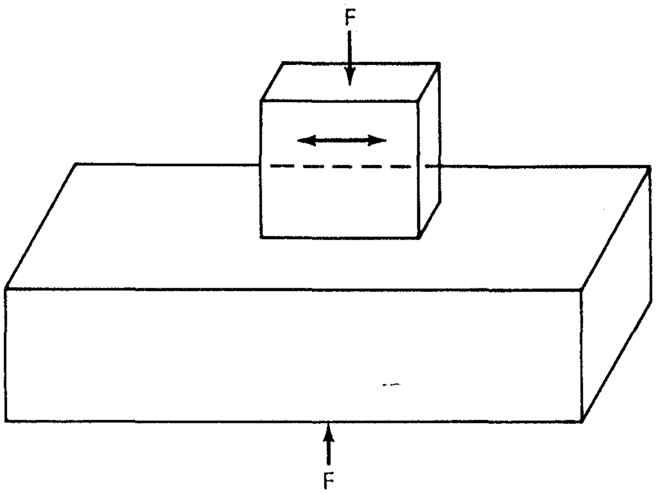


Figure 23.7C–Linear Reciprocating Friction Welding

PROCESS CHARACTERIZATION

WHILE SPECIFIC DETAILS of the bonding process are unclear, the welding cycle can be divided into two stages: the rubbing or friction stage, and the upsetting or forging stage. The welding heat is developed during the first stage, and the weld is consolidated and cooled during the second stage.

FRICTION STAGE

WITH IDENTICAL WORKPIECES, the joining mechanism occurs in steps. When the pieces make contact, rubbing takes place between the faying surfaces, and strong adhesion takes place at various points of contact. The unit pressure is high. At some points, the adhesion is stronger than the metal on either side. Shearing takes place and metal is transferred from one surface to the other. As rubbing continues, the torque and interfacial temperature both increase. The sizes of transferred fragments grow until they become a continuous layer of plasticized metal. If a liquid film forms, it occurs at this point. During this period, the torque peaks and decreases to some minimum value, which remains reasonably constant as metal is heated and forced from the interface and axial shortening continues.

FORGING STAGE

TOWARD THE END of the heating process, forging pressure is applied to the workpiece to cause axial shortening. This upset results in the flash shown in Figure 23.1(D). Comparing Figures 23.2 and 23.3, it can be seen that the latter part of the direct drive and the inertia friction welding processes is very similar with respect to axial shortening (upset), speed and pressure. As the speed decreases, a second torque peak occurs when the interface bonds and cools from its maximum temperature. The torque then decreases as the RPM drops to zero.

The bonding mechanism with dissimilar metals is more complex. A number of factors, including physical and mechanical properties, surface energy, crystal structure, mutual solubility, and intermetallic compounds, may play a role in the bonding mechanism. It is likely that some alloying will occur in a very narrow region at the interface as a result of mechanical mixing and diffusion. The properties of this layer may have a significant effect on overall joint properties. Mechanical mixing and interlocking may also contribute to bonding. The complexity makes prediction of weldability of dissimilar metals very difficult. Suitability of a particular combination should be established for each application with a series of tests designed for that purpose.

RELATIONSHIP BETWEEN VARIABLES

Speed

THE FUNCTION OF rotation is to produce a relative velocity at the faying surfaces. From a weld quality standpoint, speed is not generally a critical variable; that is, it can vary within a fairly broad tolerance band and still provide sound welds. For steels, the tangential velocity should be in the range of 250 ft/min (1.3 m/s). This is true for both solid and tubular workpieces. Tangential speeds below 250 ft/min produce very high torques that cause work clamping problems, nonuniform upset, and metal tearing. Production machines are normally designed to operate with speeds of 300 to 650 rpm. For example, a spindle speed of 600 rpm can be used to weld steel products of 2 to 4 in. (50 to 101 mm) diameters (310 to 620 ft/min or 1.6 to 3.2 m/s).

High rotational speeds and the lower heat inputs associated with them, see Figure 23.8, can be used to weld hardenable steels. Longer heating time preheats the metal to control cooling rates and avoid quench cracking. Conversely, for certain dissimilar metal combinations, low velocities (and their shorter heating times) can minimize the formation of brittle intermetallic compounds. In practice, however, heating time (for a given amount of upset) is usually controlled by varying the friction welding pressure.

Pressure

THE EFFECTIVE PRESSURE ranges are also broad for heating and forging, although the selected pressures should be reproducible for any specific operation. The pressure controls the temperature gradient in the weld zone, the required drive power, and the axial shortening. The specific pressure depends upon the metals being joined and the joint geometry. Pressure can be used to compensate for heat loss to a large mass, as in the case of tube-to-plate welds.

Heating pressure must be high enough to hold the faying surfaces in intimate contact to avoid oxidation. For a set spindle speed, low pressure limits heating with little or no axial shortening. High pressure causes local heating to high temperature and rapid axial shortening. With mild steel, the rate of axial shortening is approximately proportional to heating pressure, as illustrated in Figure 23.9. It also

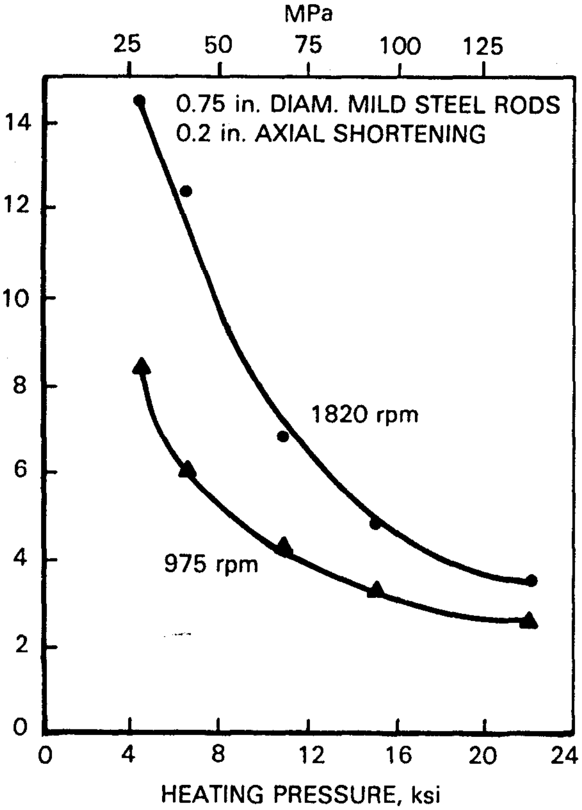


Figure 23.8–Relationship Between Heating Time and Heating Pressure for Mild Steel with Continuous Drive Friction Welding

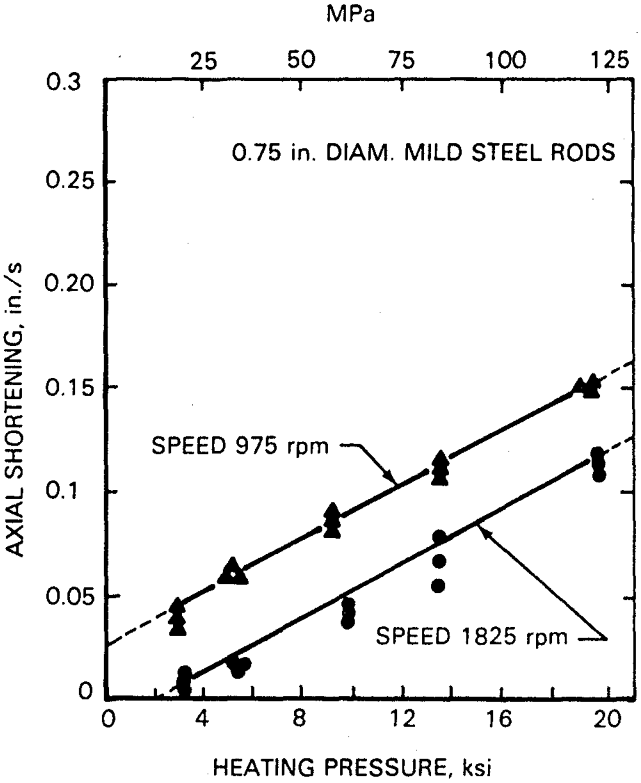


Figure 23.9–Relationship Between Axial Shortening and Heating Pressure for Mild Steel With Continuous Drive Friction Welding

shows that for a given pressure during the heating phase, axial shortening is greater at low speed than at high speed. Joint quality is improved in many metals, including steels, by applying an increased forging force at the end of the heating period.

For steels, a wide range of pressures is applicable for making sound welds. In the case of mild steel, heating pressures of 4500 to 8700 psi (31 to 60 MPa) and forging pressures of 11 000 to 22 000 psi (76 to 152 MPa) are acceptable. Commonly used values are 8000 and 20 000 psi (55 and 138 MPa), respectively. High, hot-strength alloys, such as stainless steels and nickel base alloys, will require higher forging pressures.

If a "preheat" effect is desired in order to achieve a slower cooling rate, a pressure of about 3000 psi (21 MPa) can be applied for a brief period at the initiation of the weld cycle. The pressure is then increased to that required for welding.

Heating Time

FOR A PARTICULAR application, heating time is determined during setup or from previous experience. Excessive heating time limits productivity and wastes material. Insufficient time may result in uneven heating as well as entrapped oxides and unbonded areas at the interface. Uneven heating is typical of friction welds in barstock. Near the center of a rotating bar, the surface velocity may be too low to generate adequate frictional heating. Hence, thermal diffusion from the outer portion of the faying surface must take place in order to insure a sound bond overall.

Heating time can be controlled in two ways. The first is with a suitable timing device that stops rotation at the end of a preset time. Preheat and forging functions can be incorporated with heating time using a sequence timer.

The second method is to stop rotation after a predetermined axial shortening. This method is set to consume a sufficient length to assure adequate heating prior to upsetting. Variations in surface condition can be accommodated without a sacrifice in weld quality.

In summary, for a given axial shortening when welding mild steel, the heating time will be significantly influenced by heating pressure and speed. Heating time is reduced at a decreasing rate as heating pressure is increased. It also decreases with speed at the same heating pressure.

INERTIA FRICTION WELDING

WITH INERTIA FRICTION welding, the speed continuously decreases with time during both the friction and forging stages. This contrasts to direct drive friction welding where the friction stage occurs at constant speed. Speed is decreasing during the forging phase of both processes. Throughout the friction stage the thickness of the plasticized layer is related to the rubbing speed. As the speed decreases at the end of the friction stage, the generation of heat decreases, the thickness of the hot plasticized layer decreases, and the torque peaks as the weld enters the forging stage. The axial pressure forces the hot metal from the joint. During this time, the rate of axial shortening increases and then stops as the joint cools.

Relationship Between Variables

THERE ARE THREE welding variables with this method: moment of inertia of the flywheel, initial flywheel speed, and axial pressure. The first two variables determine the total kinetic energy available to accomplish welding. The amount of pressure is generally based on the material to be welded and the interface area. The energy in the flywheel at any instant during the welding cycle is defined by the equation:

$$E = \frac{I\,S^2}{C} \qquad (23.1)$$

where

$E =$ Energy, ft-lb (J)
$I =$ Moment of inertia, lb-ft^2 (kg-m^2)
$S =$ Speed, rpm
$C =$ 5873 when the moment of inertia is in lb-ft^2
$C =$ 182.4 when the moment of inertia is in kg-m^2

For mathematical modeling and parameter calculations, the derived value of "Unit Energy" is defined by the following equation:

$$E_u = \frac{E}{A} \qquad (23.2)$$

where

$E_u =$ Unit Energy, ft-lb/in.^{2} (J/mm^2)
$E =$ energy, ft-lb (J)
$A =$ Faying Surface Area, in.^{2} (mm^2)

Unit energy can be used to scale or extrapolate data from one material, size or geometry to another. This can often serve as a first approximation.

With a particular flywheel system, the energy in the flywheel is determined by its rotational speed. If the mass of the flywheel is changed, the available energy at any particular speed changes. Therefore, the capacity of an inertia welding machine can be modified by changing the flywheel within the limits of the machine capability.

During welding, energy is extracted from the flywheel, and its speed decreases. The total time for the wheel to come to rest depends on the average rate at which the energy is being removed and converted to heat.

The shape of the heat-affected zone can be adjusted by varying the flywheel moment of inertia, heating pressure, and speed. Also, the heat input can be adjusted to control the width of the heat-affected zone and the cooling rate of the weldment. The effect of flywheel energy, heating pressure, and tangential velocity on the heat pattern and flash formation of welds in steel are shown in Figure 23.10.

Flywheel Effect

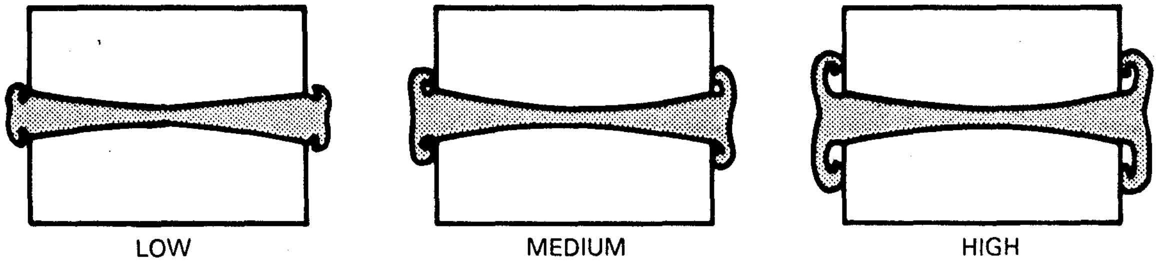
THE MOMENT OF inertia of the flywheel depends upon its section shape, diameter, and mass. For a specific application and initial speed, the energy available for welding can be increased by changing to a flywheel with a larger moment of inertia. The product of flywheel moment of inertia and the square of its initial velocity varies inversely for a given total energy requirement.

The amount of upset near the end of the welding cycle depends upon the remaining energy in the flywheel as well as the heating or forging pressure. For low carbon steel, forging usually starts at a peripheral velocity of about 200 ft/min (1.0 m/s). Large flywheels can prolong the forging or upsetting phase. If the flywheel is too small, the upset may be insufficient to consolidate the weld and eject impurities from the interface.

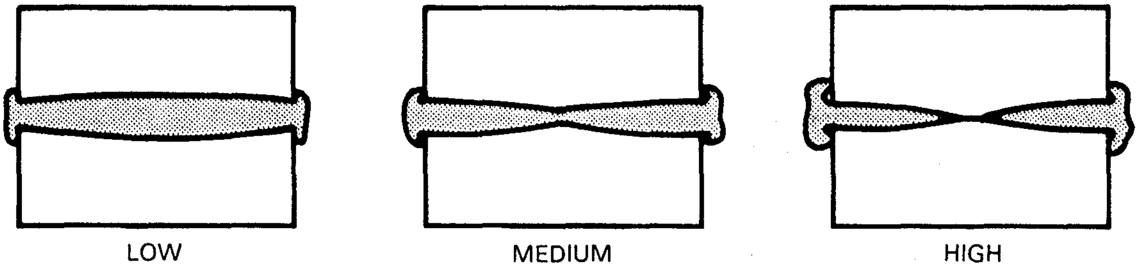
For a given initial velocity and heating pressure, a larger flywheel will increase the available energy. The effect of this is shown in Figure 23.10(A). As the available energy is increased, the amount of plasticized metal becomes greater as do the upset and flow of metal from the interface. The heating pattern remains fairly uniform, but the excessive energy wastes metal in the form of flash.

Velocity

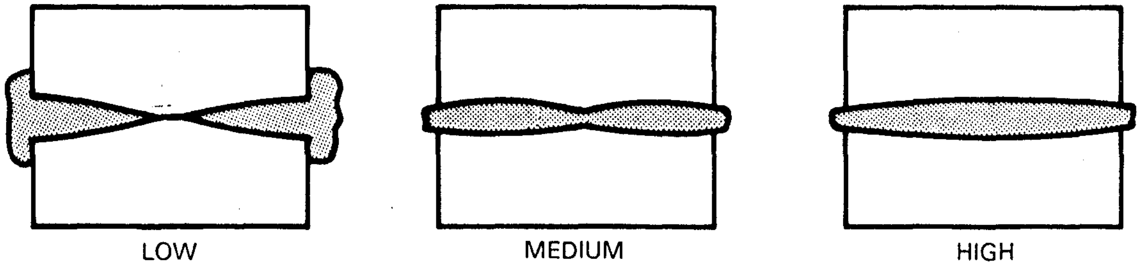
THE INSTANTANEOUS TANGENTIAL velocity varies directly with the radius and rotational speed according to the following equation:



(A) ENERGY



(B) PRESSURE



(C) VELOCITY

Figure 23.10–Effect of Welding Variables on the Heat Pattern at the Interface and Flash Formation of Inertia Welds

$$V_t = K\ r\ s \tag{23.3}$$

where

V_t = tangential velocity, ft/min
r = radius, in. (m)
s = instantaneous speed, rpm
K = 0.52 when r is in inches
K = 0.1 when r is in meters

With a rotating solid rod, the velocity varies linearly from zero at the center to a maximum at the periphery. This contrasts with the behavior of a thin wall tube where the change in velocity across the faying surface is minor. Hence, the energy required for welding a rod and a tube of the same alloy and equal faying surface area will be different.

For each metal, there is a range of peripheral velocities that produces the best weld properties. For welding solid bars of steel, the recommended initial peripheral velocity of the workpiece ranges from 500 to 1500 ft/min (2.5 to 7.5 m/s); however, welds can be made at velocities as low as 300 ft/min (1.5 m/s). If the velocity is too low, whether at the required energy level or not, the heating at the center will be too low to produce a bond across the entire interface and the flash will be rough and uneven. This is illustrated in Figure 23.10(C). At medium velocities of 300 to 800 ft/min (1.5 to 4.1 m/s), the heating pattern in steel has an hourglass shape at the lower end of the range and gradually flattens at the upper end of the range. At initial velocities above 1200 ft/min (6.1 m/s) for steel, the weld becomes rounded and is thicker at the center than at the periphery.

Heating Pressure

THE EFFECT OF varying heating pressure is generally opposite to that of velocity. As Figure 23.10(B) shows, welds made at low heating pressure resemble welds made at high velocity with regard to the formation and appearance of weld upset and heat-affected zones. Excessive pressure produces a weld that lacks good bonding at the center and has a large amount of weld upset, similar to a weld made at low velocity. The effective heating pressure range for a solid bar of medium carbon steel is 22 000 to 30 000 psi (152 to 207 Mpa).

ADVANTAGES AND LIMITATIONS

FRICTION WELDING, LIKE any welding process, has its specific advantages and disadvantages.

ADVANTANGES

THE FOLLOWING ARE some advantages of friction welding:

(1) No filler metal is needed.
(2) Flux and shielding gas are not required.
(3) The process is environmentally clean; no arcs, sparks, smoke or fumes are generated by clean parts.
(4) Surface cleanliness is not as significant, compared with other welding processes, since friction welding tends to disrupt and displace surface films.
(5) There are narrow heat-affected zones.
(6) Friction welding is suitable for welding most engineering materials and is well suited for joining many dissimilar metal combinations.
(7) In most cases, the weld strength is as strong or stronger than the weaker of the two materials being joined.
(8) Operators are not required to have manual welding skills.
(9) The process is easily automated for mass production.
(10) Welds are made rapidly compared to other welding processes.
(11) Plant requirements (space, power, special foundations, etc.) are minimal.

LIMITATIONS

SOME LIMITATIONS OF the process are as follows:

(1) In general, one workpiece must have an axis of symmetry and be capable of being rotated about that axis.
(2) Preparation and alignment of the workpieces may be critical for developing uniform rubbing and heating, particularly with diameters greater than 2 in. (50 mm).
(3) Capital equipment and tooling costs are high.
(4) Dry bearing and nonforgeable materials cannot be welded.
(5) If both parts are longer than 3 ft (1 m), special machines are required.
(6) Free-machining alloys are difficult to weld.

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as a guide. Specific weldability may depend upon a number of factors including specific alloy compositions, applicable process variation, component design, and service requirements.

In principle, almost any metal that can be hot forged and is unsuitable for dry bearing applications can be friction welded. Some metals may require postweld heat treatment to remove the effect of the severe deformation or quench hardening at the weld interface. Free-machining types of alloys should be welded with caution because redistribution of inclusions may create planes of weakness in the weld zone. Such welds exhibit low strength, decreased ductility, and reduced notch toughness.

In general, a consequence of reorienting the inclusion population into the weld plane is that the ductility and toughness across the joint will tend to approach the wrought short transverse properties of the materials being welded. If these properties are critical, it is essential to use microstructurally clean materials.

There are a number of dissimilar metal combinations that have marginal weldability. These may involve combinations that have high and low thermal conductivities, a large difference in forging temperatures, or the tendency to form brittle intermetallic compounds. Examples are aluminum alloys to both copper and steel and titanium alloys to stainless steel.

The metallurgical structures produced by friction welding are generally those resulting from elevated temperature deformation. Time at temperature is short, and the temperatures achieved are generally below the melting point. With nonhardenable metals such as mild steel, changes in properties are negligible in the weld zone. On the other hand, with hardenable steels, structural changes may occur in the heat-affected zone. They should be welded with a relatively long heating time to achieve a slower cooling rate and preserve toughness.

The interface structures of dissimilar metal combinations are significantly affected by the particular welding conditions employed. The longer the welding time, the greater the consideration that must be given to diffusion across the interface. Proper welding conditions will usually minimize undesired diffusion or intermetallic compound formation. The interface between an aluminum and carbon steel friction weld is shown in Figure 23.12. A very narrow diffusion zone is apparent.

In some cases, joints between dissimilar metals will show a mechanical mixing at the interface. Such action in a joint between Type 302 stainless steel and tantalum is shown in Figure 23.13.

JOINT DESIGN

THE NATURE OF friction welding suggests that the joint face of at least one workpiece must be essentially round, except in the cases of orbital and linear reciprocating friction welding. The rotated workpiece should be somewhat balanced in shape because it is revolved at relatively high speed. Preparation of surfaces to be joined is not normally critical except in the case of alloys with distinct differences in mechanical or thermal properties, or both.

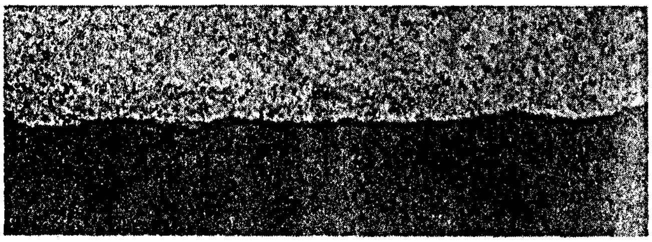


Figure 23.12–Interface of a Friction Weld Between Aluminum (top) and Carbon Steel (bottom) (x1000)

The basic joint designs for combinations of bars, tubes, and plates are illustrated in Figure 23.14. When bars or tubes are welded to plates, most of the flash comes from the bar or tube. This is true because there is less mass in the smaller section and the heat penetrates deeper into it. This effect can be usefully employed in joints between dissimilar metals with widely different mechanical or thermal properties. The material of lower forging strength or lower thermal conductivity should have a larger cross-sectional area.

Conical joints are usually designed with the faces at 45 to 60 degrees to the axis of rotation, as shown in Figure 23.15. For low-strength metals, large angles are preferred to support the axial thrust required to produce adequate

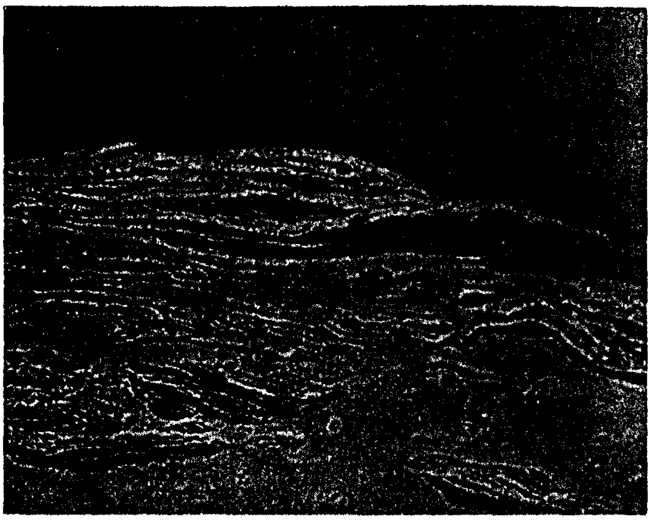
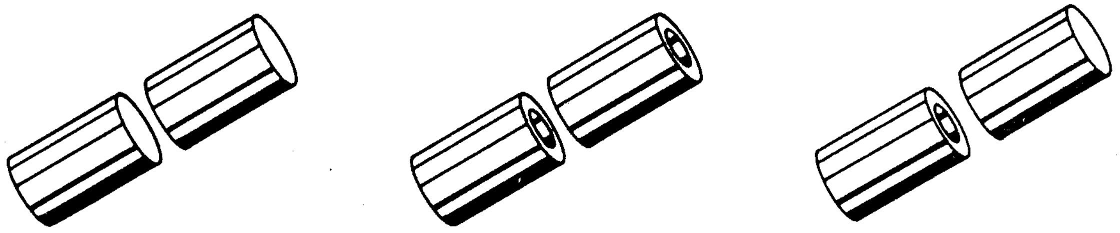
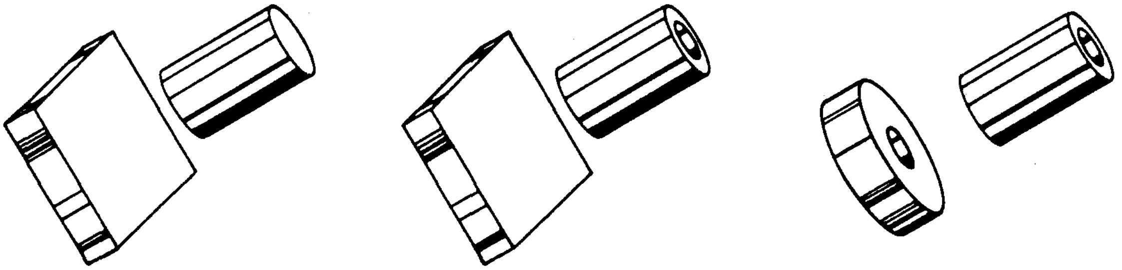


Figure 23.13–Interface of a Friction Weld Between Tantalum (top) and Type 302 Stainless Steel (bottom) (x200 and reduced 66 percent)



(A) BAR-TO-BAR (B) TUBE-TO-TUBE (C) BAR-TO-TUBE



(D) BAR-TO-PLATE (E) TUBE-TO-PLATE (F) TUBE-TO-DISC

Figure 23.14–Typical Friction Weld Joint Applications

heating pressure. Certain applications may require the use of conical joints; however, experience has shown that a butt weld (perpendicular) geometry is superior. The butt geometry leads to less residual stress and distortion.

For applications where the flash cannot be removed but must be isolated for cosmetic or functional reasons, clearance for it can be provided in one or both workpieces (flashtraps). Two flashtrap configurations are illustrated in Figures 23.16A and B.

FRICTION WELDING MACHINES

A TYPICAL FRICTION welding machine consists of the following components:

(1) Head
(2) Base
(3) Clamping arrangements
(4) Rotating and upsetting mechanisms
(5) Power supply
(6) Controls
(7) Optional monitoring devices

This is true for both process variations. However, the machines for each variation differ somewhat in design and method of operation.

Equipment is currently available (circa 1989) from 200 lb (890 N) to 275 tons (250 metric tons) maximum forge force in direct drive friction welders and up to 2250 tons (2040 metric tons) maximum forge force in inertia friction welders. This translates to parts ranging from 0.06 in (1.5 mm) diameter barstock to 24 in. (600 cm) diameter tubes. The faying surface area ranges from .003 to 250 in.^{2} (2 to 160 000 mm^2). A given machine can generally make welds which have a faying area range of eight to one. For example, a 30 ton (27 metric tons) maximum forge force machine can make welds in barstock ranging from 0.5 in. (13 mm) diameter to slightly less than 1.5 in. (38 mm) diameter. The above information is based on manufacturers recommendations for mild steel.

Direct Drive Welding Machines

WITH DIRECT DRIVE friction welding machines, one of the workpieces to be welded is clamped in a vise. The other workpiece is held in a centering chuck that is mounted on

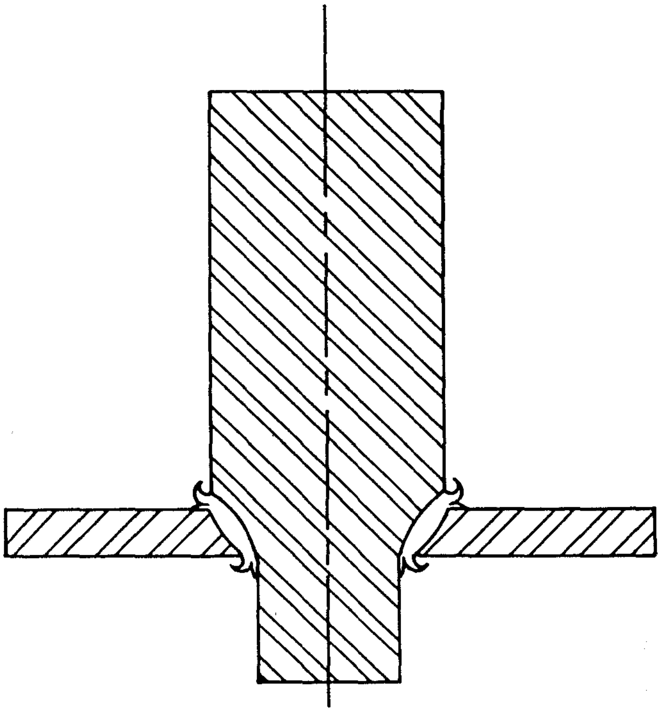


Figure 23.15–Typical Conical Weld Joint Design

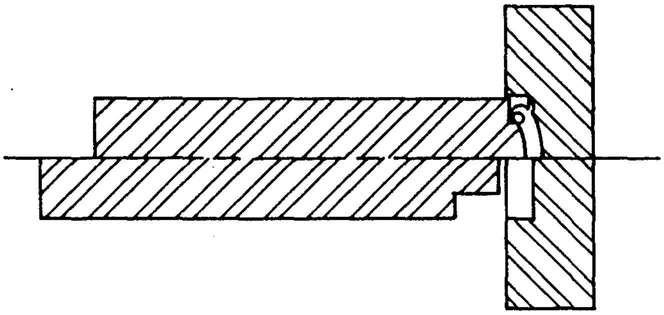


Figure 23.16A–Typical Flashtrap Joint Design Bar to Plate Weld

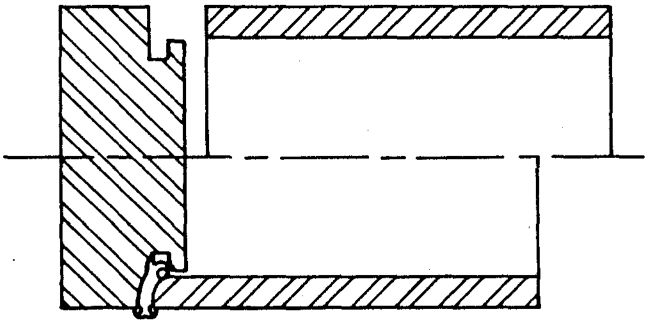


Figure 23.16B–Typical Flashtrap Joint Design

a rotatable spindle. The spindle is driven by a motor through a single- or variable-speed drive.

To make a weld, the rotating workpiece is thrust against the stationary workpiece to produce frictional heat at the contact surfaces as illustrated in Figure 23.17. The combination of speed and pressure raises the contact surfaces to a suitable temperature and deformation (upset) occurs. Rotation is then stopped and the pressure is maintained or increased to further upset the interface and complete the weld. A typical weld cycle is illustrated in Figure 23.3.

The machine spindle can be driven directly by a motor and allowed to stop under its natural deceleration characteristics and the retarding torque exerted by the weld. In

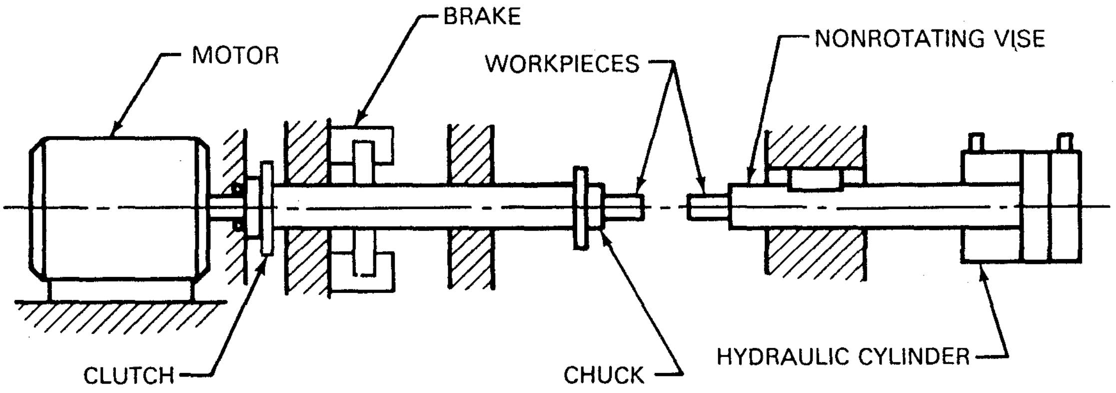


Figure 23.17–Basic Arrangement of a Direct Drive Welding Machine

practice, however, a clutch is normally used between the motor and spindle so that the motor can run continuously. The spindle can be engaged when required for the welding operation. This also conserves the starting energy that would be consumed if the motor is started for each weld.

A common practice is to include a fast-acting brake on the spindle. The function of the brake is to rapidly terminate rotation at the end of a specified heating time or after a preset axial shortening of the weldment. This feature provides good control of overall weldment length and broadens the acceptable range of welding variables for critical applications.

Two variables are used to control the friction heating phase. These are axial shortening and heating time. Under distance setting control, in axial shortening, the friction heating phase continues until a given part length is achieved. This is used to compensate for variations in preweld part length. The time setting control mode is intended to provide repeatable energy input. It is also possible to combine both options; a preweld distance can be set after which control changes to a time based mode (or vice versa).

For critical applications, where the workpieces would normally be of uniform length before welding, the time mode is preferred. In all cases, a minimum loss in length must occur between the components to ensure the removal of contaminants at the interface and a resulting sound weld.

There are a number of variables associated with this method:

(1) Rotation speed (rpm)
(2) Preheat pressure
(3) Preheat distance or time
(4) Friction pressure
(5) Friction distance or time
(6) Braking time (includes delay and rate)
(7) Forge Pressure
(8) Forge time (includes delay and rate)

This list is comprehensive, and not all machines or weld schedules will require every setting.

Inertia Welding Machines

WITH AN INERTIA welding machine, a flywheel is mounted on the spindle between the drive and the rotating chuck, as shown in Figure 23.18. The flywheel, spindle, chuck, and workpiece are accelerated to a selected speed corresponding to a specific energy level. When that speed is attained, driving is stopped and the flywheel and workpiece are allowed to spin freely. The two workpieces are then brought together and a specific axial thrust is applied. The kinetic energy of the flywheel is transferred to the weld interface and converted to heat. As a result, the flywheel speed decreases and finally comes to rest. Simultaneously, the tangential velocity is decreasing to zero with time in an essentially parabolic mode. Heating time is only a matter of seconds.

In the majority of applications, inertia friction welding uses a single axial thrust to produce heating and forging pressure. However, the machines are normally capable of applying more than one level of thrust. When forging pressure is used, it is triggered at a selected speed setting near the end of the cycle. A typical weld cycle is shown in Figure 23.3. This multiple force technique can also be used to provide a preheat effect before welding occurs, as with the direct drive method.

A distance setting control mode can also be achieved in inertia friction welding. Energy input is varied by adjusting

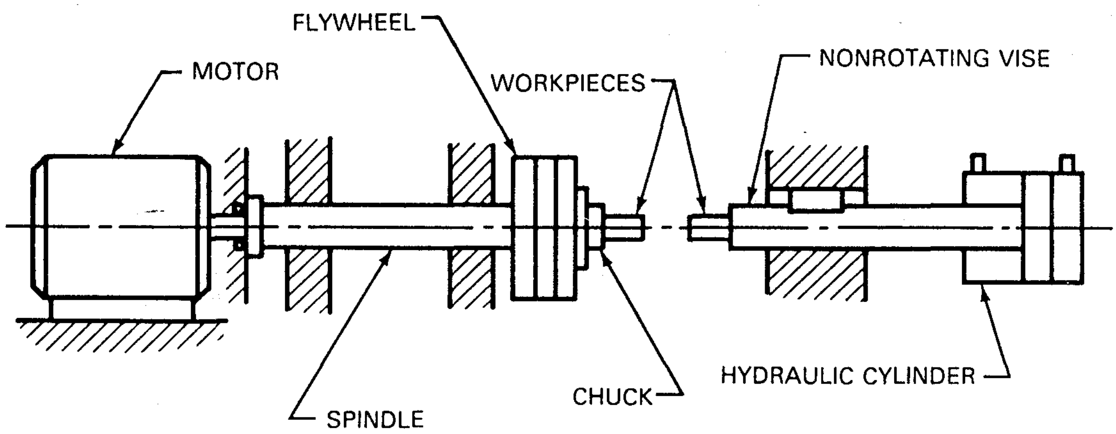


Figure 23.18–Basic Arrangement of an Inertia Welding Machine

RPM depending upon initial part lengths. An experimental correlation between energy and upset must be established before employing this mode.

The variables that control the weld quality are as follows:

(1) Total moment of inertia
(2) Weld speed (initial rpm)
(3) Weld pressure
(4) Upset speed (rpm at which upset pressure is applied)
(5) Upset pressure

Most welds are performed by varying weld speed and pressure only.

WELDING PROCEDURES

SURFACE PREPARATION AND FIT-UP

AS WITH ANY welding process, surface preparation can affect weld quality. Weld quality and consistency will be best when the faying surfaces are free of dirt, oxide or scale, grease, oil, or other foreign materials. In addition, the faying surfaces should mate together with very little gap.

In noncritical applications, some contamination and nonuniform contact of the faying surface may be tolerated. This is true if sufficient axial shortening is used to account for the gap and to extrude sufficient plasticized metal from the interface in order to carry away any contaminants. Sheared, flame cut, or sawed surfaces may be used with adequate axial shortening, provided the surfaces are essentially perpendicular to the axis of rotation. If the surfaces are not perpendicular, joint mismatch could result. For best practice, the squareness should be within 0.010 in./in. (0.01 mm/mm) of joint diameter.

Thick layers of mill scale should be removed from steel workpieces prior to welding to avoid unstable heating. A thin layer of rust may not be detrimental with adequate axial shortening.

Center projections left by cutoff tools are not harmful. However, pilot holes or concave surfaces should be avoided since they may entrap air or impurities at the interface.

For dissimilar metal welds between materials with large differences in hot-forging behavior, surface cleanliness of both workpieces is critical. Additionally, the squareness of the harder material is critical. Examples include steel to aluminum, steel to copper, and copper to aluminum.

TOOLING AND FIXTURES

ALL GRIPPING DEVICES used for holding the workpieces must be reliable. Slippage of a workpiece in relation to the chuck results either in a poor weld or in damage to the gripping device or the workpiece.

The gripping mechanism of the chucking devices must be rigid and resist the applied thrust. The extension of the workpiece from the device should be as short as practical to minimize deflection, eccentricity, and misalignment. Grip diameter must be as large or larger than the diameter of the weld interface, otherwise the workpiece may shear at the grips. Serrated gripping jaws are recommended for maximum clamping reliability.

There are two basic types of tooling: rotating and nonrotating. The machines in Figure 23.19 are equipped with both types. Each type, in turn, is either manual or power operated. As a rule, manually actuated tooling is used only for small quantity production.

Rotating tooling must be well balanced, have high strength, and provide good gripping power. Collet chucks meet these requirements and are most frequently used.

The most commonly used nonrotating gripping device is a vicelike fixture with a provision for absorbing the thrust. This device permits reasonable tolerance in the stationary workpiece diameter and yet maintains concentricity with the other piece in the collet chuck. More accurate devices may be used where concentricity is very critical.

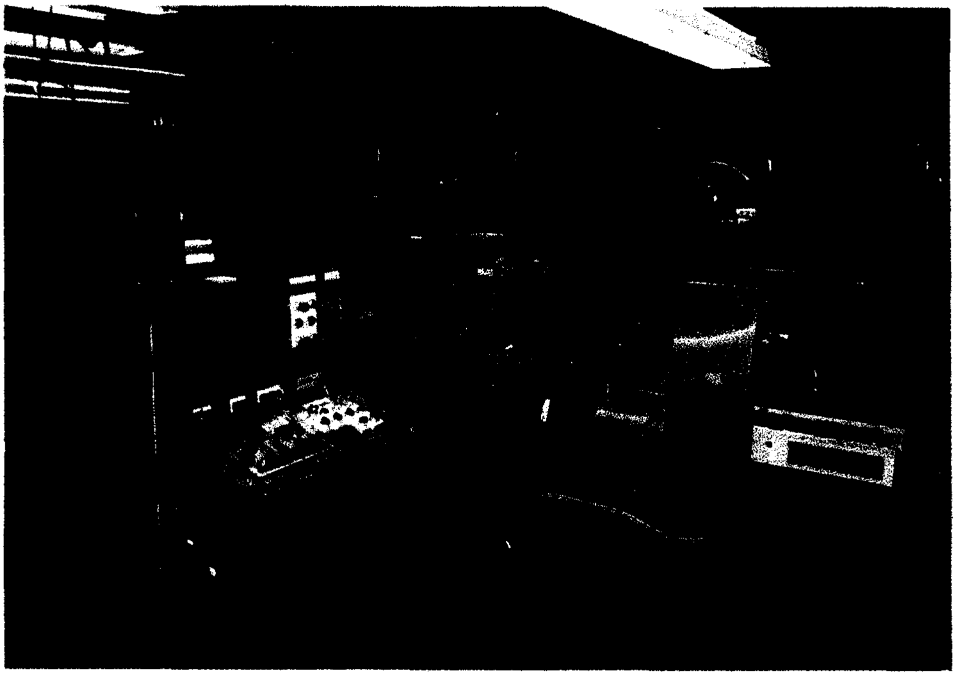
Mating of faying surfaces and concentricity of the workpieces depend upon the accuracy of manufacture, projecting length from the clamping fixture, and the rigidity of the tooling.

HEAT TREATMENT

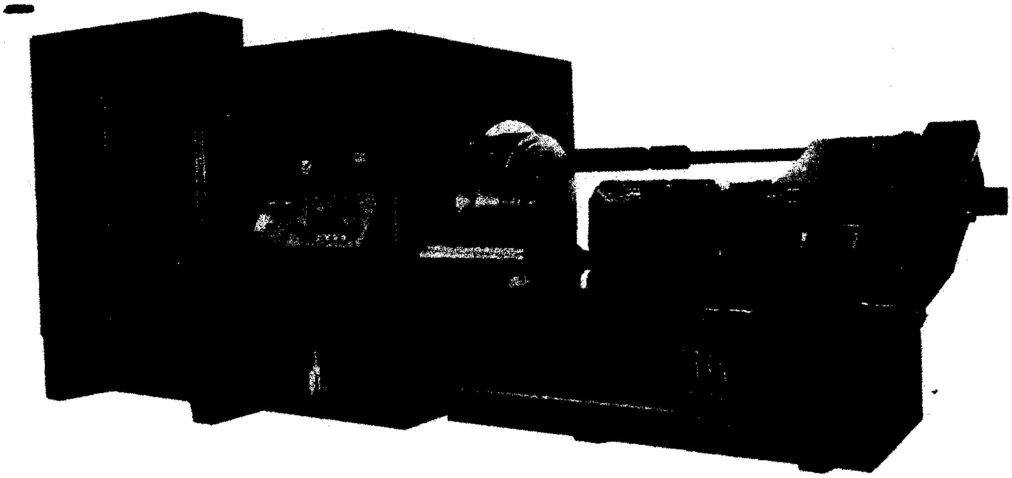
PRIOR HEAT TREATMENT of the workpieces generally has little effect on the ability to friction weld specific alloys. However, it may affect the mechanical properties of the heat-affected zone and the gripping of the workpieces.

Postweld heat treatment is often employed to produce the desired properties in the base metal, the welded joint, or both. A postweld anneal may be used to soften or stress relieve the joint. This heat treatment improves the ductility.

In the case of dissimilar metal welds, a postweld heat treatment should not contribute to the formation or expansion of an intermetallic layer at the interface which may lower joint ductility or strength. The postweld heat treatment should be evaluated for the application by destructive testing.



(A) DIRECT DRIVE MACHINE



(B) INERTIA DRIVE MACHINE

Figure 23.19–Typical Friction Welding Machines

WELD QUALITY

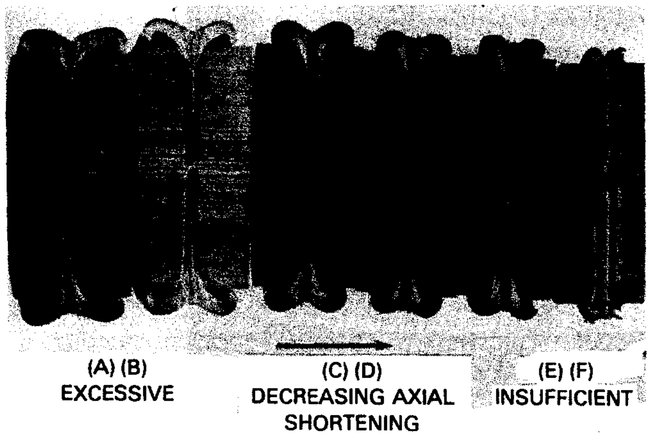
Weld quality is dependent upon the proper selection of material (type and quality) and welding variables. Good welds can be made between like metals with a wide range of speeds, pressures and times. Dissimilar material combinations are more critical with respect to welding parameters.

JOINT DISCONTINUITIES

DISCONTINUITIES CHARACTERISTIC OF fusion welds, such as gas porosity and slag inclusions, are not encountered in friction welding. However, other types of discontinuities may occur. These are associated with improper surface preparation, incorrect welding conditions, defective material or combinations of the above.

Discontinuities at the center of a weld may occur for various reasons, such as welding conditions not creating sufficient heating at the center for coalescence. Inertia welds made with the same speed and inertial mass but with a decreasing heating pressure (axial shortening) from left to right are shown in Figure 23.20. Two cross sections, shown in Figures 23.20(E) and (F), exhibit center defects due to insufficient pressure. Lack of center bonding may also occur in continuous drive friction welds when inadequate speed, heating time or heating pressure is used.

Concave faying surfaces that prevent uniform contact during the early stages of welding can limit center heating and entrap oxides. A weld with a discontinuity that resulted when a center hole for machining operations was not removed prior to welding is shown in Figure 23.21.



The center defects in (e) and (f) are indicated with arrows.

Figure 23.20–Effect of Axial Shortening on Bond Joint of Friction Welds

PROCESS MONITORING

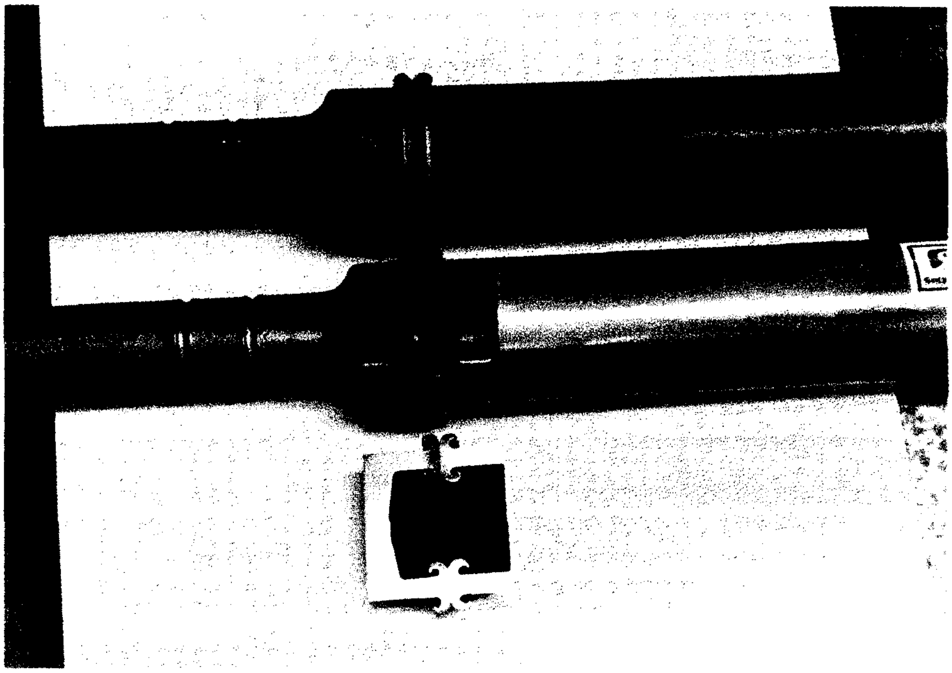
The advent of reliable computerized data acquisition and analysis systems has revolutionized process monitoring in friction welding. Microprocessor controlled welding machines are capable of maximizing both output and quality. Particularly useful is their ability to document each weld and manipulate data for statistical process control (SPC) purposes.

Factors which are documented include: friction and forge pressures, speed, upset and time. Other parameters such as torque and energy may also be monitored in specific cases.

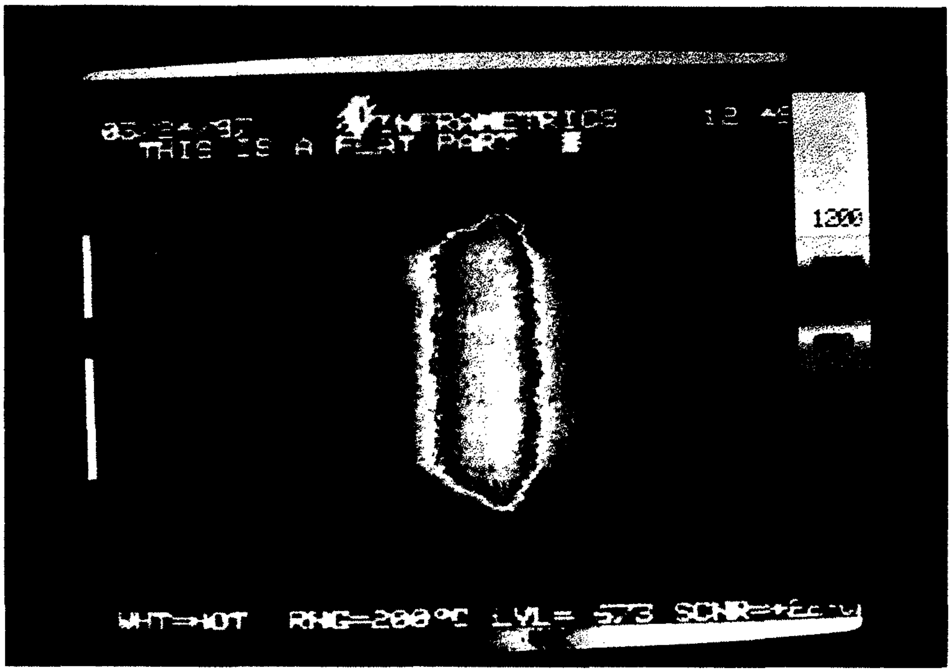
INSPECTION AND TESTING

INSPECTION AND TESTING are applied both to input materials and resulting weldments. Rather than relying upon destructive testing to guarantee quality, in-process monitoring and nondestructive inspection are increasingly being employed. Depending upon the quality level needed, this may range from simple visual inspection and mechanical tests to the latest advances in nondestructive techniques. A photograph of a friction welded automotive "halfshaft" is shown in Figure 23.22(A). Peak temperature is used as a process control, and the inframetric image of the weld is shown in Figure 23.22(B).

Figure 23.21–Discontinuity at the Center of a Friction Weld Caused by a Prior Center Hole



(A) AUTOMOTIVE "HALFSHAFT" FRICTION WELD JOINT



(B) INFRAMETRIC IMAGE

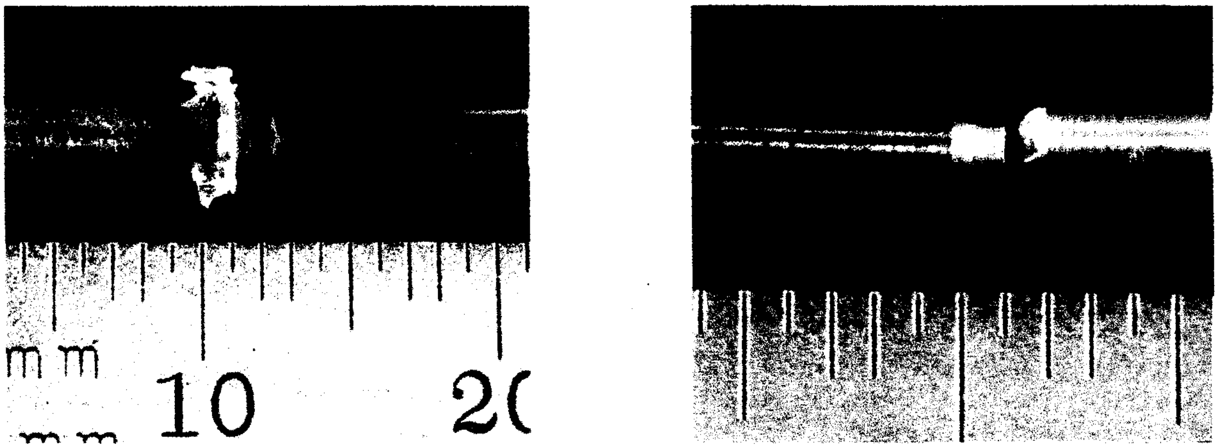
Figure 23.22–Inframetric Imagerty Used to Measure Peak Weld Temperature

APPLICATIONS

FRICTION WELDED PARTS in production applications span the aerospace, agricultural, automotive, defense, marine, and oil industries. Everything from tongholds on forging billets to critical aircraft engine components are friction welded in production.

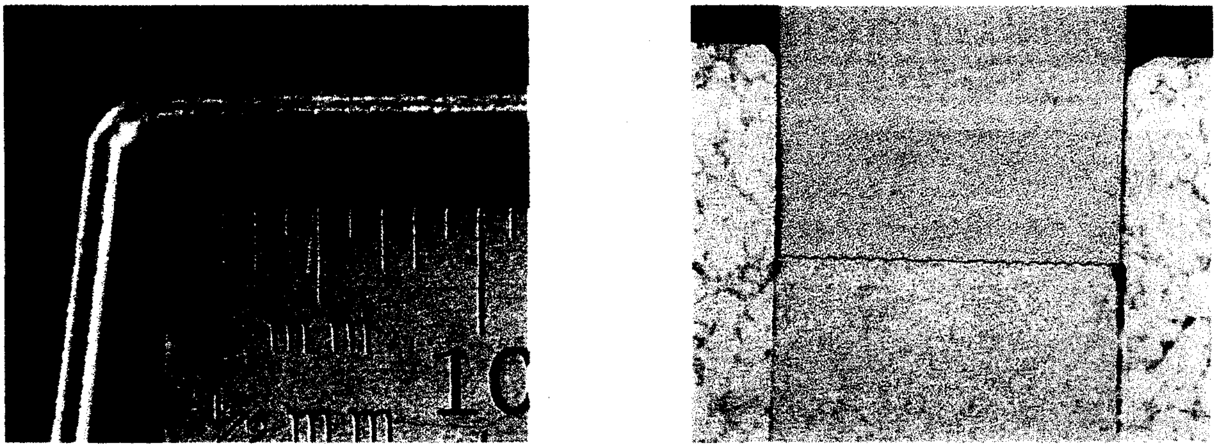
Automotive parts which are manufactured by friction welding include gears, engine valves, axle tubes, driveline components, strut rods and shock absorbers. Hydraulic piston rods, track rollers, gears, bushings, axles and similar parts are commonly friction welded by the manufacturers of agricultural equipment. Friction welded aluminum/copper joints are in wide usage in the electrical industry. Stainless steels are friction welded to carbon steel in various sizes for use in marine drive systems and water pumps for home and industrial use. Friction welded assemblies are often used to replace expensive castings and forgings.

Some typical applications, including automotive, aircraft and medical, are shown in Figures 23.23 through 23.28.



(A) AS-WELDED—NOTE FLASH ON 4043 ONLY

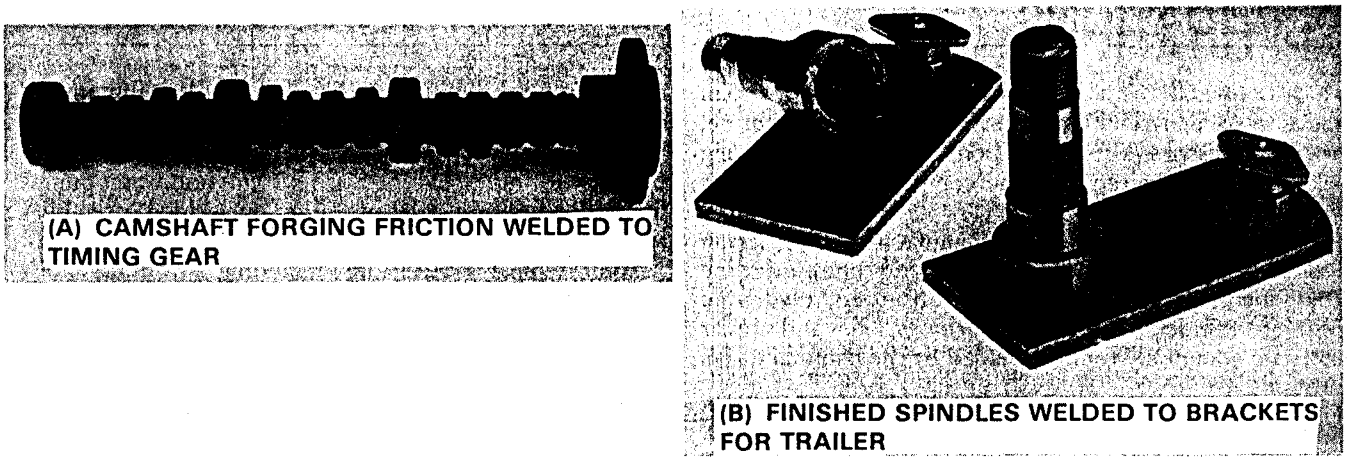
(C) REDUCED SECTION TENSILE TEST SHOWING FAILURE AWAY FROM THE INERTIA WELD



(B) REDUCED SECTION BEND TEST

(D) METALLOGRAPHIC SECTION SHOWING FRICTION WELD INTERFACE

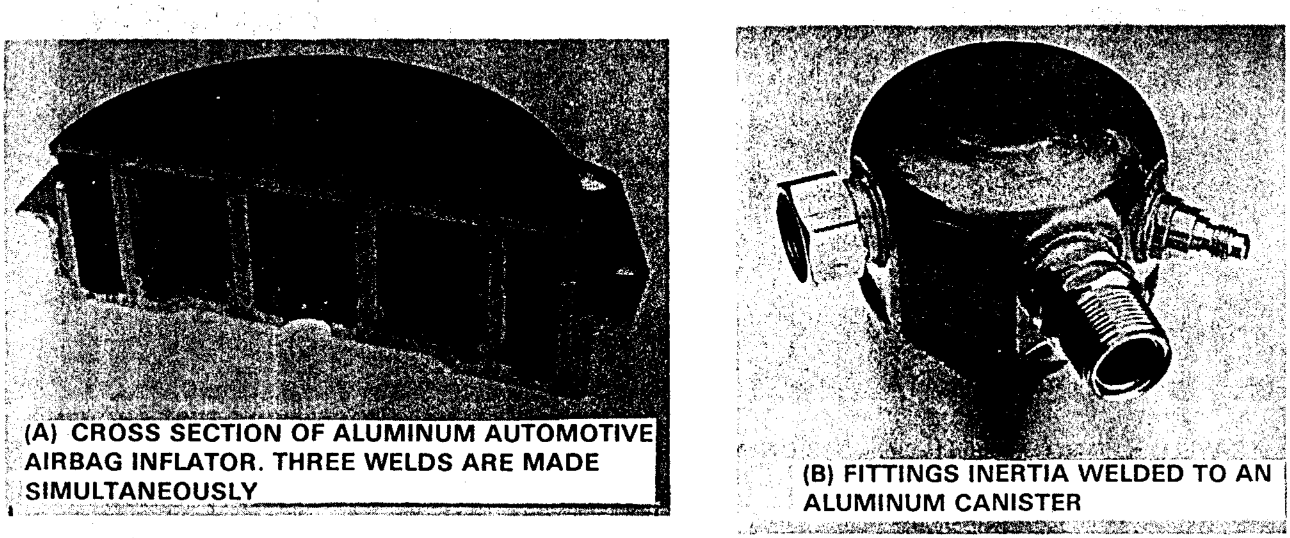
Figure 23.23–An Inertia Welded Transition Joint Between OFHC Copper and 4043 Aluminum to Facilitate Simultaneous Solderability and Weldability of a Ground Pin



(A) CAMSHAFT FORGING FRICTION WELDED TO TIMING GEAR

(B) FINISHED SPINDLES WELDED TO BRACKETS FOR TRAILER

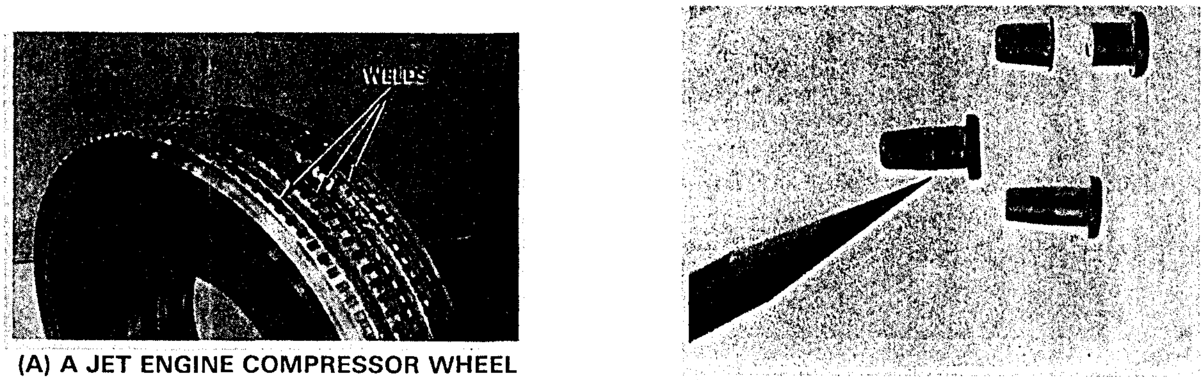
Figure 23.24–Typical Steel Automotive Applications



(A) CROSS SECTION OF ALUMINUM AUTOMOTIVE AIRBAG INFLATOR. THREE WELDS ARE MADE SIMULTANEOUSLY

(B) FITTINGS INERTIA WELDED TO AN ALUMINUM CANISTER

Figure 23.25–Two Typical Aluminum Automotive Applications



(A) A JET ENGINE COMPRESSOR WHEEL FABRICATED BY FRICTION WELDING

(B) TITANIUM-TO-TITANIUM ALLOY AIRCRAFT RIVETS

Figure 23.26–Typical Aircraft Applications

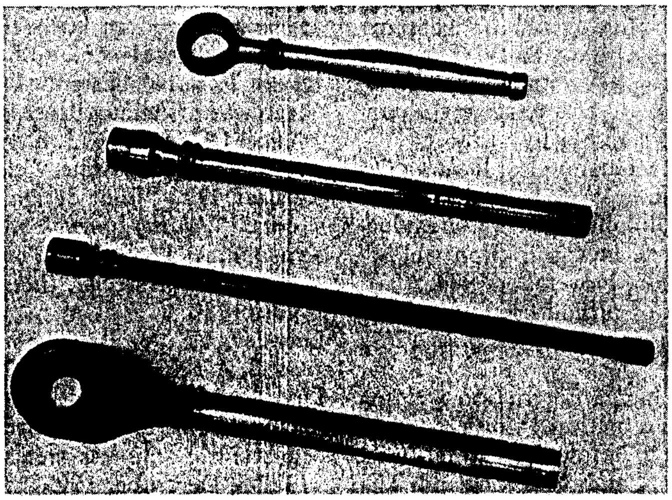
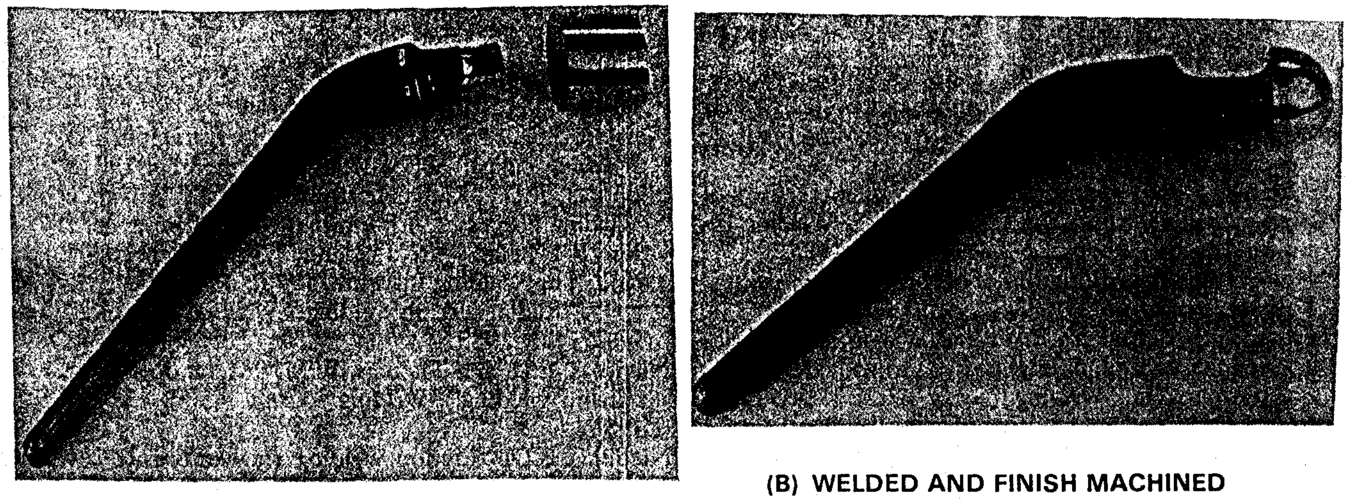


Figure 23.27–Hand Tools Inertia Welded From Forgings



(B) WELDED AND FINISH MACHINED

(A) RAW STOCK

Figure 23.28–Cobalt Alloy Hip Replacement Prothesis

SAFETY

FRICTION WELDING MACHINES are similar to machine tool lathes in that one workpiece is rotated by a drive system. They are also similar to hydraulic presses in that one workpiece is forced against the other with high loads. Safe practices for lathes and power presses should be used as guides for the design and operation of friction welding machines. Typical hazards include high noise levels, high rotational speeds, and flying particles.

Machines should be equipped with appropriate mechanical guards and shields as well as two-hand operating switches and electrical interlocks. These devices should be designed to prevent operation of the machine when the work area, rotating drive, or force system is accessible to the operator or other personnel.

Operating personnel should wear appropriate eye and ear protection and safety apparel commonly used with machine tool operations. Ear protection should be provided to guard against high noise levels produced during friction welding. In any case, applicable OSHA standards should be strictly observed.

The machine manufacturers literature should be studied for complete safety precautions.

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CHAPTER 24

EXPLOSION WELDING

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CHAPTER 24

EXPLOSION WELDING

FUNDAMENTALS OF THE PROCESS

DEFINITION AND GENERAL DESCRIPTION

EXPLOSION WELDING IS a solid-state welding process that produces a weld by high velocity impact of the workpieces as the result of controlled detonation. The explosion accelerates the metal to a speed at which a metallic bond will form between them when they collide. The weld is produced in a fraction of a second without the addition of filler metal. This is essentially a room temperature process in that gross heating of the workpieces does not occur. The faying surfaces, however, are heated to some extent by the energy of the collision, and welding is accomplished through plastic flow of the metal on those surfaces.

Welding takes place progressively as the explosion and the forces it creates advance from one end of the joint to the other. Deformation of the weldment varies with the type of joint. There may be no noticeable deformation in some weldments, and there is no measureable loss of metal. Welding is usually done in air, although it can be done in other atmospheres or in a vacuum where circumstances dictate. Most explosion welding is done on sections with relatively large surface areas, although there are applications for sections with small surface areas as well.

PRINCIPLES OF OPERATION

A TYPICAL ARRANGEMENT of the components for explosion welding is shown in Figure 24.1. Fundamentally, there are three components:

(1) Base metal
(2) Prime or cladding metal
(3) Explosive

The base component remains stationary as the prime component is welded to it. The base component may be supported by a backer or an anvil, particularly when it is relatively thin. The base component by itself or in combination with the backer should have sufficient mass to minimize distortion during the explosion welding operation.

The prime component usually is positioned parallel to the base component; however, for special applications it may be at some small angle with the base component. In the parallel arrangement, the two are separated by a specified spacing, referred to as the *standoff distance*. In the angular arrangement, a standoff distance may or may not be used at the apex of the angle. The explosion locally bends and accelerates the prime component across the standoff distance at a high velocity so that it collides at an angle with and welds to the base component. This angular collision and welding front progresses across the joint as the explosion takes place.

The explosive, almost always in granular form, is distributed uniformly over the top surface of the prime component. The force which the explosion exerts on the prime component depends upon the detonation characteristics and the quantity of the explosive.

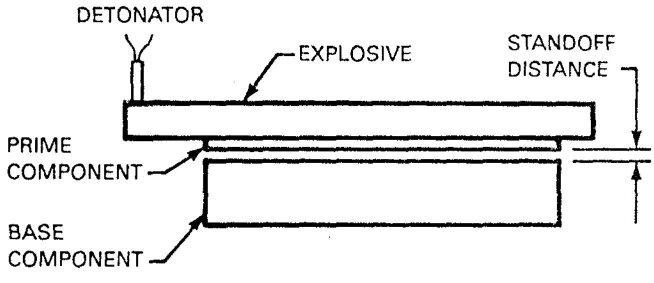

Figure 24.1–Typical Component Arrangement for Explosion Welding

A buffer layer such as neoprene material may be required between the explosive and the prime component to protect the surface of that component from erosion by the detonating explosive.

Explosive Detonation

THE ACTION THAT occurs during explosion welding is illustrated in Figure 24.2. The manner in which the explosive is detonated is extremely important. Detonation must take place progressively across the surface of the prime component. The speed of the detonation front establishes the velocity at which the collision progresses over the joint area. This is known as the *collision velocity* and is one of the important variables of the process. The selection of an explosive that will produce the required detonation velocity is of utmost importance in consistently obtaining good welds. Moreover, the explosive must provide uniform detonation so the collision velocity will be uniform from the start to the finish of the weld.

Prime Component Velocity and Angle

AS THE DETONATION front moves across the surface of the prime component, both the intense pressure in the front and the pressure generated by the expanding gases immediately behind the front accelerate the prime component to a certain angle and velocity. This angle and velocity depend upon the type and amount of explosive, the thickness and mechanical properties of the prime component, and the standoff distance employed.

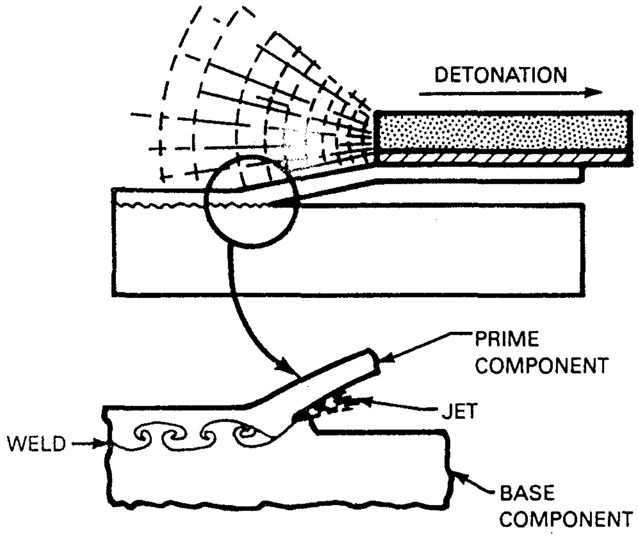

Figure 24.2–Action Between Components During Explosion Welding

Collision, Jetting, and Welding

THE FOLLOWING ARE important interrelated variables of the explosion welding process:

(1) Collision velocity
(2) Collision angle
(3) Prime component velocity

The intense pressure necessary to make a weld is generated at the collision point when any two of these variables are within certain well defined limits. These limits are determined by the properties of the particular metals to be joined. Pressure forces the surfaces of the two components into intimate contact and causes localized plastic flow in the immediate area of the collision point. At the same time, a jet is formed at the collision point, as shown in Figure 24.2. The jet sweeps away the original surface layer on each component, along with any contaminating film that might be present. This exposes clean underlying metal which is required to make a strong metallurgical bond. Residual pressures within the system are maintained long enough after collision to avoid release of the intimate contact of the metal components and to complete the weld.

NATURE OF THE BOND

THE INTERFACE BETWEEN the two components of an explosion weld is almost always wavy on a microscale, the wave size being dependant on the collision conditions employed in making the weld. A typical wavy explosion weld interface is shown in Figure 24.3. Most welds with a wavy

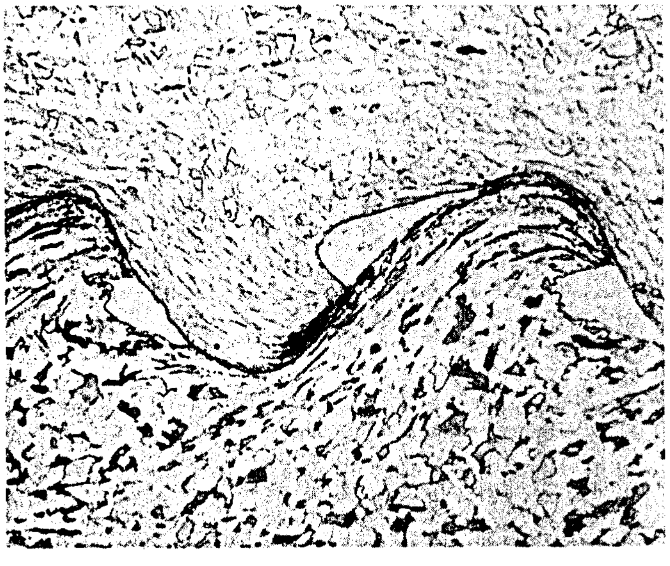

Figure 24.3–Typical Wavy Interface Formed Between Two Explosion Welded Components (Stainless Steel to Mild Steel)

interface contain small pockets of jet material which normally are located on the front and back slopes of the waves. This material is composed of some combination of the two parent metals, and partial or complete melting of the material generally occurs. The pockets will be ductile when the metal combinations can form solid solutions, but they may be brittle or may show discontinuities in those combinations that form intermetallic compounds. Pockets of the latter material may not be detrimental, if they are very small. Good welding practices will produce small pockets.

Large pockets, on the other hand, occur with excessive collision conditions (prime component velocity, collision velocity, and collision angle) or may even produce a continuous melted layer. The large pockets and the continuous melted layer often contain a substantial number of shrinkage voids and other discontinuities that reduce strength and ductility. They are usually detrimental to the soundness and serviceability of the weld. For this reason, welding practices that produce an excessively large wave size or a continuous melted layer must be avoided.

On certain occasions, a flat weld interface can be formed when the collision velocity is below some critical value for the particular combination of metals being welded. Welds of this type usually possess satisfactory mechanical properties but as a rule are not sought in practice. Small variations in the collision conditions which produce a flat weld interface can result in lack of bonding.

EXPLOSIVE MATERIAL PROPERTIES

EXPLOSIVES USED FOR the explosion welding process are almost always granular, and their composition is usually based around ammonium nitrate as the primary ingredient. This allows them to detonate in the velocity range of 6500 to 9800 ft/s (2000 to 3000 m/s) which is normally required to produce the collision point conditions necessary for optimal welding conditions. In general, the detonation velocity of an explosive will depend upon its composition, thickness, and packing or loading density.

PARALLEL AND PRESET ANGLE STANDOFFS

TWO TYPES OF standoffs can be employed for explosion welding: parallel or preset angle. The use of the preset angle approach is normally restricted to small areas or short length welds such as tube-to-tubesheet welding, lap welding between sheet or tube components, or other specialized small area welds. The parallel or constant standoff is used for all larger area welding which constitutes the majority of the explosion welding applications. For other than flat plate cladding operations, the standoff distance geometry and amount of explosive must be allowed for in the design of the prewelding components.

STANDOFF DISTANCE

THE STANDOFF DISTANCE employed in the explosion welding setup will have some influence on the interfacial wave size. Increasing the standoff distance increases the collision angle between the prime and base components (see Figure 24.2) up to the limiting dynamic bend angle to which the particular explosive loading being used is capable of accelerating the cladding component. The interfacial wave size correspondingly increases with the increasing angle of collision.

In general terms, the standoff distance in a parallel welding setup will normally be between one half and one times the thickness of the cladding component being accelerated by the explosive. In an angular arrangement, the preset angle will typically range between one and eight degrees.

JOINT QUALITY

THE QUALITY OF an explosion weld will depend upon the nature of the interface and the effect the process has on the properties of the metal components. The properties of the metal include strength, toughness, and ductility. The effect of welding on these properties can be determined by comparing the results of tension, impact, bending, and fatigue tests of welded and unwelded materials. Standard ASTM testing procedures may be used.

The quality of the bond can be determined by destructive and nondestructive tests. Since the size of test samples is limited by the thickness of the components and the weld is planar and in essence has no thickness, special destructive tests are used for evaluation of the bond. The tests should reflect the conditions the weld will have to endure in service.

NONDESTRUCTIVE INSPECTION

DUE TO THE nature of explosion welds, nondestructive inspection is restricted almost totally to the ultrasonic method. Radiographic inspection is only applicable to welds between metals with significant differences in density and an interface with a large wavy pattern.

Ultrasonic Inspection

ULTRASONIC INSPECTION IS the most widely used nondestructive method for the examination of explosion welds. It will not determine the strength of the weld, but it will indicate weld soundness. Pulse-echo techniques are normally used for clad steels in pressure vessels.[1] An ultrasonic frequency in the range of 2.5 to 10 MHz usually is adequate. Allowance needs to be made for the differences in acoustical impedance of various metals.

The ultrasonic instrument should be calibrated on standard samples containing both bonded and known unbonded areas which will provide a display signal amplitude of 50 to 75 percent of full screen height for the bonded area. Unbonded areas reflect the signal before it can complete the circuit. This shows up in the height of the signal at the appropriate location on the display scope. C-Scan recordings can be made to give a permanent record of the results of the examination.

For large clad plates where scanning 100 percent of the surface area is not necessary, the examination can be carried out on a rectangular grid pattern laid out on the plate. Unbonded areas which are detected should be investigated to determine whether they are small enough to be acceptable or are so large or so numerous that they are unacceptable. The size and number of unbonded areas that can be permitted in a clad plate depend upon the intended service for the plate. Clad plates for heat exchangers sometimes require over 98 percent bond, and limits are placed on the size and number of unbonded areas that are permitted.

Radiographic Inspection

RADIOGRAPHY CAN BE used to inspect explosion welds in metals that have significantly different densities and a wave size sufficiently large to be resolvable on a radiograph. Radiographs are marked to identify the plate and the precise location of the area they represent. The radiographs are taken perpendicular to the surface from the side with the high density metal. The film must be in intimate contact with the surface on the low density side. Radiographs can delineate a wavy interface as uniformly spaced light and dark lines. The number of waves per unit length is then counted and the weld quality correlated through previous destructive testing to the wave size. Further, those areas in which no wave patterns are delineated would indicate either a flat weld interface or no weld at all.

DESTRUCTIVE TESTING

DESTRUCTIVE TESTING IS used to determine the strength of the weld and the effect of the process on the properties of the base metals. Standard testing techniques can be used, but specially designed tests sometimes are required to determine bond strength for some configurations.

Clad Plates

THE REQUIREMENTS FOR carbon steel plates clad with copper, stainless steel, or nickel alloys are covered in appropriate ANSI/ASTM standards.[2] These Standards primarily use simple bend and shear tests to determine the strength of the composite.

Chisel Test

THE CHISEL TEST is widely used to determine the integrity of the bond in an explosion weld. The test is performed by driving a chisel into and along the interface. The ability of the interface to resist separation by the force of the chisel provides an excellent qualitative measure of the bond strength. If the weld is not good, failure will occur along the interface in advance of the chisel point. If the weld is good, either the chisel will cut through the weaker of the two parent metals or fracture will occur in one of the two parent metals away from the weld interface.

Tension-Shear Test

THIS TEST IS designed to determine the shear strength of the weld. The specimen configuration is shown in Figure 24.4. Equal thicknesses of the two components are preferred. The length of the shear zone, "d", should be selected so that little or no bending will occur in either component. Failure should occur by shear, parallel to the weld line. If failure occurs through one of the base metals, the shear strength of the weld is obviously greater than the strength of the base metal. In any event, the results are useful for comparison purposes only, using a common test specimen.

Tension Test

A SPECIAL "RAM" or ring rupture tension test can be used for evaluation of the tensile strength of explosion welds. As shown in Figure 24.5, the specimen is designed to subject the weld interface to a tensile load. The cross-sectional area of the specimen is the annulus between the outside and inside diameters. The typical specimen has a short gage length which is intended to cause failure at or immediately adjacent to the weld interface. If failure occurs in one of

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[1] See ANSI/ASTM A578, *Standard Specification for Straight Beam Ultrasonic Inspection of Plain and Clad Steel Plates for Special Applications* (latest edition).

[2] See ANSI/ASTM standard specifications A263, A264, A265 and B432 (latest editions).

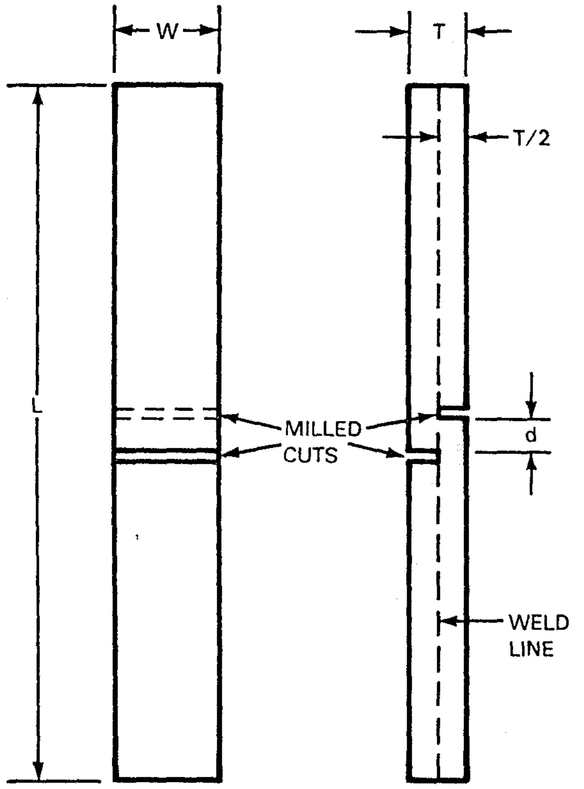

Figure 24.4–Tensile Shear Test Sample Configuration

the base metals, the test shows that the weld is stronger than the base metal.

The test is conducted by placing the specimen on the base block with the ram in the hole. A compressive load is then applied through the ram and base. Load at failure is recorded.

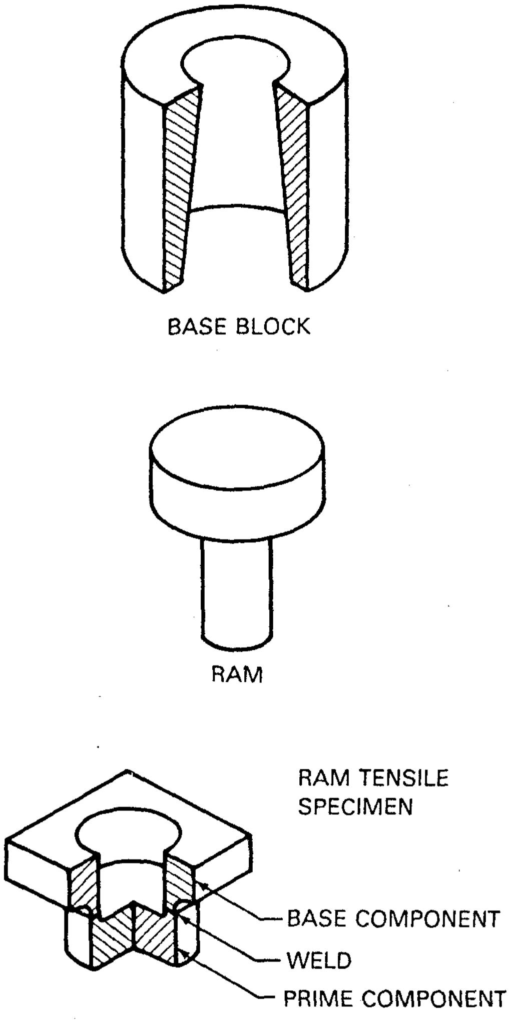

Figure 24.5–Typical RAM or Ring Rupture Test Sample Configuration

Metallographic Examination

METALLOGRAPHY CAN PROVIDE useful information about the quality of explosion welds. The section for metallographic examination should be taken so that the interface can be examined on a plane parallel to the direction of detonation and normal to the surfaces of the welded components. A well-formed, well-defined wave pattern is generally indicative of a good weld. Depending on the combination of materials being evaluated, the amplitude and frequency of the wave can vary somewhat without significant influence on the strength of the weld. Small, isolated pockets of melt resulting from the vortices of the jet are usually not detrimental to the weld quality. Large melt pockets containing voids or even microcracks in the swirls indicate that the collision angle and energy were too high and the weld is poor.

Excessive collision conditions with metals such as titanium, high strength nickel alloys, and martensitic steels can produce strain bands emanating from the interface wave slopes as a result of localized shear. Proper welding conditions must be employed to minimize the occurrence of these bands and their potential detrimental affect on the performance of the clad product.

Samples for metallographic examination should be taken from an area that is representative of the entire weld. Edge effects may result in areas of less than optimum weld quality along the edges of a weld. Samples taken from such locations would not be representative of the rest of the weld.

WELDING PROCEDURES

TYPES OF JOINTS

EXPLOSION WELDING IS limited to joints that overlap or have faying surfaces. In the case of cladding, the surfaces of both components have the same geometry, and one component overlays the other. In transition joints in pipe or tubing and tube-to-tube sheet joints, an overlapping joint configuration is usually used. The overlap and weld in such joints should be long enough to insure that it will not fail in service by shear along the interface.

SURFACE PREPARATION

THE SURFACES TO be joined should be clean and free of gross imperfections to produce welds of consistent soundness, strength, and ductility. The smoothness required depends upon the metals to be joined. In general, a surface finish of 150 microinches or better is required to obtain high quality welds.

FIXTURING AND BACKUP

FOR CONSISTENT QUALITY, the welding conditions should be uniform over the entire area to be joined. These include stand off distance with parallel components or initial angle with inclined components and sufficient rigidity or support for the base component. For cladding with a relatively thick prime component, spacers or supports for providing the required standoff distance are usually placed around the outer edges of the cladding plate where edges effects will normally be removed. Where the prime or cladding component is so thin that deflection due to its own weight combined with the weight of the explosive on top of it will cause a problem in maintaining the necessary standoff distance, additional gapping support may be required in the central areas. Typically, light weight materials such as small foam or balsa wood blocks are strategically placed under the middle areas of the cladding plate. They are normally consumed in the welding process and have minimal effect on the resulting weld.

During the cladding of plates with thicker base or backer components, the base is typically placed directly on packed sand or earth. If the base component is relatively thin or subject to more extensive deformation during the explosion welding process, it should be supported uniformly on a more rigid, massive anvil to minimize deflection. When cladding pipe or tubing, an internal or external mandrel normally is required to back up the base component.

CAPABILITIES AND LIMITATIONS

ONE ATTRIBUTE OF the explosion welding process is its ability to join a wide variety of similar and dissimilar metals. The dissimilar metal combinations range from those that are commonly joined by other welding processes, such as carbon steel to stainless steel, to those that are metallurgically incompatible for fusion welding or diffusion bonding processes, such as aluminum or titanium to steel.

The process can be used to join components of a wide range of sizes. Surface areas ranging from less than 1 in.^{2} (6.5 cm^2) to over 400 ft^2 (37m^2) can be welded. Since the base component is stationary during welding, there is no upper limit on its thickness. The thickness of the prime component may range from 0.001 to 1.25 in. (0.25 to 31.8 mm) or more depending on the material.

Geometric configurations that can be explosion welded are those which allow a uniform progression of the detonation front and, hence, the collision front. These include flat plates as well as cylindrical and conical structures. Welds may also be made in certain complex configurations, but such work requires thorough understanding and precise control of the process.

APPLICATIONS

METALS WELDED

AS A GENERAL rule, any metal can be explosion welded if it possesses sufficient strength and ductility to withstand the deformation required at the high velocities associated with the process. Metals that will crack when exposed to the shock associated with detonation of the explosive and the collision of the two components cannot be explosion welded. Metals with elongations of at least five to six percent [in a 2 in. (51 mm) gage length] and Charpy V-notch impact strengths of 10 ft-lb (13.6J) or better can be welded by this process. In special cases, metals with low ductility can be welded by preheating them to a slightly elevated temperature at which point they will have adequate impact resistance; however, the use of explosives in conjunction with elevated temperature components requires special safety considerations. The commercially significant metals and alloys that can be joined by explosion welding are given in Figure 24.6.

	ZIRCONIUM	MAGNESIUM	COBALT ALLOYS	PLATINUM	GOLD	SILVER	COLUMBIUM	TANTALUM	TITANIUM	NICKEL ALLOYS	COPPER ALLOYS	ALUMINUM ALLOYS	STAINLESS STEELS	ALLOY STEELS	CARBON STEELS
CARBON STEELS	●	●			●	●	●	●	●	●	●	●	●	●	●
ALLOY STEELS	●	●	●					●	●	●	●	●	●	●	
STAINLESS STEELS			●		●	●	●	●	●	●	●	●	●		
ALUMINUM ALLOYS		●				●	●	●	●	●	●	●			
COPPER ALLOYS					●	●	●	●	●	●	●				
NICKEL ALLOYS		●		●	●			●	●	●					
TITANIUM	●	●				●	●	●	●						
TANTALUM					●		●	●							
COLUMBIUM				●			●								
SILVER						●									
GOLD															
PLATINUM				●											
COBALT ALLOYS															
MAGNESIUM		●													
ZIRCONIUM	●														

Figure 24.6–Commercially Significant Metals and Alloys that can be Joined by Explosion Welding

While explosion welding does not produce changes in the bulk properties, it can produce some noteable changes in the mechanical properties and hardness of metals, particularly in the immediate area of the weld interface as indicated in Figure 24.7. In general, the severe localized plastic flow along the interface during welding increases the hardness and strength of the material in this region. Accordingly, the ductility decreases. Such effects may be erased by a postweld heat treatment as shown in Figure 24.7. However, the particular heat treatment applied should be one that will not reduce the ductility of the weld by unfavorable diffusion or the formation of brittle intermetallic compounds at the interface.

CLADDING

Plate

THE CLADDING OF flat plate constitutes the major commercial application of explosion welding. A typical clad plate is shown in Figure 24.8. It is customary to supply explosion clad plate in the as-welded condition because the hardening which occurs immediately adjacent to the interface usually does not significantly affect the bulk engineering properties of the plate. Despite this, some service requirements may demand postweld heat treatment. Clad plates usually are distorted somewhat during explosion welding and must be straightened to meet standard flatness specifications (Figure 24.9). Straightening is usually done with a press or a roller leveler.

Pressure vessel heads and other components can be made from explosion clad plates by conventional hot or cold forming techniques (see Figures 24.10, 24.11, and 24.12). Hot forming must take into account the metallurgical properties of the materials and the possibility that undesirable diffusion may occur at the interface. Compatible alloy combinations, such as stainless and carbon steel, may be formed by methods traditionally used for clad materials. Incompatible combinations such as titanium and steel, on the other hand, may require special procedures to limit the formation of undesirable intermetallic compounds at the interface. Titanium clad steel, for instance, should be hot formed at temperatures no higher than 1400°F (760°C) to prevent the formation of undesirable intermetallics which could lead to brittle failure of the bond.

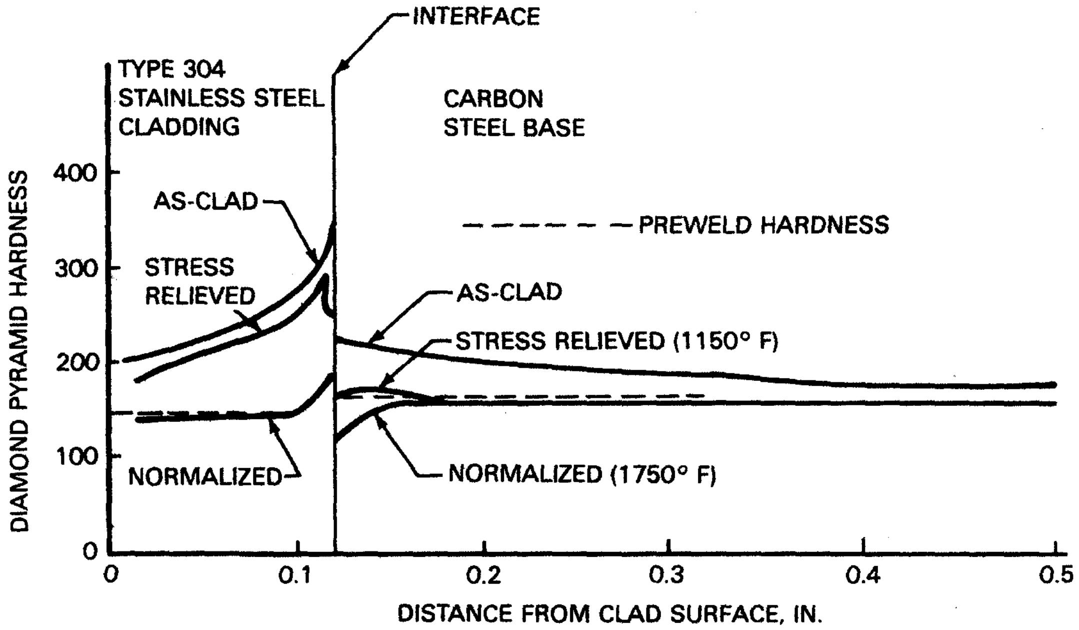

Figure 24.7–Hardness Profile Across Stainless Steel to Carbon Steel Clad Plate, As-Welded and After Heat Treatment

Figure 24.8–As-Explosion Clad Flat Plate Consisting of 13/16-Inch 304L Stainless Steel Clad on 8-Inch-Thick SA 516-70 Steel (DuPont photograph)

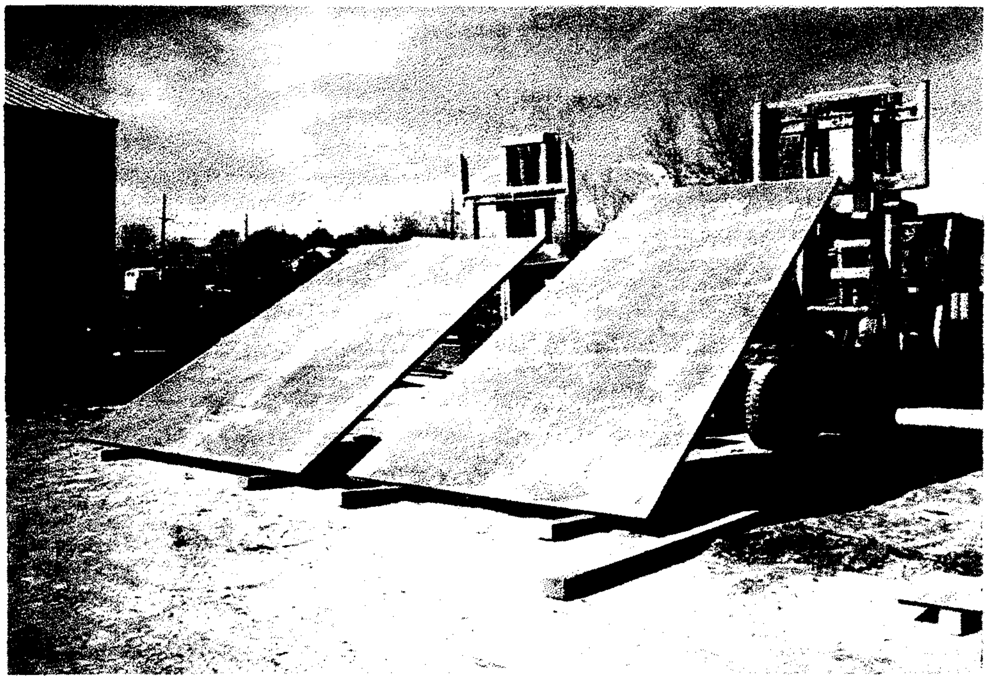

Figure 24.9–Explosion Clad Titanium (1/4-Inch) Steel (1-3/4-Inch) Tube Sheet Blanks Following Post Welding Flattening (Explosive Fabricators, Inc. photograph)

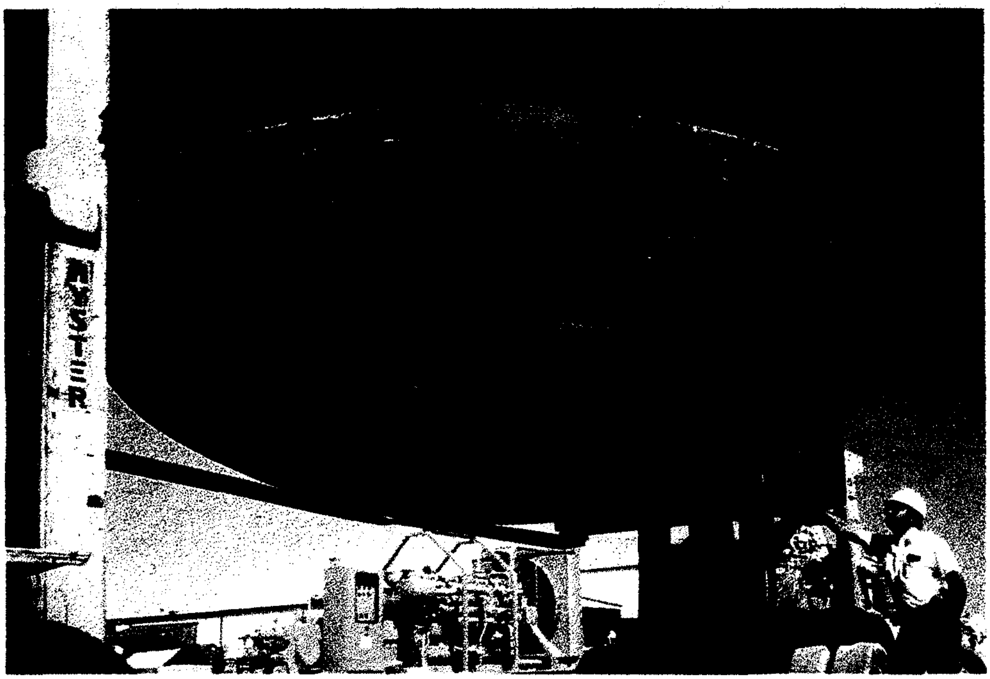

Figure 24.10–180 Inch Diameter Dome of 3/16 Inch Type 410 Stainless Steel on 3 Inch Thick A387 Steel Formed From Explosion Clad Plate (Explosive Fabricators, Inc. photograph)

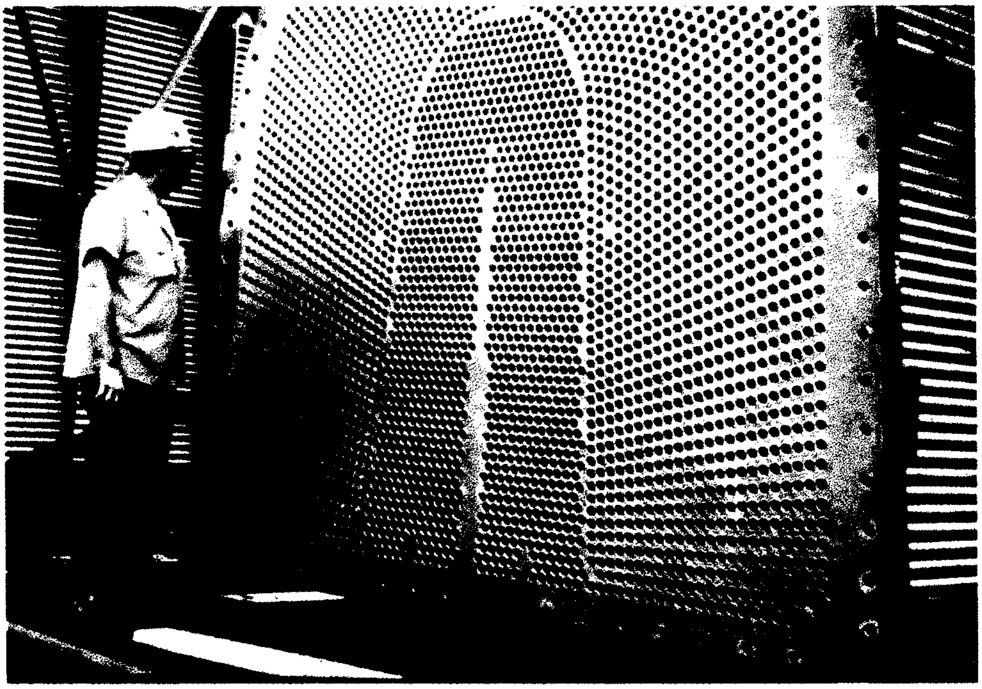

Figure 24.11–Titanium (1/4-Inch) Clad Steel (1 1/4-Inch) Condenser Sheet (Explosive Fabricators, Inc. photograph)

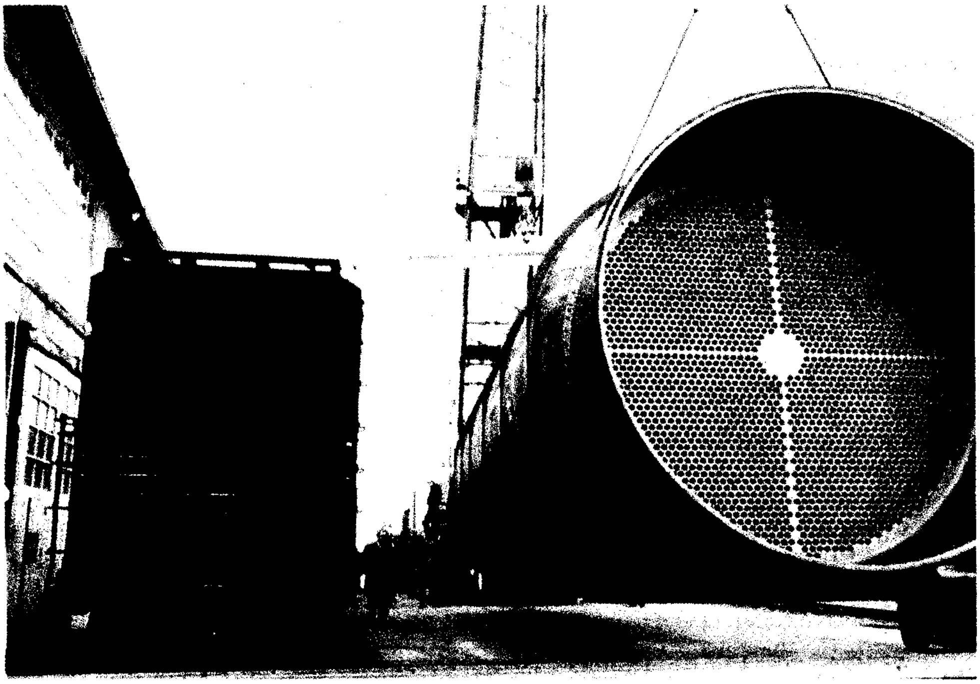

Figure 24.12–Finished Vessel Fabricated From Explosion Clad Plate (Explosive Fabricators, Inc. photograph)

Reducing the thickness of clad plate by rolling (termed *conversion rolling*) provides a convenient and economical means of producing bimetal sheets of proper thickness for subsequent processing.

Cylinders

EXPLOSION WELDING CAN be used to clad cylinders on their inside or outside surfaces. One application of this is the internal cladding of steel forgings with stainless steel to make nozzles for connection to heavy-walled pressure vessels. Clad nozzles with inside diameters of 1/2 to 24 in. (13 to 610 mm) and lengths up to 3 ft (900 mm) have been made. A typical internally clad cylinder is shown in Figure 24.13.

Transition Joints

FUSION WELDED JOINTS between two incompatible metals are difficult or impossible to make. Some of those that can be made exhibit low strength and ductility. Transition joints produced by explosion welding may provide a solution to that problem. Many such joints can be cut from a single large clad plate. Conventional fusion welding practices may then be used to attach the members of the transition joint to their respective similar metal components. Care must be taken, however, to limit the installation temperature and subsequently the service temperature at the weld interface to a level suitable for the materials combination in the joint.

Electrical

ALUMINUM, COPPER, AND steel are the metals most commonly used in electrical systems. Joints between them frequently are necessary to take advantage of the special properties of each. Such joints must be sound if they are to conduct high amperages efficiently, minimize power losses, and avoid overheating of the member in service. Transition joints cut from thick explosion welded plates of aluminum and copper or aluminum and steel provide efficient conductors of electricity. This concept is routinely used in the fabrication of anodes for the primary aluminum industry.

Temperature limits for transition joints between aluminum and steel are 500°F (260°C) or less for long-term service. Copper-aluminum joints should be limited to 300°F (150°C). High quality transition welds are unaffected by thermal cycling below these temperatures. Short term exposure (10 to 15 minutes) during attachment welding, for example, may reach 550 to 600°F (290 to 315°C) with aluminum to steel and 400 to 500°F (200 to 260°C) with aluminum to copper without harm.

In the presence of an electrolyte such as salt water, aluminum and steel form a galvanic cell. In a mechanical connection, crevice corrosion in the joint can become a severe problem. A welded transition joint is metallurgically bonded, and there is no crevice in which the electrolyte can act. Structural transition joints are used to attach aluminum superstructures to the steel decks of naval vessels and commercial ships.

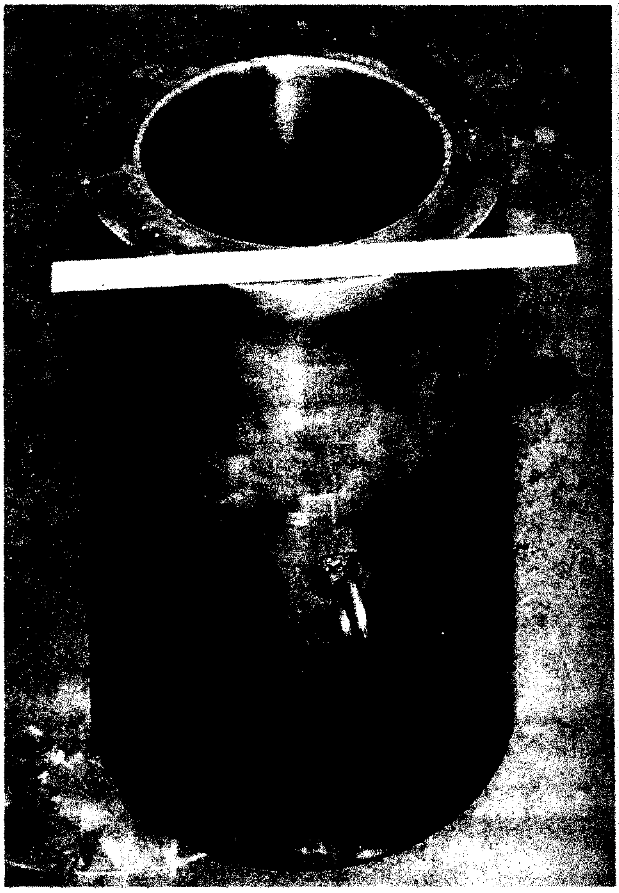

Figure 24.13–Steel Nozzle Internally Clad With 1/4-Inch Thick Inconel® 600 (The internal bore size is 9 inches.)

Tubular

TUBULAR TRANSITION JOINTS in various configurations can be machined from thick clad plate. The interface of the explosion weld is perpendicular to the axis of the tube in this case. Examples of a variety of transition joints machined from explosively clad plate are shown in Figure 24.14. While the majority of explosively welded tubular transition joints are aluminum to steel, other metal combinations for this type of joint include titanium to stainless steel, zirconium to stainless steel, zirconium to nickel-base alloys, and copper to aluminum.

Joints can also be fabricated directly by explosion welding in an over-lapping or telescoping style similar to a cylindrical cladding operation. They offer the advantage of a long overlap and frequently require little or no machining

Figure 24.14—Examples of Aluminum to Steel, Titanium to Aluminum, and Titanium to Stainless Steel Tubular Transition Joints Machined from Explosion Clad Plate (Explosion Fabricators, Inc. photograph)

after welding. Typical direct explosion welded tubular transition joints are shown in Figure 24.15.

OTHER

Heat Exchangers

EXPLOSION WELDING MAY be used to make tube-to-tube sheet joints in heat exchanger fabrication. The process is essentially a version of short length internal cylinder cladding with a small explosive charge used to make the joint. In most instances, the weld is located near the front of the tube sheet and has a length of approximately 1/2 in. (13 mm) or three to five times the thickness of the wall of the tube, whichever is greater. Points that must be considered in determining whether explosion welding is suitable for particular tube-to-tube sheet application include the diameter of the tube, the ratio of the wall thickness to the diameter of the tube, the thickness of the ligament between the holes in the tube sheet, and the thickness of the tube sheet. Tubes may be welded individually or in groups. The number in any group is controlled by the quantity of explosive that can be detonated safely at any one time.

Most applications of explosion welding in tube-to-tube sheet joints involve tube diameters in the range of 1/2 to 1.5 in. (13 to 38.1 mm). Metal combinations include steel to steel, stainless steel to stainless steel, copper alloy to copper alloy, nickel alloy to nickel alloy clad steel, and both aluminum and titanium to steel.

Feed Water and Heat Exchanger Tube Plugging

EXPLOSION WELDING CAN be used for plugging leaking tubes in heat exchangers. Electric utilities and petro-chemical companies use the process because it is quick, easy, and reliable. Although the process appears simple, only qualified, trained technicians should implement it. An explosive handling permit is required.

Two examples of tube plugs are shown in Figures 24.16 and 24.17. All plugs are completely assembled by the manufacturer, ready for installation. Materials that match the tube or general purpose nickel alloy material can be used.

The actual welding process is identical with those described previously. Following insertion of the plug into the tube and detonation, the welding occurs automatically. Preparation for field use of this process, however, requires careful attention. This is due to the tubes being plugged having corrosion or process fluids in the tubes.

Figure 24.15—Explosion Welded 12-Inch-Diameter 3003 Aluminum to A106 Grade B Steel Tubular Transition Joint (Battelle photograph)

Preparation of the tubes for plugging requires the following steps:

(1) Remove all fluid from the tube. This is best accomplished by blowing air through the tube.

(2) If water or fluid reappears, a rubber plug may be inserted into the tube 6 to 8 in. (150 to 200 mm) deep to keep the fluid away from the weld area.

(3) The tube ID must be cleaned to a bright shiny surface. Use a carbide burr or other abrasive to clean the surface if wire brushing does not remove oxides or corrosion products. The tube should be cleaned to a depth of 3 1/2 to 4 in. (90 to 100 mm).

(4) Inspect the tube for grooves. These must be removed or reduced to only a few thousandths in depth.

Note: If the tubesheet has enough depth, some of the tube may be removed by drilling to the tubesheet diameter and the plug inserted directly in the tubesheet.

(5) Ensure the surface is clean and dry when the explosive plug is inserted.

The actual explosive weld can now be completed by detonating the inserted plug. Since this requires explosives, only specially trained and licensed technicians perform this step of the process. Once the area has been cleared of smoke and explosion cases, the plug is ready for inspection. Depending upon the availability of equipment and quality requirements, various testing methods may be used. Following a visual examination the plug may be tested using pneumatic pressure, hydrostatic pressure, or a helium gas sniffer. Careful attention to avoid plug ejection paths must be avoided during any pressure test. Repairs to a plug which failed testing requires removal of the plug and restoration of the surface to clean, dry conditions without grooves for rewelding using another plug.

Pipeline Welding

IN THE EARLY 1980's, the procedure for joining lengths of large diameter gas and oil transmission pipelines by explosion welding was commercialized as a field procedure. The first commercial application of this procedure was employed to join a 3.7 mile (6 km) long section of 42 in. (1067 mm) diameter line in 1984. The approach involved the use of balanced external and internal explosive charges (see Figure 24.18) to achieve the required short overlap or telescope type weld without the requirement for any support tooling and to allow the weld to be made quickly and economically.

Buildup and Repair

EXPLOSION WELDING MAY be used for buildup and repair of worn components. It is particularly applicable to the repair of inside and outside surfaces of cylindrical components. The worn area is clad with an appropriate thickness of metal and machined to the proper dimensions. In some instances, such as bearing surfaces, the repair can be made with a material that is superior to the original material.

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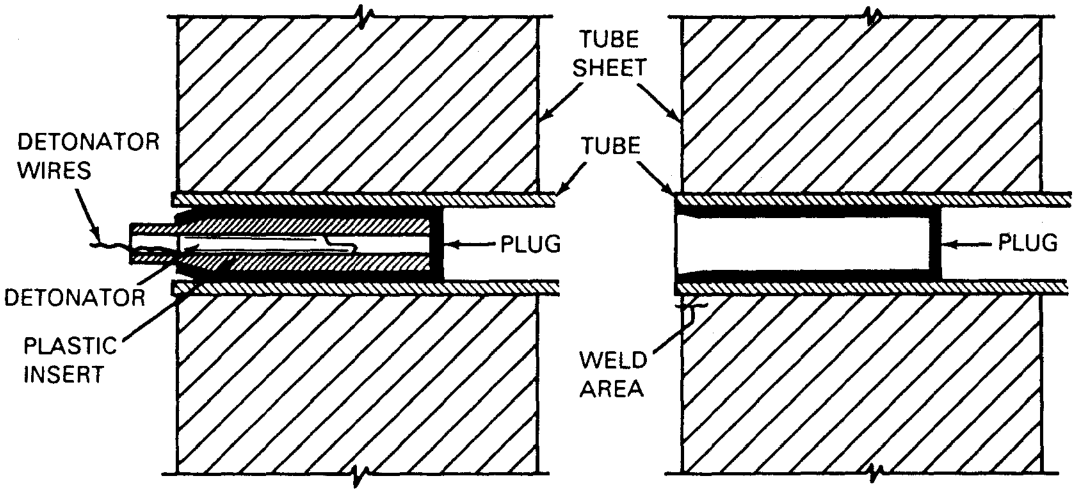
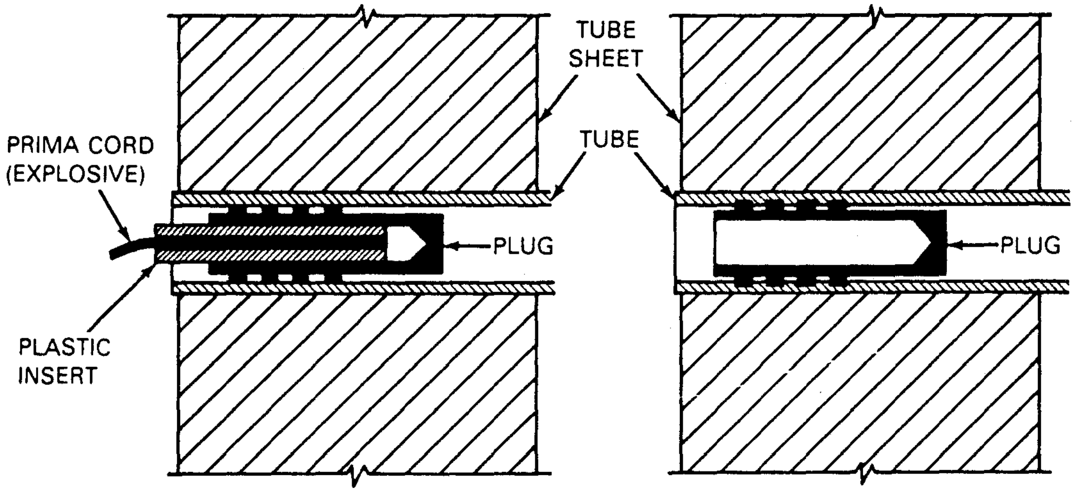


PLUG PLACED IN THE TUBE
BEFORE WELDING

PLUG EXPLOSIVELY WELDED
TO THE TUBE

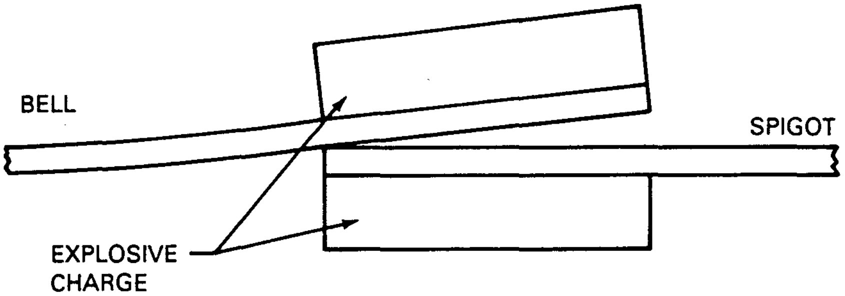
Figure 24.16–Explosively Welded Plug



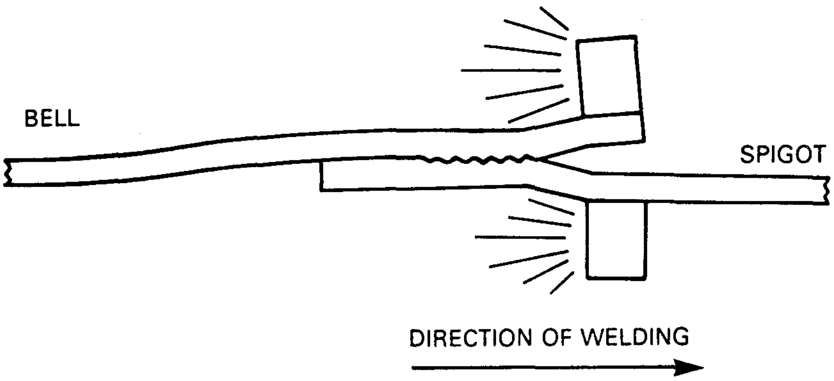
PLUG BEFORE EXPANSION

PLUG AFTER EXPANSION

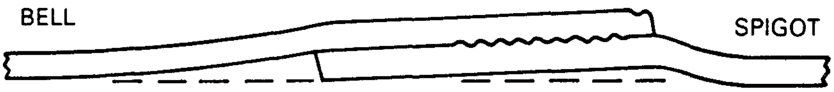
Figure 24.17–Explosively Expanded Plug



(A) GENERAL ARRANGEMENT OF PIPE ENDS AND EXPLOSIVES BEFORE WELDING



(B) DURING EXPLOSION WELDING



(C) FINAL JOINT CONFIGURATION AFTER WELDING

Figure 24.18–Schematic of Explosion Welding of Girth Joint in Pipe

SAFETY

EXPLOSIVES AND EXPLOSIVE devices are a part of explosion welding. Such materials and devices are inherently dangerous. Safe methods for handling them do exist. However, if the materials are misused, they can kill or injure anyone in the area and destroy or damage property.

Explosive materials should be handled and used by competent people who are experienced in that field. Handling and safety procedures must comply with all applicable federal, state, and local regulations. Federal jurisdiction over the sale, transport, storage, and use of explosives is through the U.S. Bureau of Alcohol, Tobacco, and Firearms; the Hazardous Materials Regulation Board of the U.S. Department of Transportation; the Occupational Safety and Health Agency; and the Environmental Protection Agency. Many states and local governments require a blasting license or permit, and some cities have special explosive requirements.

The Institute of Makers of Explosives provides educational publications to promote the safe handling, storage, and use of explosives. The National Fire Protective Association provides recommendations for safe manufacture, storage, handling, and use of explosives.

Personnel working in the vicinity of the explosion welding operation should be provided with eye protection (safety glasses) to guard against flying particles. They should also have ear protection to guard against the noise of explosions. Warning signs should be installed to warn people to wear eye and ear protection and to keep away from detonation areas.

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CHAPTER 25

ULTRASONIC WELDING

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CHAPTER 25

ULTRASONIC WELDING

FUNDAMENTALS

DEFINITIONS AND GENERAL DESCRIPTION

ULTRASONIC WELDING (USW) is a solid-state welding process that produces a weld by local application of high-frequency vibratory energy while the workpieces are held together under pressure. A sound metallurgical bond is produced without melting of the base material.

Typical components of an ultrasonic welding system are illustrated in Figure 25.1. The ultrasonic vibration is generated in the transducer. This vibration is transmitted through a coupling system or sonotrode,[1] which is represented by the wedge and reed members in Figure 25.1. The sonotrode tip is the component that directly contacts one of the workpieces and transmits the vibratory energy into it. The clamping force is applied through at least part of the sonotrode, which in this case is the reed member. The anvil supports the weldment and opposes the clamping force.

Ultrasonic welding is used for applications involving both monometallic and bimetallic joints. The process is used to produce lap joints between metal sheets or foils, between wires or ribbons and flat surfaces, between crossed or parallel wires, and for joining other types of assemblies that can be supported on an anvil.

This process is being used as a production tool in the semiconductor, microcircuit, and electrical contact industries; for fabricating small motor armatures; in the manufacture of aluminum foil; and in the assembly of aluminum components. It is receiving acceptance as a structural joining method by the automotive and aerospace industries. The process is uniquely useful for encapsulating materials such as explosives, pyrotechnics, and reactive chemicals that require hermetic sealing but cannot be processed by high temperature joining methods.

PROCESS VARIATIONS

THERE ARE FOUR variations of the process, based on the type of weld produced. These are spot, ring, line, and continuous seam welding. Furthermore, two variants of ultrasonic spot welding are used in microelectronics.

Spot Welding

IN SPOT WELDING, individual weld spots are produced by the momentary introduction of vibratory energy into the workpieces as they are held together under pressure between the sonotrode tip and the anvil face. The tip vibrates in a plane essentially parallel to the plane of the weld interface, perpendicular to the axis of static force application. Spot welds between sheets are roughly elliptical in shape at the interface. They can be overlapped to produce an essentially continuous weld joint. This type of seam may contain as few as 5 to 10 welds per inch. Closer weld spacing may be necessary if a leak-tight joint is required.

Ring Welding

RING WELDING PRODUCES a closed loop weld which is usually circular in form but may also be square, rectangular, or oval. Here, the sonotrode tip is hollow, and the tip face is contoured to the shape of the desired weld. The tip is vibrated torsionally in a plane parallel to the weld interface. The weld is completed in a single, brief weld cycle.

Line Welding

LINE WELDING IS a variation of spot welding in which the workpieces are clamped between an anvil and a linear sonotrode tip. The tip is oscillated parallel to the plane of the

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[1] The sonotrode is the acoustical equivalent of the electrode and its holder used in resistance spot or seam welding.

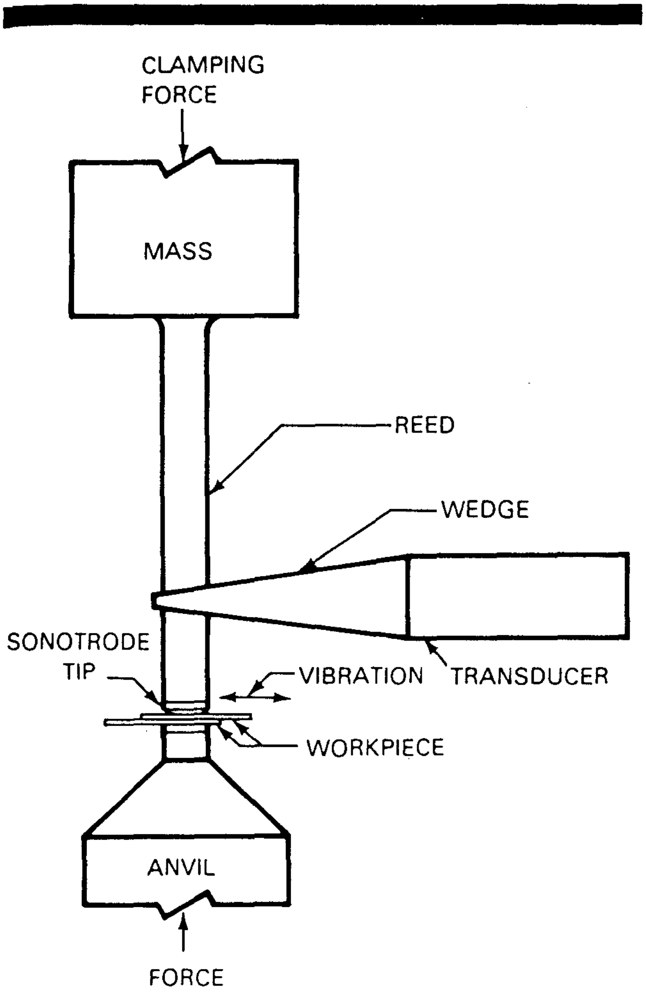

Figure 25.1–Wedge-Reed Ultrasonic Spot Welding System

weld interface and perpendicular to both the weld line and the direction of applied static force. The result is a narrow linear weld, which can be up to 6 in. in length, produced in a single weld cycle.

Continuous Seam Welding

IN CONTINUOUS SEAM welding, joints are produced between workpieces that are passed between a rotating, disk-shaped sonotrode tip and a roller type or flat anvil. The tip may traverse the work while it is supported on a fixed anvil, or the work may be moved between the tip and a counter-rotating or traversing anvil. Area bonds may be produced by overlapping seam welds.

MICROMINIATURE WELDING

THERE IS A consistency in the mechanism of ultrasonic joining throughout its various types of applications including microelectronic wire bonding. In microelectronic applications, the wire diameter normally varies from 0.001 to 0.020 in. (25 to 500 µm), with the highest volume usage occurring in the 0.001 to 0.002 in. (25 to 50 µm) range. The significance of the material flow induced by ultrasonic energy can easily be observed by placing the bonding wedge on the wire to be joined to a substrate using the full bonding force, but with no ultrasonic energy being applied. With this condition, the flow of the wire is hardly noticeable.

Gradual application of ultrasonic power over time results in increased wire flow and a gradual bonding action between the outer surface of the deformed wire and the substrate material. The center of the bond area remains undisturbed, confirming the stable relationship between the bonding members. The vibratory action effectively removes surface contaminants to expose fresh material for welding. Using a scanning electron microscope as a diagnostic tool, the disruption of surface contaminants can readily be observed below the heel of the weld on the substrate.

Reflected sound and light are used to reveal the movements of the bonding tool. The magnitude of the wedge movement increases with increasing ultrasonic energy. By gradually increasing the power and the time for a given load on the wedge, characteristics of the ultrasonic wire bond interface can be observed. For a given combination of wire and substrate materials, a "window" or range of power (bond tool movement), time, and machine load variables can be determined which will provide acceptable weld strength values. There is a trade-off between reducing the wire strength because of deformation and strength of the bond interface itself. For reliable bonding, the wire itself should always be weaker than the bond interface.

MICROMINIATURE THERMOSONIC WELDING

MICROELECTRONIC WIRE JOINING represents a growing volume of industrial activity. Millions of wire bonds are performed daily. Because of the volume and the importance of the reliability of the products, wire bonding continues to evolve.

Ultrasonic wire bonding in the early 1970's was predominately the joining of aluminum wires to aluminum metallized bond pads on semiconductor devices, and joining wires to either aluminum-clad or gold-plated leads on the package. From purely ultrasonic and purely thermocompression[2] types of solid-state bonding has emerged today's thermosonic bonding. Thermosonic welding involves ultrasonic welding with heated substrates. Interface temperatures of 215 to 400° F (100 to 200° C) are normally used. It

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[2] Thermocompression welding is a deformation welding process in which fresh metal surfaces are exposed for welding by mechanical disruption of surface films. It is typically done at temperatures ranging from 215 to 660° F (100 to 350° C).

is now the most popular method of wire joining. Billions of wire joints were produced with this process each year during the late 1980's.

With the continually evolving improvements in wire bonding have come increasingly improved bonding machines and processes, bonding wedge designs and materials, bonding wire materials, and techniques for measuring bond quality. Ultrasonic wire bonding has been transformed from its "art" form in the 1960's to a common production technology in 1990.

MECHANISM OF THE PROCESS

ULTRASONIC WELDING INVOLVES complex relationships between the static clamping force, the oscillating shear forces, and a moderate temperature rise in the weld zone. The magnitudes of these factors required to produce a weld are functions of the thickness, surface condition, and the mechanical properties of the workpieces.

STRESS PATTERNS

IN ALL TYPES of ultrasonic welding, static clamping force is applied perpendicular to the interface between the workpieces. The contacting sonotrode tip oscillates approximately parallel to this interface. Combined static and oscillating shear forces create dynamic internal stresses in the workpieces at the faying surfaces, resulting in elastoplastic deformation.

Photoelastic stress models reveal significant aspects of these stress patterns. With applied static force only, the stress pattern is symmetrical about the axis of force application. With the superimposition of a lateral force, such as that occurring during one-half cycle of vibration, the force shifts in the direction of this lateral force, and shear stress is produced on that side of the axis. When the direction of the lateral force is reversed, as in the second half of the vibratory cycle, the shear stress shifts to the opposite side of the axis. During welding, the shear stress changes direction thousands of times per second.

As long as the stresses in the metal are below the elastic limit, the metal deforms only elastically. When the stresses exceed their threshold value, highly localized interfacial slip occurs, with no gross sliding. This action tends to break up and disperse surface films and permits metal-to-metal contact at many points. Continued oscillation breaks down surface asperities so that the contact area can grow until a physically continuous weld area is produced. At the same time, atomic diffusion occurs across the interface, and the metal recrystallizes to a very fine grained structure having the properties of moderately cold-worked metal.

Temperature Developed in Weld Zone

ULTRASONIC WELDING OF metals at room temperature produces a localized temperature rise from the combined effects of elastic hysteresis, localized interfacial slip, and plastic deformation. However, similar metals do not melt at the interface when the clamping force, power, and weld time are set correctly. Sections examined with both optical and electron microscopy have shown phase transformation, recrystallization, diffusion, and other metallurgical phenomena, but no evidence of melting.

Interfacial temperature studies made with very fine thermocouples and rapidly responding recorders show a high initial rise in temperature at the interface, followed by a leveling off. The maximum temperature achieved is dependent upon the welding machine settings. Increasing the power raises the maximum temperature achieved. Increased clamping force increases the initial rate of temperature rise, but lowers the maximum temperature achieved. Thus, it is possible to control the temperature profile, within limits, by appropriate adjustment of machine settings.

The interface temperature rise is also related to the thermal properties of the metal being welded. Generally, the temperature produced in a metal of low thermal conductivity, such as iron, is higher than that in a metal of high thermal conductivity, such as aluminum or copper.

Temperature measurements during welding of metals having a wide range of melting temperatures show that the maximum temperature in the weld is approximately 35 to 50 percent of the absolute melting temperature of the metal, when suitable welding machine settings are used.

Energy Delivered to the Weld Zone

THE FLOW OF energy through an ultrasonic welding system begins with the introduction of 60 Hz electrical power into a frequency converter. This device converts the applied frequency to that required for the welding system, which is usually in the range of from 10 to 75 kHz. The high-frequency electrical energy is conducted to one or more transducers in the welding system, where it is converted to mechanical vibratory energy of the same frequency. The vibratory energy is transmitted through the sonotrode and sonotrode tip into the workpiece. Some of the energy passes through the weld zone and dissipates in the anvil support structure.

Power losses occur throughout the system, in the frequency converter, transducer, sonotrode, and the interfaces between these components. However, with a well-designed system, as much as 80 to 90 percent of the input power to the converter may be delivered into the weld zone.

For practical usage, the power required for welding is usually measured in terms of the high-frequency electrical power delivered to the transducer. This power can be monitored continuously and provides a reliable average value to associate with equipment performance as well as with weld quality. The product of the power in watts and welding time in seconds is the energy, in watt-seconds or joules, used in welding.

Power Requirements and Weldability

THE ENERGY REQUIRED to make an ultrasonic weld can be related to the hardness of the workpieces and the thickness of the part in contact with the sonotrode tip. Analysis of data covering a wide range of materials and thicknesses has led to the following empirical relationship, which is accurate to a first approximation:

$$E = K(HT)^{3/2} \qquad (25.1)$$

where:

E = electrical energy, W·s (J)
K = a constant for a given welding system
H = Vickers hardness number
T = thickness of the sheet in contact with the sonotrode tip, in. (mm)

The constant "K" is a complex function that appears to involve primarily the electromechanical conversion efficiency of the transducer, the impedance match into the weld, and other characteristics of the welding system. Different types of transducer systems should have substantially different K values.

The above relationship has not been verified for welds used in microelectronics. This relationship predicts values that are about two orders of magnitude too high for microelectronic welds.

Figure 25.2 shows the relationship between the energy required for sound spot welds and the hardness of various sheet thicknesses of any weldable metal, based on the above equation. It provides a convenient first approximation of the minimum electrical input energy required (to produce sound welds) for a ceramic transducer type spot welding machine based on the Vickers hardness of the metal and the sheet thickness. Similar data can be derived for ring, line, and seam welds. For seam welds, the energy would be expressed in terms of the unit length of seam.

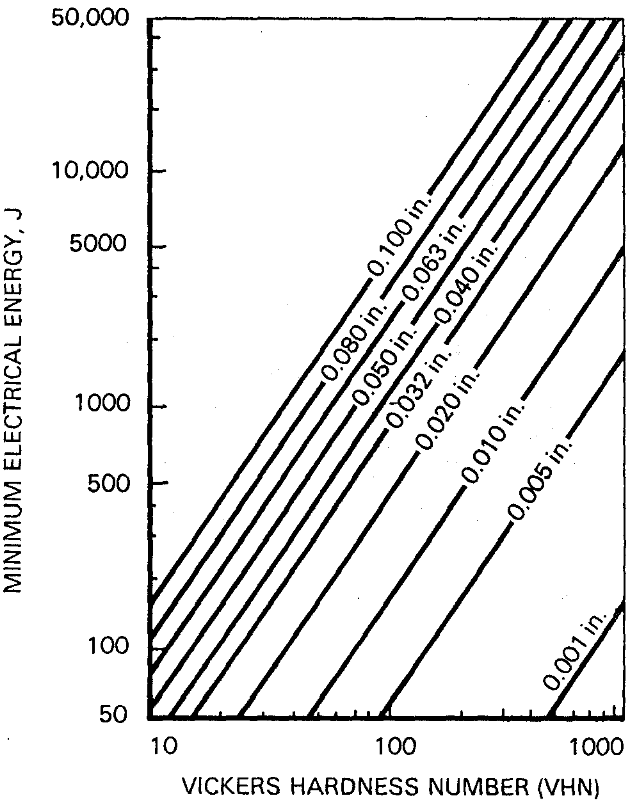


Figure 25.2–The Relationship Between the Minimum Electrical Energy Required for Ultrasonic (ceramic transducer) Spot Welding and Metal Hardness for Several Sheet Thicknesses

WELDING MICROELECTRONIC DEVICES

SMALL ULTRASONIC WELDS used in microelectronics are made with highly deformable materials such as aluminum, copper, and gold. The wire diameters are usually 25 to 50 µm. The welding process is complex but can be summarized as follows: Wire-to-substrate interfacial motion may occur during the first few milliseconds, resulting in only minimal temperature rise [120 to 210°F (50 to 100°C)]. After this time, small microwelds form along or just inside the perimeter of the mated surfaces, and it is assumed that this interfacial motion slows and ceases as these microwelds grow. At this point, the interfacial motion progresses into the bonding tool-to-wire interface, and more ultrasonic energy is absorbed into the weld area. The microwelds join together and grow toward the center as shown in Figure 25.3, generally leaving the center unwelded.

The clamping force then deforms the wire and this process sweeps aside brittle surface oxides and contaminants, leaving clean surfaces in contact. Little deformation takes place in the center of the weld, so this area is often left unwelded, as shown in Figure 25.4. Transmission and scanning electron micrographs taken along the interface of monometallic welds have variously shown grain boundaries, no grain boundaries, debris zones of oxides and contaminants, and numerous crystallographic defects. Gold-alumi-

Figure 25.3–Typical Ultrasonic Bond Between a 25 μm Diameter Aluminum, 1% Silicon Wire and an Aluminum Substrate Using 50 ms Weld Time and 25 Kg Load (Note: The Wire has Been Lifted up so the Weld Pattern May be Seen. The Center is Unwelded).

Figure 25.4–Example of the Initial Stage of a Bond Between an Aluminum, 1% Silicon Ribbon (12 μm by 37μm Cross Section) and an Aluminum Substrate (Note: The Ribbon has been Removed, Revealing Microwelds Beginning to Form at the Perimeter of the Joint Where Deformation is Largest.)

num and other bimetallic welds made at room temperature do not show the formation of intermetallic compounds, but a clear boundary, similar to a grain boundary, is always observed.

The connections to essentially all semiconductor chips are welded in the same manner. The exceptions are a few types of devices that are specially prepared with solder bumps on their bond pads. Aluminum-to-aluminum cold ultrasonic welds are made between fine aluminum - 1 percent silicon wire, 25 to 50 μm in diameter, to various aluminum alloy (e.g., alloys with 1 percent Si, 1 to 2 percent Cu, etc.) bonding pads on semiconductor chips. Larger diameter wire, up to about 0.03 in. (0.75 mm), supplied in the fully annealed condition, is used to connect power devices that require higher currents.

The vast majority of interconnections to integrated circuits are made by thermosonic welding of gold wire. Thermocompression (solid state) welding usually requires interfacial temperatures between 575 and 750°F (300 and 400°C). This can damage plastics used to attach the chip to its package, whereas thermosonic welding can keep the interface temperature as low as 300°F (150°C). That lower temperature does not damage the plastics. The weld is matured with ultrasonic energy which, in combination with this temperature, can be kept small enough to prevent damage to the semiconductor chip.

Currently, gold wires are ultrasonically welded to semiconductor chips. However, there is a large effort to use copper wires in place of gold. Thermosonic ball bonding would then be used to produce the copper wire welds. If successful, copper should replace much of the gold wire in the future.

Tape automated bonding (TAB) is used to connect semiconductor devices where several hundred connections per device are required. For this technology, small leads of tin- or gold-plated copper ribbon are attached to plastic tape for rigidity. The leads are placed over a chip, which was designed with raised bonding pads. These tape-supported leads are then attached to the chip by either thermocompression or liquid interface bonding all at one time, or individually by modified automated wire welding equipment. In the latter case, the welds may be made by thermosonic, laser-heated thermocompression, laser-heated thermosonic, or liquid interface methods. This is a rapidly evolving technology.

An example of an ultrasonic transducer (60 kHz excitation) used in microelectronics welding including the capillary (sonotrode) is illustrated in Figure 25.5.

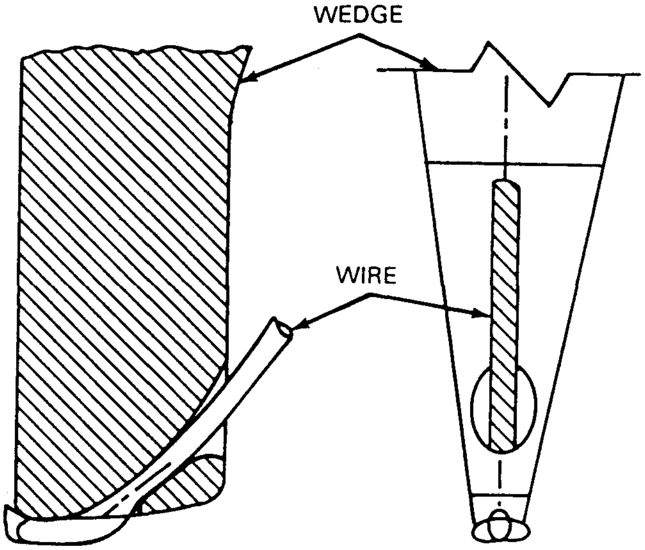


Figure 25.5–Ultrasonic Bonding Wedge With Wire

PROCESS ADVANTAGES AND DISADVANTAGES

ULTRASONIC WELDING HAS advantages over resistance spot welding in that little heat is applied during joining and no melting of the metal occurs. Consequently, no cast nugget or brittle intermetallics are formed. There can be no arc, and there is no tendency to expel molten metal from the joint.

The process permits welding thin to thick sections, as well as joining a wide variety of dissimilar metals. Welds can be made through certain types of surface coatings and platings.

Ultrasonic welding of aluminum, copper, and other high thermal conductivity metals requires substantially less energy than does resistance welding.

The pressures used in ultrasonic welding are much lower, welding times are shorter, and thickness deformation is significantly lower than for cold welding.

A major disadvantage is that the thickness of the component adjacent to the sonotrode tip must not exceed relatively thin gages because of the power limitations of present ultrasonic welding equipment. The range of thicknesses of a particular metal that can be welded depends upon the properties of that metal.

In addition, ultrasonic welding of metal is limited to lap joints. Butt welds cannot be made in metals because there is no effective means of supporting the workpieces and applying clamping force. However, ultrasonic butt welds are made in some polymer systems.

WELDABLE METALS

MOST METALS AND their alloys can be ultrasonically welded. Figure 25.6 identifies some of the monometallic and bimetallic combinations that currently can be welded on a commercial basis. Blank spaces in the chart indicate combinations that have not been attempted or are not known to have been successfully welded.

Various metals differ in weldability according to their composition and properties. The metals considered more difficult to weld are those that require either high power or long weld times, or both, and those that incur operational problems such as tip sticking or short tip life.

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al ALLOYS	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be ALLOYS		●	●			●										●		
Cu ALLOYS			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe ALLOYS						●		●	●	●	●		●	●		●	●	●
Mg ALLOYS							●						●			●		
Mo ALLOYS								●	●		●			●		●	●	●
Ni ALLOYS									●	●	●			●		●	●	
Pd										●			●	●				
Pt ALLOYS											●	●		●		●	●	
Si													●	●				
Ag ALLOYS													●	●				●
Ta ALLOYS														●		●	●	
Sn															●			
Ti ALLOYS																●	●	
W ALLOYS																	●	
Zr ALLOYS																		●

Figure 25.6—Metal Combinations That Can Be Ultrasonically Welded

ALUMINUM ALLOYS

ALL COMBINATIONS OF aluminum alloys form a weldable pair. They may be joined in any available form: cast, extruded, rolled, forged, or heat-treated. Soft aluminum cladding on the surface of these alloys facilitates welding. Aluminum can be welded to most other metals including germanium and silicon, the primary semiconductor materials.

COPPER ALLOYS

COPPER AND ITS alloys, such as brass and gilding metal, are relatively easy to weld. High thermal conductivity is not a deterrent factor in ultrasonic welding, as it is in fusion welding. Surface condition is an especially important variable in ultrasonic welding of copper alloys.

IRON AND STEEL

SATISFACTORY WELDS CAN be produced in iron and steel of various types, such as ingot iron, low carbon steels, tool and die steels, austenitic stainless steels, and precipitation-hardening steels. The power requirements are higher than for aluminum and copper.

PRECIOUS METALS

THE PRECIOUS METALS, including gold, silver, platinum, palladium, and their alloys, can be ultrasonically welded without difficulty. Most precious metals can be satisfactorily welded to other metals and to germanium and silicon.

REFRACTORY METALS

THE REFRACTORY METALS, including molybdenum, columbium, tantalum, tungsten, and some of their alloys, are among the most difficult metals to weld ultrasonically. Thin foil thicknesses of these metals can be joined if they are relatively free from contamination and surface or internal defects.

OTHER METALS

NICKEL, TITANIUM, ZIRCONIUM, beryllium, magnesium, and many of their alloys can be ultrasonically welded in thin gages to themselves and to other metals. Metal foils and wires are readily joined to thermally sprayed metals on glass, ceramics, or silicon. Such welds are particularly useful in the semiconductor industry. Typical combinations are shown in Table 25.1.

MULTIPLE-LAYER WELDING

MULTIPLE-LAYER WELDING IS feasible; for example, as many as 20 layers of 0.001 in. (25 μm) thick aluminum foil can be joined simultaneously with either spot welds or continuous seam welds. Several layers of dissimilar metals can also be welded together.

LIMITATIONS

THERE IS AN upper limit to the thickness of any metal that can be ultrasonically welded effectively, because the power output of available equipment is limited. For a readily weldable metal, such as Type 1100 aluminum, the maximum thickness in which reproducible high-strength welds can be produced is approximately 0.10 in. (2.5 mm). The present upper limit of harder metals is in the range of 0.015 to 0.040 in. (0.4 to 1.0 mm). This limitation applies only to the member of the weldment that is in contact with the welding tip; the other member may have greater thickness.

Table 25.1
Metal Wire and Ribbon Leads That May be Ultrasonically Welded to Thin Metal Surfaces on Nonmetallic Substrates

		Lead	
Substrate	Metal Film	Material	Diameter or Thickness Range, in.
Glass	Aluminum	Aluminum wire	0.002-0.010
	Aluminum	Gold wire	0.003
	Nickel	Aluminum wire	0.002-0.020
	Nickel	Gold wire	0.002-0.010
	Copper	Aluminum wire	0.002-0.010
	Gold	Aluminum wire	0.002-0.010
	Gold	Gold wire	0.003
	Tantalum	Aluminum wire	0.002-0.020
	Chromel	Aluminum wire	0.002-0.010
	Chromel	Gold wire	0.003
	Nichrome	Aluminum wire	0.0025-0.020
	Platinum	Aluminum wire	0.010
	Gold-platinum	Aluminum wire	0.010
	Palladium	Aluminum wire	0.010
	Silver	Aluminum wire	0.010
	Copper on silver	Copper ribbon	0.028
Alumina	Molybdenum	Aluminum ribbon	0.003-0.005
	Gold-platinum	Aluminum wire	0.010
	Gold on molybdenum-lithium	Nickel ribbon	0.002
	Copper	Nickel ribbon	0.002
	Silver on molybdenum-manganese	Nickel ribbon	0.002
Silicon	Aluminum	Aluminum wire	0.010-0.020
	Aluminum	Gold wire	0.002
Quartz	Silver	Aluminum wire	0.010
Ceramic	Silver	Aluminum wire	0.010

Extremely thin sections can be welded successfully. For example, fine wires less than 0.0005 in. (0.01 mm) in diameter and thin foils of 0.00017 in. (0.004 mm) thickness have been welded.

Where a weld is difficult to achieve with available power levels, good quality joints might be made by inserting a foil of another metal in between the two workpieces. Three examples of this are (1) 0.0005 in. (0.01 mm) thick nickel or platinum foil has been used between molybdenum components; (2) beryllium foil has been welded to AISI Type 310 stainless steel using an interleaf of thin Type 1100-H14 aluminum foil; and (3) the weldable range of Type 2014-T6 aluminum alloy has been extended by using a foil interleaf of Type 1100-O aluminum.

For some metals, use of abrasive or textured tips and anvils will decrease the required clamping force and the welding power. This may permit welding thicker sections with a particular machine size.

Generally, ultrasonic welding can be used to join a metal within the thickness limitations of the process provided there is the following:

(1) Adequate joint overlap

(2) Access for the sonotrode tip to contact the parts

(3) An avenue for anvil support and clamping force application

APPLICATIONS

ELECTRONIC COMPONENTS

THE MOST IMPORTANT application of the USW process is the assembly of miniaturized electronics components. Fine aluminum and gold lead wires are attached to transistors, diodes, and other semiconductor devices. Wires and ribbons are bonded to thin films and microminiaturized circuits. Diode and transistor chips are mounted directly on substrates. Reliable joints with low electrical resistance are produced without contamination or thermal distortion of the components.

ELECTRICAL CONNECTIONS

ELECTRICAL CONNECTIONS OF various types are effectively made by ultrasonic welding. Both single and stranded wires can be joined to other wires and to terminals. The joints are frequently made through anodized coatings on aluminum, or through certain types of electrical insulation. Other current-carrying devices, such as electric motors, field coils, harnesses, transformers, and capacitors may be assembled with ultrasonically welded connections. A typical example is the field coil assembly for automotive starter motors shown in Figure 25.7. Ultrasonic welds are used here for joining aluminum ribbon to itself, to copper ribbon, to consolidated stranded copper wire, and to copper terminals.

For the starter motor armature of Figure 25.8, two wires are welded simultaneously into each slot of the barrel commutator. The entire process is accomplished automatically at rates up to 180 complete armatures per hour. Armatures for small motors in appliances, hand tools, fans, computers, and other electrical devices are assembled in a similar manner.

Thermocouple junctions involving a wide variety of dissimilar metals can be produced by this means.

FOIL AND SHEET SPLICING

BROKEN AND RANDOM lengths of aluminum foil are welded in continuous seams by foil rolling mills. Highly reliable splices, capable of withstanding annealing operations, are made rapidly in foils up to 0.005 in. (0.13 mm) thick and 72 in. (180 cm) wide. The splices are almost undetectable after subsequent working operations. Alumi-

Figure 25.7–Field Coil Assembled by Ultrasonic Welding

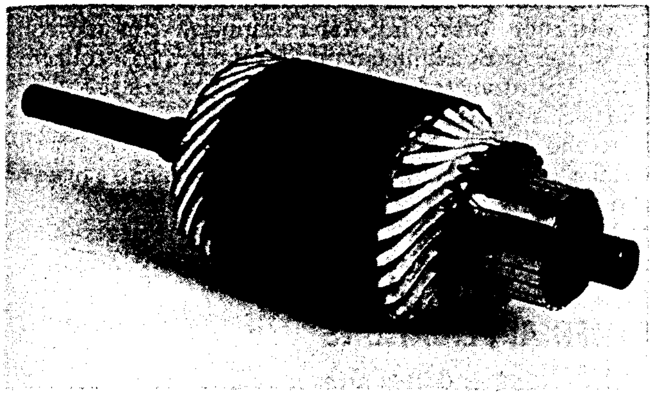


Figure 25.8–Starter Motor Armature With Wires Joined in Commutator Slots by Ultrasonic Welding

num and copper sheet up to about 0.020 in. (0.5 mm) thick can be spliced together by ultrasonic welding using special processing and tooling.

ENCAPSULATION AND PACKAGING

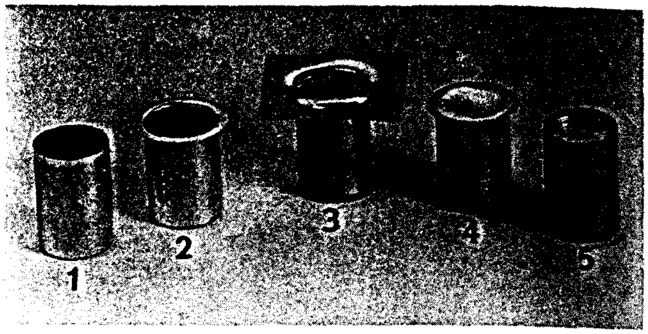
ULTRASONIC WELDING IS used for a wide variety of packaging applications that range from soft foil packets to pressurized cans. Leak tight seals are produced by ring, seam, and line welding.

The process is useful for encapsulating materials that are sensitive to heat or electrical current. Such materials may be primary explosives, slow-burning propellants and pyrotechnics, high-energy fuels and oxidizers, and living-tissue cultures.

Ultrasonic welding can be accomplished in a protective atmosphere or vacuum, and therefore instrument parts, ball bearings, and other items that must be protected from dust or contamination are frequently joined by the process. This capability also permits encapsulation of chemicals that react with air.

Ring welds up to about 1.5 in. (38 mm) diameter can be produced, but these welds are limited to thin sections of aluminum or copper. Straight cylindrical containers are often welded with a flanging and re-forming technique such as that shown in Figure 25.9. The cylinder ends are flared to form a 90° flange. The covers are ultrasonically welded to the flange, and then the welded flange is subsequently reformed to the original cylindrical geometry.

Line welding is used for packaging with one or more straight line seams, such as sealing the ends of squeeze tubes. Square or rectangular packets are produced by intersecting line welds on each of the four edges. Continuous seam welding is used to seal packages that cannot be accommodated with ring or line welding.



SEQUENCE:
1. AS-RECEIVED CONTAINER
2. FLANGE FORMED
3. COVER WELDED TO THE FLANGE
4. COVER TRIMMED
5. CYLINDER REDRAWN

Figure 25.9–Cylinder Closure by the Flange-Weld-Redraw Technique

STRUCTURAL WELDING

ULTRASONIC WELDING PROVIDES joints of high integrity for structural applications within the limitations of weldable sheet thickness. The process is being used to assemble aircraft secondary structures, such as the helicopter access door in Figure 25.10. This assembly consists of inner and outer skins of aluminum alloy joined by multiple ultrasonic spot welds. Individual ultrasonic welds had 2.5 times the minimum average strength requirements for resistance spot welds in the same metals and thicknesses. Assembled doors sustained loads 5 to 10 times the design load without weld failure in air load tests. Significant savings in fabrication and energy costs were evident when compared to those of adhesive bonding.

In another application, small clips are attached to cylindrical reactor fuel elements with ultrasonic spot welds. Eight clips are attached to each element, and production rates of about 200 elements per hour are achieved in a semiautomatic setup.

SOLAR ENERGY SYSTEMS

ULTRASONIC WELDING HAS reduced fabrication costs for some solar energy conversion and collection systems. Systems for converting solar heat to electricity frequently involve photovoltaic modules of silicon cells which are connected by aluminum connectors. An ultrasonic seam welding machine, operating at speeds up to 30 feet per minute, joins all connectors in a single row in a fraction of the time required for hand soldering or individual spot welding. After all connections are made on one side of the assembly, the process is repeated on the opposite side.

Solar collectors for hot-water heating systems may consist of copper or aluminum tubing attached to a collector plate. An automated ultrasonic system makes successive spot welds spaced on 1-in. (25 mm) centers between the plate and tubing as the assembly is passed beneath the welding tip. A 36 in. (1 m) tube can be welded to a plate in about 2 minutes, at an energy cost of about 0.3 cent. Fabrication costs are lower than those of soldering, resistance spot welding, or roll welding.

OTHER APPLICATIONS

APPLICATIONS IN OTHER areas have also been successful. Continuous seam welding was used to assemble components of corrugated heat exchangers. Strainer screens were welded without clogging the holes. Beryllium foil windows for space radiation counters were ultrasonic ring welded to stainless steel frames to provide a helium leak-tight bond.

Currently, pinch-off weld closures in copper and aluminum tubing, which are used with tubes in refrigeration and air conditioning, are produced with special serrated bar tips and anvils. Aluminum foil, surrounding fiberglass insulated ducting, is overlapped and welded with a traversing-head seam welding machine.

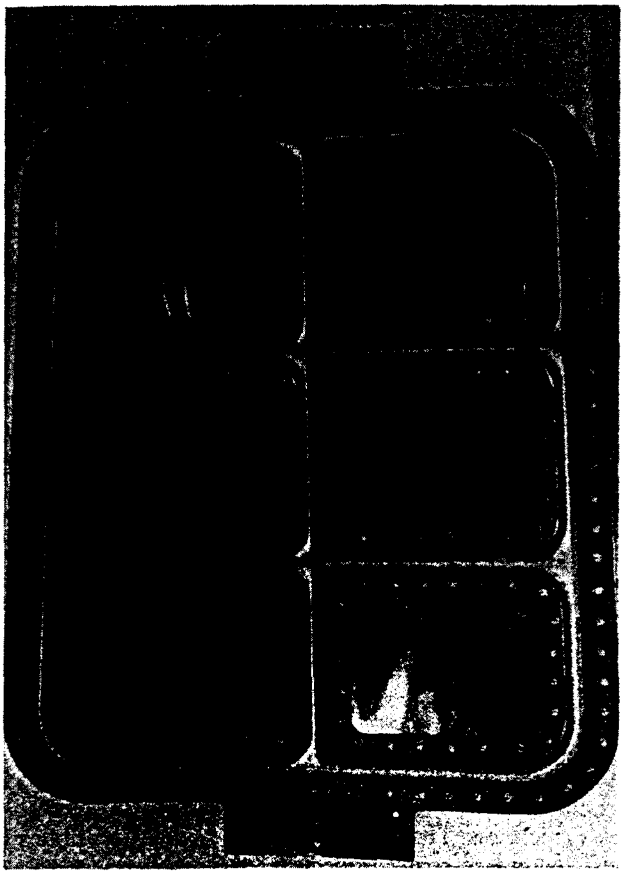


Figure 25.10–Ultrasonically Welded Helicopter Access Door

EQUIPMENT

GENERAL DESCRIPTION

AN ULTRASONIC WELDING machine consists of the following components:

(1) A frequency converter to provide electrical power at the design frequency of the welding system

(2) A transducer-sonotrode system to convert this power into elastic vibratory energy and deliver it to the weld zone

(3) An anvil which serves as a support for the workpieces

(4) A force application mechanism

(5) Either a timing device to control the weld interval in spot, ring, and line welding, or a rotating and translating mechanism for seam welding

(6) Appropriate electrical, electronic, and hydraulic or pneumatic controls

Vibratory Frequency

ULTRASONIC WELDING CAN be accomplished over a broad frequency range from less than 0.1 to about 300 kHz. However, the frequencies used for welding machines are usually in the range of 10 to 75 kHz.

An ultrasonic welding machine is designed to operate at a single frequency. There is no critical frequency for welding of specific metals or thicknesses. Due to the practical fundamentals of transducer-sonotrode design, it is expedient to build both light, low-power machines that operate at high frequencies, and heavy, high-power machines that operate at low frequencies. For example, welding machines in the power range of about 1200 to 8000 W operate with frequencies in the 10 to 20 kHz range. Conversely, small machines joining fine wires may have a power capacity of only a few watts and an operating frequency in the range of about 40 to 75 kHz.

A machine is designed to operate at some nominal frequency that may actually vary about 1 percent above or below the design frequency due to manufacturing variations. Adjustments are provided to tune the equipment to its optimum operating frequency.

Transducer-Sonotrode System

BOTH MAGNETOSTRICTIVE AND piezoelectric types of transducers are used in ultrasonic welding systems. Magnetostrictive materials have the property of changing length under the influence of varying magnetic flux density. Such transducers, which usually consist of a laminated stack of nickel or nickel alloy sheets, are rugged and serviceable for continuous duty operation but have low electromechanical conversion efficiency. Piezoelectric ceramic materials, such as lead zirconate titanate, are capable of changing dimensions under the influence of an electrical field. These materials have a conversion efficiency of more than twice that of magnetostrictive transducers. When they are operated at high duty cycles, both types of transducers must be cooled to prevent overheating and a loss of transduction characteristics.

The sonotrode system is designed to operate at the resonant frequency of the transducer and usually to provide gain in the amplitude of the delivered vibration. Sonotrode materials are selected to provide low energy losses and high fatigue strength under the applied static and vibratory stresses. A titanium alloy and stainless steel are the most commonly used sonotrode materials.

For high reliability, the various joints in the system must have high integrity and excellent fatigue life. Because of the high-frequency vibration, brazed, welded, and mechanical junctions have been used, but most current welding machines use mechanical joints for ease of interchangeability.

Transducer-sonotrode systems usually have acoustically designed mounting arrangements to ensure maximum efficiency of energy transmission when static force is applied through the system. These force-insensitive mounts prevent any shift of the resonant frequency of the system, and minimize loss of vibratory energy into the supporting structure.

Anvil

THE ANVIL, IN addition to supporting the workpiece, provides the necessary reaction to the applied clamping force. Its geometry is seldom critical except that it must not permit the workpiece to vibrate in compliance with the applied frequency.

Clamping Mechanism

THE STATIC LOAD is always applied normal to the plane of the weld interface. The means for applying this load depend upon the overall design of the welding machine. With larger units, hydraulic systems are satisfactory. Intermediate size units may incorporate pneumatically actuated or spring loaded systems. Miniature welding machines that require very small clamping loads may be spring actuated or dead-weight loaded. Such mechanical devices are suitable for production applications where frequent adjustments are not required.

Frequency Converter

THE FUNCTION OF the frequency converter is to change electrical line power of 50 or 60 Hz to the design frequency of the welding system in an oscillator stage, and then to amplify the output power in an amplifier stage. The output of such a system is the high-frequency electrical power of the ultrasonic transducer in the welding head.

Most ultrasonic welding systems use a solid-state frequency converter of the silicon-controlled rectifier (SCR) or transistor type. Transistors can operate efficiently at high frequencies, but their power-handling capability is low. At high power levels, multiple units must be used, resulting in a more complex but less reliable circuit. SCRs can handle more power per device and are normally useful at frequencies below 20 kHz. SCRs cannot be turned off by a control signal but require commutating circuitry, which adds to cost and reduces efficiency. The overall efficiency of SCR and transistor converters is approximately the same.

Automatic frequency control is a standard feature on frequency converters. Both SCR and transistor circuits can be either controlled by free-running oscillators or operated in a self-excited mode through positive feedback derived from the load. The self-excited mode is preferable because such systems automatically track the mechanical resonance of the loaded transducer, which assures optimum load matching under all conditions.

Some ultrasonic welding machines also incorporate constant amplitude control. By keeping the transducer mechanical amplitude constant, regardless of load, transducer dissipation is held at a safe level for all loading conditions, and the sonotrode tip amplitude is constant.

In most ultrasonic welding machines, the frequency converter and the welding head are separate assemblies connected by lightweight cables. In some of the low-power units, the converter is attached to the welding head.

TYPES OF EQUIPMENT

Spot Welding Machines

ULTRASONIC SPOT WELDING machines all operate on the same basic principle. They deliver single pulses of high-frequency vibration to the weld interface to produce a spot weld. Two different systems are used to apply the clamping force and transmit the ultrasonic energy to the workpiece: the wedge-reed system and the lateral drive system. Spot welding machines range in size from about 10 W to 8000 W capacity. Figure 25.11 indicates the capabilities of various machines for welding some common metals.

Wedge-Reed System. In the wedge-reed system, the transducer drives a wedge-shaped coupler in longitudinal vibration, as shown in Figure 25.1. The wedge is rigidly attached to the reed and produces flexural vibration in it. The sonotrode at the end of the reed undergoes essentially lateral vibration in a plane parallel to that of the weld interface. For very high powers, two or more transducers may be used to drive the wedge.

Some systems have a movable head and a fixed anvil, with force being applied through the reed. Other systems have a fixed head and a movable anvil, and force is applied through the anvil. In both cases, the reed is acoustically designed for force insensitivity so that the vibration is not damped during force application. Figure 25.12 shows a typical machine of the wedge-reed type with a movable head. A 1500 watt machine with a movable anvil and stationary wedge-reed system is shown in Figure 25.13.

Lateral Drive System. In this system, the sonotrode tip is attached to a lateral sonotrode which vibrates longitudinally to produce tip motion parallel to the weld inter-

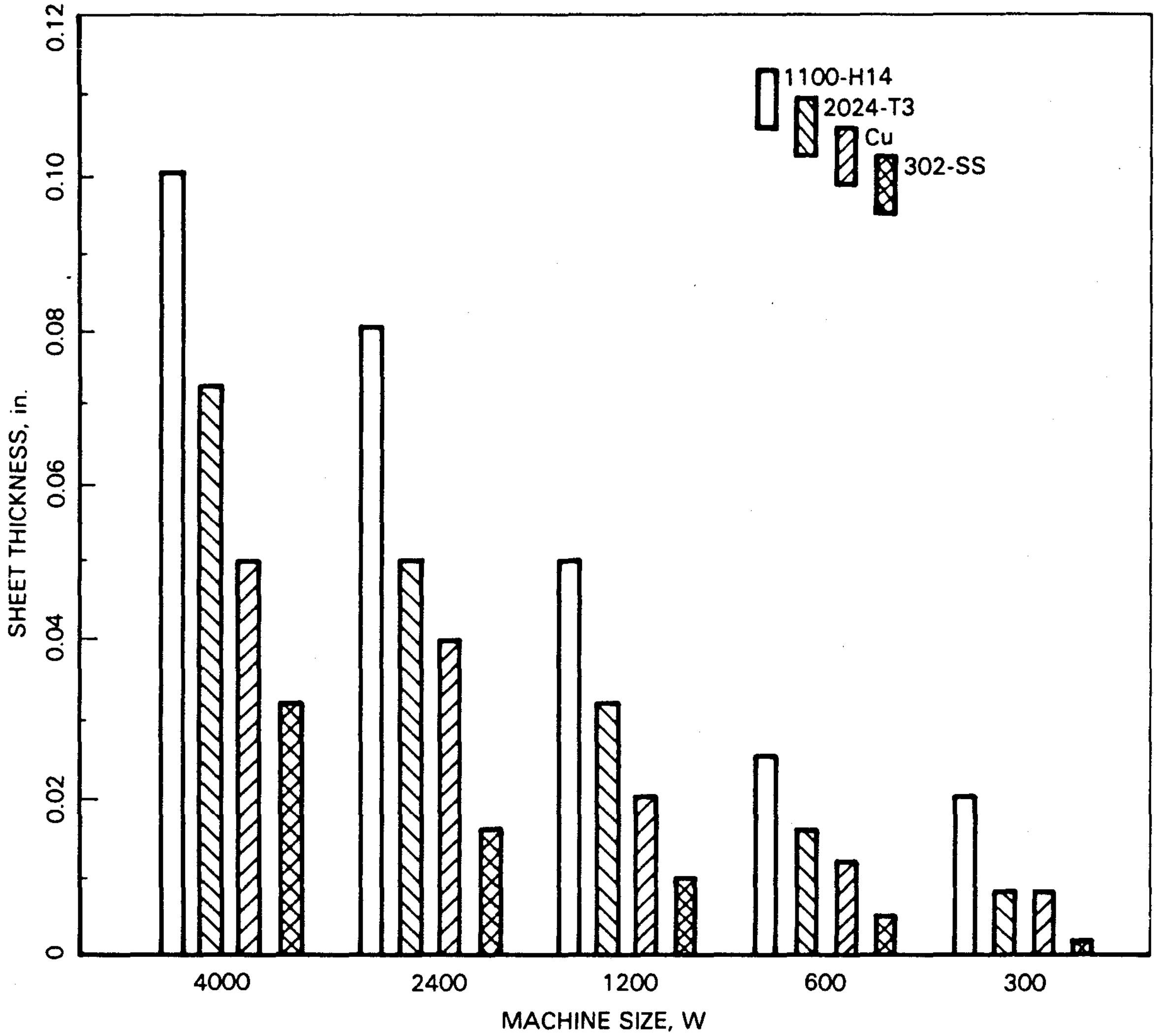


Figure 25.11–Capacities of Several Ultrasonic Spot Welding Machines for Joining Selected Metals

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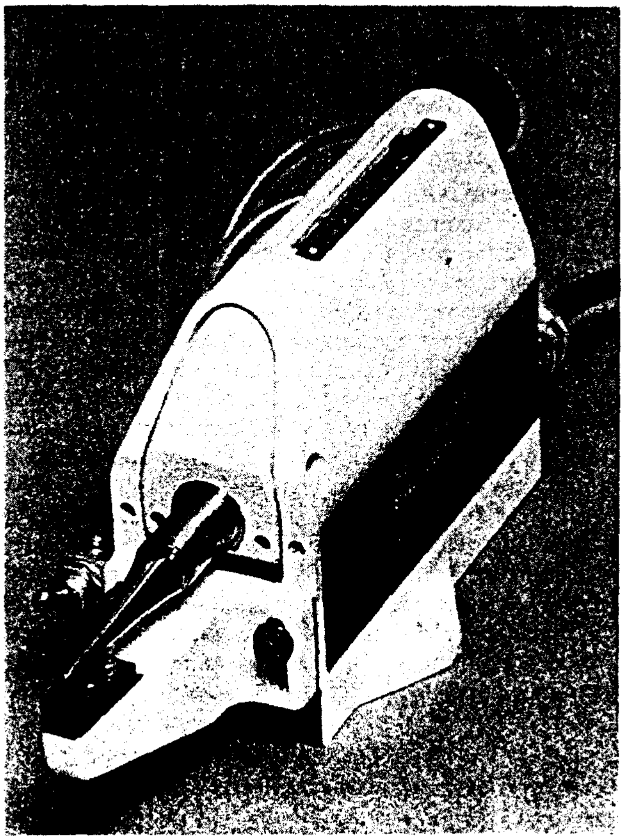


Figure 25.15–Typical 100 Watt Spot Welding Machine With Lateral Drive System

rotated by a motor drive. The rotating tip rolls on the work along the desired path. Three arrangements are used for handling the work: a roller-roller system, a traversing anvil system, and a traversing head system.

Roller-Roller System. In this arrangement, the workpiece is driven between a rotating disk tip and a counter-rotating anvil. A compact 100 W machine is used for thin foil materials. Heavier materials are welded with a 2000 W unit capable of welding rates up to 450 ft/min (135 m/min).

Traversing Anvil System. In this system, the rotating transducer-sonotrode system is mounted in a fixed position. The workpiece is located on an anvil that traverses laterally under the rotating coupler disk.

Traversing Head System. The predominant type of seam welding machine is the traversing head system in which the disk tip rotates as it traverses across the stationary workpiece. A typical unit is shown in Figure 25.17. A 100 W system of this type is used in aluminum foil mills for splicing coils. Machines of higher power capacity are used for splicing thicker materials.

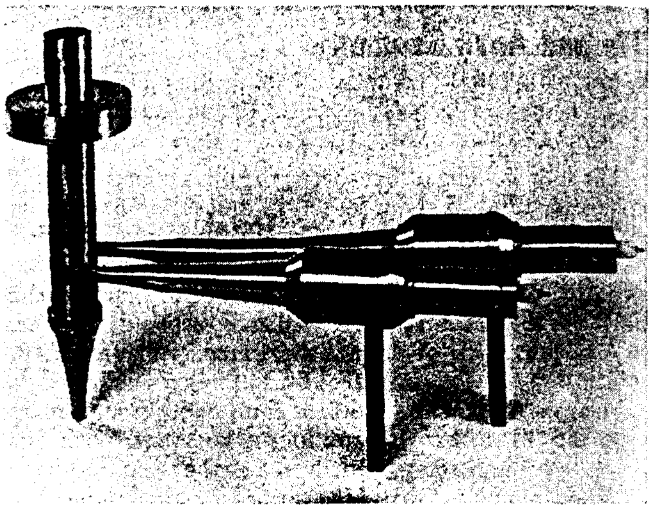


Figure 25.16–Transducer-Sono trode System for Ring Welding Machines

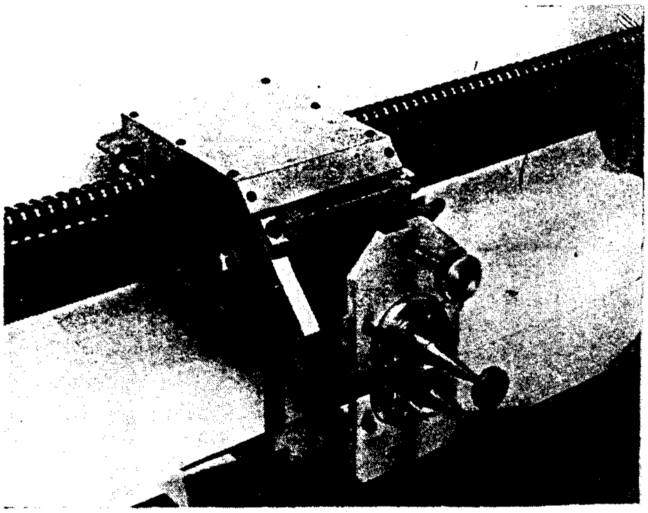


Figure 25.17–Typical Traversing Head, Continuous Seam Ultrasonic Welding Machine

SONOTRODE TIPS AND ANVILS

Tip and Anvil Geometry

WELDING IS MOST effectively accomplished when the sonotrode tip and anvil are contoured to accommodate the specific geometry of the parts being joined.

For spot welding of flat sheets, the tip is contoured to a spherical radius of about 50 to 100 times the thickness of the sheet adjacent to the tip. The anvil face is usually flat. This provides a friction-type drive in which slippage can occur between the tip and the top sheet or between the anvil and the bottom sheet as well as at the weld interface.

A positive type of drive is illustrated in Figure 25.18, which shows the arrangement for welding a small rib to a tubular member. The sonotrode tip is contoured to mate with the rib so that they are locked together. With this drive, maximum energy is delivered at the weld interface.

When joining a wire to a flat surface, the tip is preferably grooved to match the wire so that the wire is not excessively deformed during welding. With small wires, such as those used for connections to semiconductor devices, the tips must be precise in dimensions and finish. For joining two wires together, the anvil may be grooved to support and position both wires. The tip may fit into the groove and contact the upper wire.

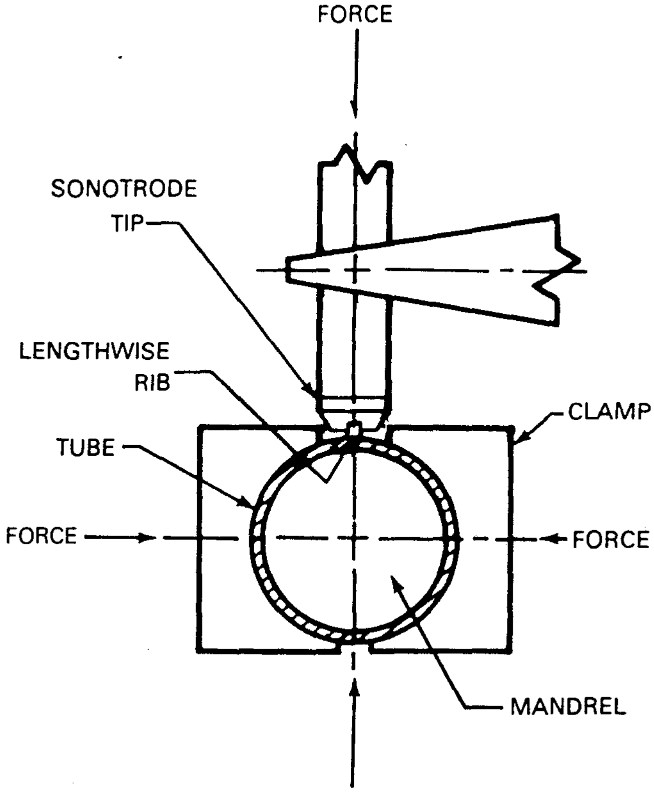


Figure 25.18–Welding Array for Joining Small Longitudinal Ribs to Cylinders

Ring welding tips are usually hollow members having the shape of the desired welds: circular, elliptical, square, or rectangular. The wall thickness is determined by the desired weld width, and the edge of the tip contacting the work is convex. Anvils may be flat or appropriately contoured to mate with the workpiece. In welding a lid to a cylindrical container, the anvil is usually recessed to accommodate the container, with the flange in contact with the anvil surface.

Line welding tips have narrow, elongated shapes with the contacting surface any desired width up to about 0.1 in. (2.5 mm). The anvil is designed to accommodate the workpiece. For line welding of can side seams, for example, the anvil consists of a cylindrical mandrel around which the can body blank is wrapped and supported with clamping jaws, as shown in Figure 25.18.

Continuous seam welding tips are resonant disks. For welding flat surfaces, the disks are machined with a convex edge. The edge of the disk may also be contoured to mate with the workpiece; for example, the entire periphery of a disk can be grooved to permit continuous seam welding of a rib to a cylinder, with an arrangement similar to that shown in Figure 25.18.

Tip Materials

AS IN RESISTANCE spot welding, wear of the sonotrode tip and anvil depends upon the properties and geometry of the parts being welded. Tips made of high-speed tool steel are generally satisfactory for welding relatively soft materials, such as aluminum, copper, iron, and low carbon steel. Tips of hardenable nickel-base alloys usually provide good service life with hard, high-strength metals and alloys. The material used for the sonotrode tip is also satisfactory for the anvil face.

Frequently, longer tip life and more effective welding are possible using tips and anvils with rough faces because they tend to prevent gross slippage between themselves and the workpieces. The roughening may be accomplished with electrical discharge machining (EDM) or by sandblasting to a finish of about 200 microinch. Abrasive tips usually permit the use of lower powers and clamping forces than are required with smooth tips.

Tip Maintenance

WHEN SONOTRODE TIPS begin to show wear, erosion, or material pickup, they may be reconditioned by cleaning and burnishing. Light sanding with 400-grit silicon carbide paper is usually sufficient.

If the wear is excessive, the tips should be replaced. Most welding machines have mechanically attached tips to simplify replacement.

The tip may tend to stick to the weld surface occasionally, particularly if improper machine settings are used. The sticking may be alleviated by increasing the clamping force or decreasing the welding time. With some materials, application of a lubricant, such as a faint trace of very dilute soap solution, to the surfaces being joined will reduce sticking. If these measures are not adequate, tip sticking may usually be eliminated by welding with a tip having an insert of tungsten carbide.

CONTROLS

THE BASIC CONTROLS for an ultrasonic welding machine are relatively simple. They consist of a master switch for introducing line power and controls to adjust clamping force, power, welding time, and sometimes resonance. Appropriate readout is normally provided for all adjustments.

The welding cycle is generally controlled automatically and is usually actuated by dual palm buttons or a foot switch. The automatic cycle consists of lowering the sonotrode tip or raising the anvil, application of clamping force, introduction of the ultrasonic pulse, and retraction of the tip or anvil.

Other controls and indicators are included on some welding machines to monitor operation of the equipment or to provide flexibility in use. Means may be provided for adjustment of the following:

(1) Sonotrode stroke length

(2) Speed of sonotrode advance and retraction from the weldment

(3) Speed of traverse for continuous seam welding machines

(4) Height of anvil to provide clearance for the workpiece

(5) Anvil position, particularly on ring welding machines, where precise alignment of tip and anvil are essential to ensure uniform contact around the periphery of the weld

Weld quality control monitors may also be included. One such device is a weld power meter which indicates the power delivered into the weld. A substantial change in load power indicates a faulty weld, which may be due to changes in part dimensions or surface finish, improper assembly of parts, or machine malfunction. On some machines, the high and low limits of acceptable power can be set, and deviations from this range can be used to trigger a visual or audible signal to alert the operator or to actuate a reject mechanism.

A recent development permits control of distance, either by controlling the distance the part is compressed or the final height of the part above an arbitrary datum, such as the anvil surface.

Microprocessor controlled machines permit selection of the controlling variables. Factors to be controlled are time, energy input, and distance. Most machines of this type are equipped with ports suitable for connection with a printer or computer. With appropriate software, statistical process control tests can be performed.

Another type of weld quality monitor is based on a constant energy principle. This system automatically adjusts welding time so that a predetermined amount of energy is delivered to each weld. When the energy cannot be delivered within the preset time, an alarm is activated.

Automated equipment may also include frequency counters, weld counters, material handling actuators, indexing mechanisms, and other devices to minimize operator functions and maximize production rates.

AUTOMATED PRODUCTION EQUIPMENT

SEVERAL FEATURES OF ultrasonic welding equipment make it particularly adaptable to automated or semiautomated production lines, namely:

(1) The welding head can be readily interfaced with other automatic processing equipment. It can be mounted on any rigid structure and in any position with the tip contacting the work from any direction.

(2) The frequency converter may be located as far as 150 ft (46 m) away from the welding head.

(3) Welding times are usually a fraction of a second, and production rates are limited primarily by the speed of the work-handling equipment.

(4) The process does not involve extensive heating of the equipment or the workpiece.

(5) In automatic filling and closing lines, accidental spillage of the contents on the weld interface usually will not significantly affect weld quality.

MICROELECTRONIC WELDING EQUIPMENT

MICROELECTRONIC WELDERS (WIRE bonders) are high-speed automated machines. Typically, they are capable of joining 6 to 8 wires/sec (12 to 16 welds). There are two basic welding process types, thermosonic ball bonding and ultrasonic wedge bonding. Both processes use ultrasonic energy; however, the tooling, operations, and materials are different. Ultrasonic energy for both process types is generated by a stacked piezo-electric sandwich structure attached to a horn (transducer). The transducer design is tapered to provide mechanical gain. The system resonates at 60 kHz. Phase locked loop circuits latch the electronic and mechanical systems for optimized output. Recent trends include the use of high-speed signal analysis to measure changes in system impedance during welding and to achieve real-time control of ultrasonics during bond formation.

Motion control is accomplished through software controlled servo systems. The thermosonic ball bonder requires three axes of motion for the welding head manipulator, plus one for the positioner. The wedge bonder requires a rotational axis. The servos are required to position the tool with an accuracy of ±2.5 microns (63.5 μm) in all three axes.

Figure 25.19 shows a ball bonding tool with an unbonded ball in position to begin the bonding process. The ball is formed by a spark discharge that melts the tip of the wire. The heat-affected zone above the ball is fully annealed by the discharge. The wire feeds through the capillary allowing the welding head to travel on the surface towards the crescent bond. In ball bonding, it is possible for the crescent bond to be located in any direction with respect to the ball bond. High-purity gold wire (99.99 percent gold) is the predominant bonding wire. Microalloying of the residual 100 ppm impurities must be carefully controlled to insure acceptable ball formation and wire loop shape control. Application of the principal welding variables: weld force, weld time and ultrasonic energy, is software controlled. Welding temperature is controlled independently.

Figure 25.5 shows an ultrasonic wedge bonding tool. Typically, wedge bonding is used with aluminum - 1 percent silicon wire in a room temperature process. However, it is also used, with heat, for bonding gold wire in microwave packages. As shown in Figure 25.5, the wire is positioned under the wedge, normal to the wedge axis. The addition of a rotational axis allows axial alignment of first and second bonds either by rotating the weldhead or by rotating the work.

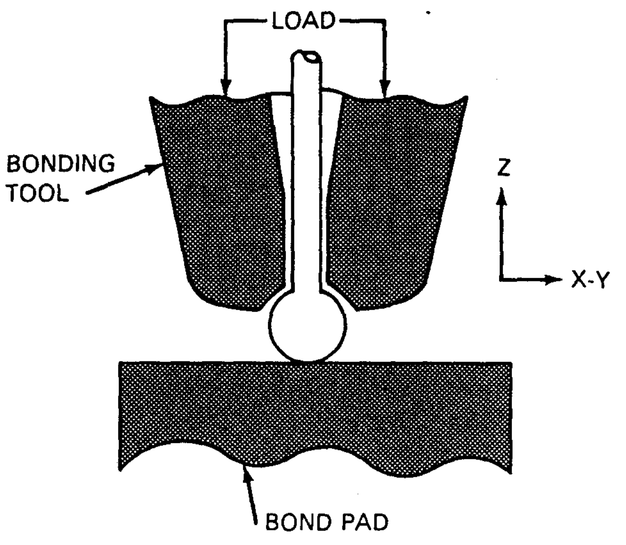


Figure 25.19–Ball Bonding Tool With Unbonded Ball

JOINING PROCEDURES

JOINT DESIGN

JOINT DESIGNS FOR ultrasonic welding are less restrictive than for some other types of welding. Edge distance is not critical. The only restriction is that the sonotrode tip should not crush or gouge the sheet edge. Welds in structural aluminum alloys of several thicknesses have shown the same strength at both 1/8 and 3/4 in. (3 and 19 mm) from the edge. Weight and material savings are achieved by using the minimum acceptable overlap.

Ultrasonic welding places no restrictions on spot spacing or row spacing with any of the four types of welds. Consecutive or overlapped welds have no effect on the quality of previously made welds, except perhaps under resonance conditions described below.

Ring welding offers unique capabilities for hermetic sealing, as indicated by the joint designs in Figure 25.20. Ring welds may also be preferred to spot welds for structural applications. The rings provide relatively uniform stress distribution with less stress concentration, less tendency toward cracking, and generally no parts resonance (see below).

CONTROL OF PARTS RESONANCE

SOMETIMES THE ENTIRE workpiece may be excited to vibration by the ultrasonic welding system. When this occurs, inferior welds may result, previously made welds may fracture, or cracks may be generated in the workpiece. Any of several remedies may be applied singly or in combination.

Resonance vibration may be eliminated by altering the workpiece dimensions or the orientation of the workpiece in the welding machine. Damping of vibration in thin sections can frequently be accomplished by applying pressure-sensitive tape to the part. Clamping of masses to the workpiece or clamping into a comparatively massive fixture usually suffices in even the most difficult cases.

SURFACE PREPARATION

A GOOD SURFACE finish contributes to the ease with which ultrasonic welds are made. Some of the more readily weldable metals, such as aluminum, copper, or brass, can be welded in the mill finish condition if not heavily oxidized, and may require only the removal of surface lubricants

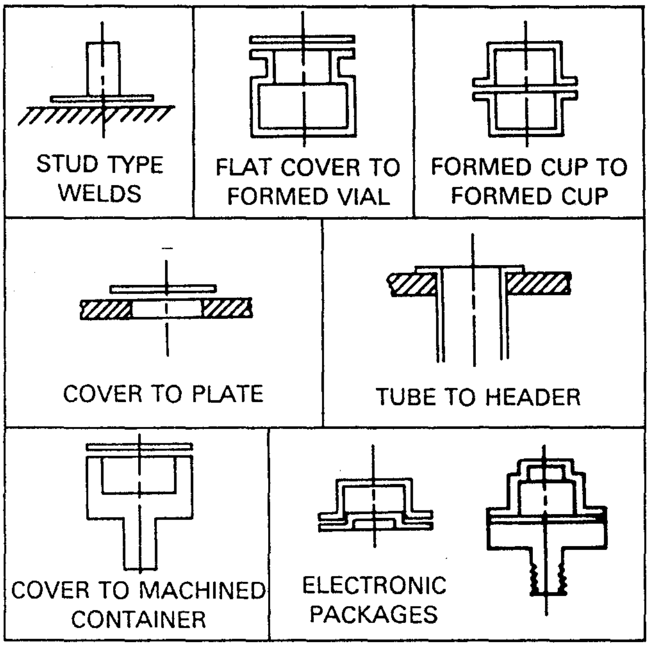


Figure 25.20–Typical Ultrasonic Ring Welding Applications

with a detergent. Normally, thin oxide films do not inhibit welding since they are disrupted and dispersed during the process.

Metals that are heavily oxidized or contain surface scale require more careful surface preparation. Mechanical abrasion or descaling in a chemical etching solution is usually necessary to provide a clean surface for welding. Once the surface scale is removed, the elapsed time before welding is not critical as long as the materials are stored in a noncorrosive environment.

It is possible to weld metals through certain surface films, coatings, or insulations, but somewhat higher ultrasonic energy levels are required. Some types of films cannot be penetrated and must always be removed prior to welding.

SPECIAL WELDING ATMOSPHERES

ULTRASONIC WELDING USUALLY does not require special atmospheres. With some metals, the process may produce discoloration of the surface in the vicinity of the weld. When such a surface is undesirable, it can be minimized by inert gas protection, such as small jets of argon impinging around the tip contact area. For packaging applications in which sensitive materials must be protected from contamination, welding can be accomplished in a chamber filled with inert gas.

PROCESS VARIABLES

THE VARIABLES OF ultrasonic power, clamping force, and welding time or speed are established experimentally for a specific application. Once determined, they usually require no adjustment unless there are alterations to the equipment, such as sonotrode tip changes or changes in the workpiece.

ULTRASONIC POWER

THE POWER SETTING may be indicated in terms of the high-frequency power input to the transducer, or the load power (the power dissipated by the transducer-sonotrode-workpiece assembly). As previously noted, the power requirement varies with the material and thickness of the workpiece adjacent to the sonotrode tip.

The minimum effective power for a given application can be established by a series of tests from which a threshold curve for welding is plotted. Details of this procedure are described later.

CLAMPING FORCE

AN ULTRASONIC WELDING machine usually provides a fairly broad range of clamping forces. Table 25.2 shows typical ranges for machines of various power capacities. The clamping-force range of machines with hydraulic or pneumatic force systems can be modified by changing the pressure cylinder.

The function of clamping force is to hold the workpieces intimately together. Excessive force produces needless surface deformation and increases the required welding power. Insufficient force permits tip slippage that may cause surface damage, excessive heating, or poor welds. Clamping force for a specific application is established in conjunction with ultrasonic power requirements.

WELDING TIME OR SPEED

THE INTERVAL DURING which ultrasonic energy is transmitted to the workpieces in spot, ring, or line welding is usually within the range of 0.005 second for very fine wires to about 1 second for heavier sections. The need for a long welding time indicates insufficient power. High power and a short welding time will usually produce welds that are superior to those achieved with low power and a long welding time. Excessive welding time causes poor surface appearance, internal heating, and internal cracks.

Table 25.2
Typical Clamping Force Ranges for Ultrasonic Welding Machines of Various Power Capacities

Machine Power Capacity, W	Approximate Clamping Force Range, lbf
20	0.009-0.39
50-100	0.5-15
300	5-180
600	70-400
1200	60-600
4000	250-3200
8000	800-4000

The same factors of power and unit time are significant in continuous seam welding. With available equipment, the travel speed for hard, thick metals may be as low as 5 ft/min. (1.5 m/min). Thin aluminum, 0.001-in. thick, can be welded at speeds up to about 500 ft/min (150 m/min).

FREQUENCY ADJUSTMENT

ADJUSTMENT OF THE frequency converter output to match the operating frequency of the welding system is necessary for good performance. A system has a given nominal frequency, but the best operating frequency may vary with changes in the sonotrode tip, the workpiece, or the clamping force. The method of frequency adjustment varies with different types of frequency converters. After the setting is established for a specific welding setup, usually no further adjustment is necessary.

INTERACTION OF WELDING VARIABLES

FOR A GIVEN application, there is an optimum clamping force at which minimum vibratory energy is required to produce acceptable welds. This condition can be established by plotting the threshold curve. This curve, illustrated in Figure 25.21, defines the conditions of best dynamic coupling between the sonotrode tip and the workpiece and, thus, the minimum energy to produce strong welds.

The technique consists of making welds at selected power and clamping force settings and conducting cursory evaluation of weld quality as noted on Figure 25.21. For ductile, thin sheets and fine wires, a useful criterion of successful bonding is the ability to pull a nugget from one of the workpieces when peel tested. Welds in hard or brittle metals may be evaluated on the basis of weld strength or evidence of material transfer when peel tested. The threshold curve is normally derived as follows:

(1) The welding time is set at a reasonable value. One-half second is a good starting point for most metals. For very thin metals, a shorter weld time is usually chosen.

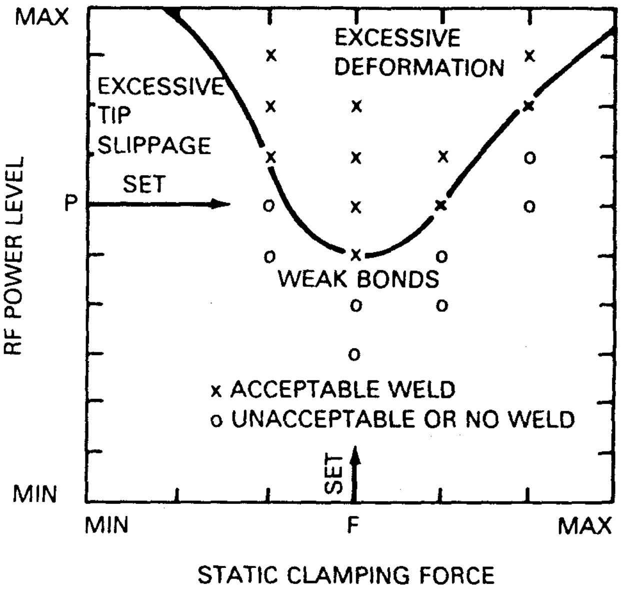
(2) Welding is started at low values of clamping force and power, and a series of test welds is made with incrementally increasing values of clamping force at a fixed power level. The welds are evaluated and the results plotted as in Figure 25.21, indicating acceptable and unacceptable welds.

(3) This procedure is then repeated at other values of ultrasonic power until an inverted bell-shaped curve is obtained.

These data will generate a curve separating the acceptable from the unacceptable welds. Welding is ordinarily done using the clamping force value for minimum acceptable power and a power level somewhat above the minimum. The product of the selected power and weld time is the total energy required. If welding time is decreased, then power must be increased accordingly. The threshold curve is a practical and efficient method for determining proper machine settings for all types of ultrasonic welds.

POWER-FORCE PROGRAMMING

CERTAIN MATERIALS, SUCH as the refractory metals and alloys, are more effectively welded when power-force programming is used. Weld strength is higher and cracking of the weld metal is minimized when these programming techniques are used.



OPTIMUM CONDITIONS FOR MINIMUM POWER ARE CLAMPING FORCE F AND POWER P

Figure 25.21–Typical Threshold Curve Relating RF Power and Clamping Force

Power-force programming involves incremental variations in power and clamping force during the welding cycle. The cycle is initiated at low power and high clamping force. After a brief interval, the power is increased and the force reduced. The cycle is accomplished automatically with special logic circuitry.

WELD QUALITY

INFLUENCING FACTORS

VARIATIONS IN WELD quality may result from several factors which are generally associated with the workpieces and the welding machine or its settings. Weld quality is ordinarily not affected by normal manufacturing variations in metal parts. Metals that meet the specification requirements can usually be consistently welded without varying machine settings. Problems are sometimes encountered, however, if close tolerances are not held. For example, nickel, copper, and gold platings on metal surfaces frequently have thickness variations that affect weld quality. Surfaces for ring welding must be flat and parallel to ensure uniform welding around the periphery.

If there is any change in the workpieces during a production operation, the welding schedule must usually be adjusted to accommodate such change. Variations in weld quality during production runs have been traced to unauthorized changes in metal alloy, geometry, or surface finish. Wires such as magnet wires that are lubricated to facilitate coil winding may be ultrasonically welded without cleaning. However, a change in the type of lubricant may cause unacceptable welds unless machine settings are appropriately adjusted.

Uniform quality welding also depends upon the mechanical precision of the welding machine. Lateral deflection of the sonotrode or looseness of the anvil can produce unacceptable aberrations in the welds. Erratic weld quality may result from the use of a force-sensitive machine if power is lost and the frequency shifts as clamping force is applied. Sonotrode tips must be acoustically designed and precision ground to the desired contour. Their surfaces must be properly maintained to ensure reproducible welds.

PHYSICAL AND METALLURGICAL PROPERTIES

ULTRASONIC WELDS HAVE distinctive characteristics when examined both internally and externally.

Surface Appearance

THE SURFACE OF the work at a weld location is usually roughened slightly by the combined compressive and shear forces. The roughness can be minimized with adjustments in the machine settings and with careful sonotrode tip maintenance. The surface contour depends primarily on tip geometry. Spot welds usually leave an elliptical impression because of the linear displacement of the tip. A weld impression is larger in soft, ductile metals, such as aluminum, than in hard metals of the same thickness with appropriate adjustment in machine settings. Spot size can be increased by using a larger tip radius.

The actual weld area does not necessarily duplicate the surface impression, except in thin sheet. Sometimes, spot welds have unwelded areas in the center. This condition can usually be eliminated by decreasing the tip radius or reducing the clamping force.

Thickness Deformation

A WELD MAY show some thickness deformation because of the applied clamping force. Such deformation in sheet metals is usually less than 20 percent of the total joint thickness, even with soft metals. With contoured parts such as wires, deformation is somewhat greater unless the tip contour mates with the workpiece. Deformation may exceed 50 percent in fine wires.

Microstructural Properties

METALLOGRAPHIC EXAMINATION OF ultrasonic welds in a wide variety of metals shows that a number of different phenomena occur as a result of the vibratory energy introduced into the weld zone. The following are three important ones:

(1) Interfacial phenomena, such as interpenetration and surface film disruption

(2) Working effects, such as plastic flow, grain distortion, and edge extrusion

(3) Heat effects, such as recrystallization, precipitation, phase transformation, and diffusion

Ultrasonic welding is usually accompanied by local plastic deformation along the faying surfaces, by interdiffusion or recrystallization at the interface, and by interruption and displacement of oxide or other barrier films. Surface films, which are broken up by the stress reversals and plastic deformations that occur along the interface, may be displaced in the vicinity of the interface or may simply be interrupted in continuity in random areas within the bond zone. The actual behavior of such films depends upon several factors, including the machine settings, the properties of the film and the base metal, and the temperature achieved at the interface.

The temperature effect is significant in welding certain metals. Recrystallization of the metal frequently occurs in the weld nugget. Sufficient heat may be generated in certain alloys that exhibit precipitation behavior or phase transformation to induce these effects. Although diffusion may occur across the interface, the extent of atom movements is limited by the short weld time.

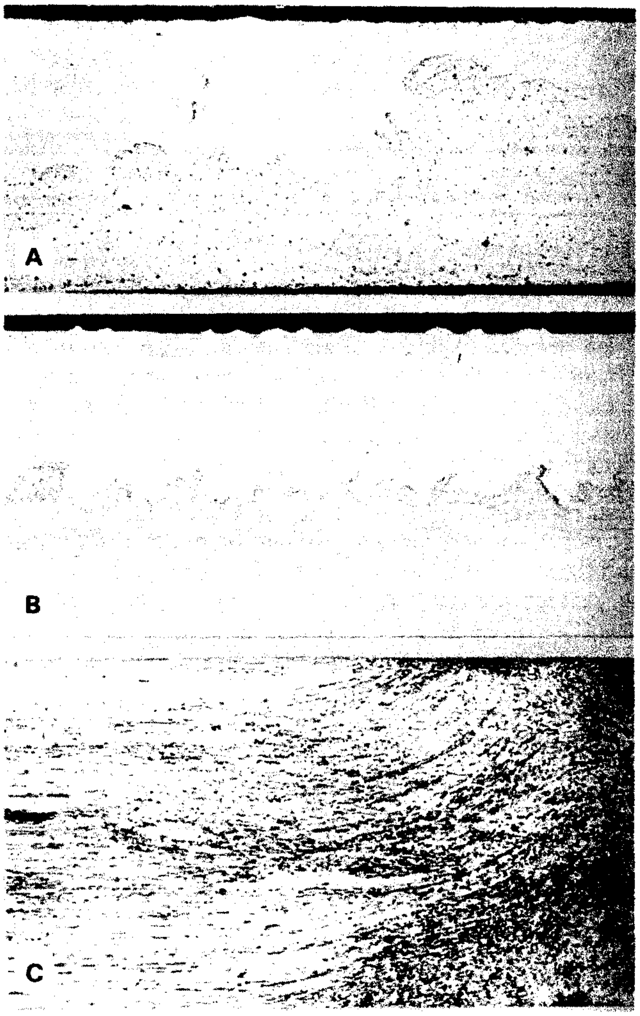
More than one of the above effects may be apparent in the same weld, and different effects may occur in welds in the same metal produced at different machine settings.

Several typical examples are illustrated in Figure 25.22. An extreme example of interpenetration across an interface is shown in Figure 25.22(A), in which a Kovar[3] foil has intruded into as much as 75 percent of the thickness of a nickel foil. A gold plate on the surface of the Kovar has been dispersed throughout the highly worked region. Interfacial ripples in a nickel-to-molybdenum weld, shown in Figure 25.22(B), illustrate the plastic flow that occurs locally. Entrapped oxide is indicated by the dark patches on the extreme right of the figure.

The weld between two sheets of arc-cast molybdenum, Figure 25.22(C), shows very little interpenetration, and the bond line is thin. Figure 25.22(D) illustrates the surface oxide film dispersion that may occur during welding of aluminum sheet. General plastic flow along the interface is observed in the Type 2024-T3 aluminum alloy weld of Figure 25.22(E) where the metal has recrystallized to a fine grain size.

Evidence of recrystallization has been observed in ultrasonic welds in several structural aluminum alloys, beryllium, low carbon steel, and other metals, even though they were not in the cold-worked condition prior to welding. For instance, in the Type 2020 aluminum alloy weld in Figure 25.22(F), mutual deformation of the surfaces and subsequent recrystallization are evident. In Figure 25.22(G), the elevated temperature during welding resulted in recrystallization of prior cold-worked nickel.

Still another effect of interfacial heating is illustrated in Figure 25.22(H), which shows a weld in solution treated and aged nickel base alloy. In the aged condition, a precipitate normally appears throughout the grains and in the grain boundaries. In the vicinity of this interface, the oxide scale is dispersed and the grain boundaries appear to stop short of the interface, indicating that the precipitate was dissolved during welding. An example of alloying that may occur in the bond between ferrous metals of different carbon content is shown in Figure 25.22(J).



(A) 0.003-in. NICKEL FOIL (TOP) TO 0.003-in. GOLD-PLATED KOVAR FOIL (X 150)

(B) 0.005-in. NICKEL FOIL (TOP) TO 0.020-in. MOLYBDENUM SHEET (X 100)

(C) 0.008-in. ARC-CAST MOLYBDENUM SHEET TO ITSELF (X 70)

Figure 25.22–Photomicrographs of Typical Ultrasonic Welds

MECHANICAL PROPERTIES

A VARIETY OF mechanical tests may be used to evaluate weld quality. The property most frequently tested is shear strength. In addition, data are reported on tensile strength,

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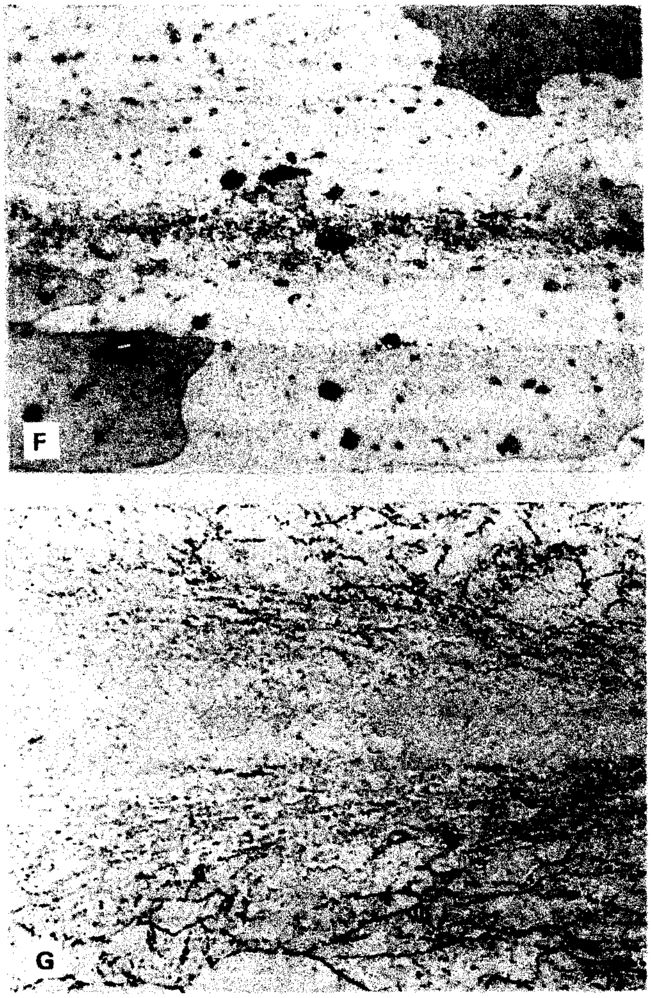
[3] Low-expansion iron-base alloy containing 29 percent nickel and 17 percent cobalt.

(D) 0.012-in. TYPE 1100-H14 ALUMINUM SHEET TO ITSELF (X 250)

(E) 0.032-in. TYPE 2024-T3 ALUMINUM ALLOY SHEET TO ITSELF (X 75)

Figure 25.22 (Continued)–Photomicrographs of Typical Ultrasonic Welds



(F) 0.040-in. TYPE 2020 ALUMINUM ALLOY SHEET TO ITSELF (X 375)

(G) 0.014-in. HALF-HARD NICKEL SHEET TO ITSELF (X 250)

Figure 25.22 (Continued)–Photomicrographs of Typical Ultrasonic Welds

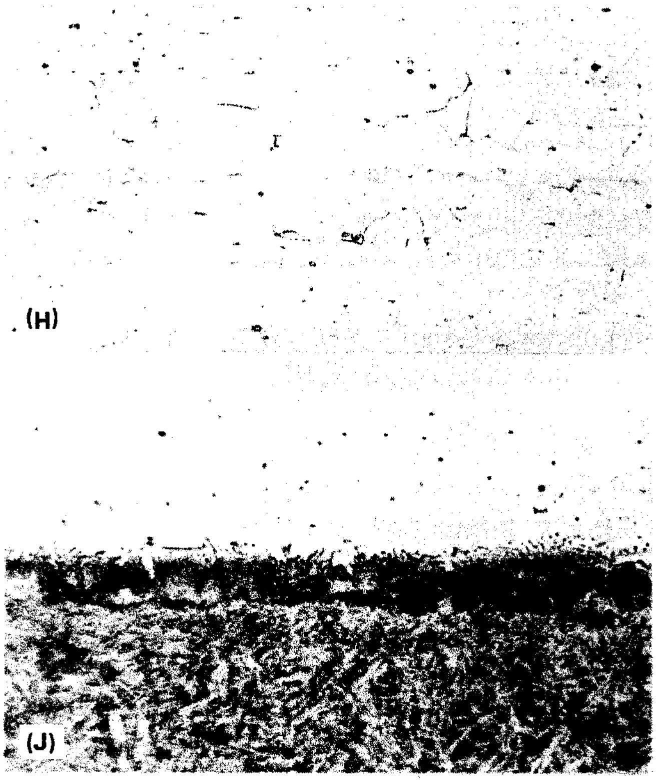
microhardness, corrosion resistance, and hermetic sealing properties. All available information indicates that the ultrasonic technique, properly applied, produces welds of acceptable strength and integrity.

Shear Strength

SHEAR TESTS ARE usually conducted on simple lap joints containing single or multiple spot welds or predetermined lengths of seam or line welds. For convenience, test specimen preparation and testing procedures essentially duplicate those used for resistance spot and seam welds. Microshear tests have also been developed for thermosonic ball bonds.

Figure 25.23 shows the increase in shear strength with sheet thickness for single-spot specimens in two aluminum alloys. Usually in the thin gages of aluminum sheet, and often in the intermediate gages, failure occurs by fracture of the base metal or by tear-out of the weld button rather than by shear of the weld itself. Similar data for several stainless steel and nickel alloys are shown in Figure 25.24 and for several refractory metals and alloys in Figure 25.25.

Typical spot-weld strengths in a variety of metals are summarized in Table 25.3. Of particular interest is the low



(H) 0.012-in. SOLUTION HEAT-TREATED AND AGED INCONEL X-750 SHEET TO ITSELF (X 75)

(J) 0.032-in. DIE STEEL (0.9% C) (TOP) TO 0.032-in. INGOT IRON (X 500)

Figure 25.22 (Continued)–Photomicrographs of Typical Ultrasonic Welds

variability associated with the strength data. In most instances this is less than 10 percent.

Line welds and seam welds show approximately the same strength as the base metal, at least with thin gages. As an example, spot seam welds in structural aluminum alloys have shown strengths equivalent to 85 to 95 percent of the ultimate tensile strength of the material under both shear and hydrostatic tests. Line welds in 0.001-in. type 5052-H16 aluminum alloy average 85 to 92 percent of the base metal strength. Continuous seam welds in thin gage 1100 aluminum show 88 to 100 percent joint efficiency.

Elevated temperature tests on welded specimens of several metals and alloys indicate that weld strength is no lower than that of the base material at the same temperature.

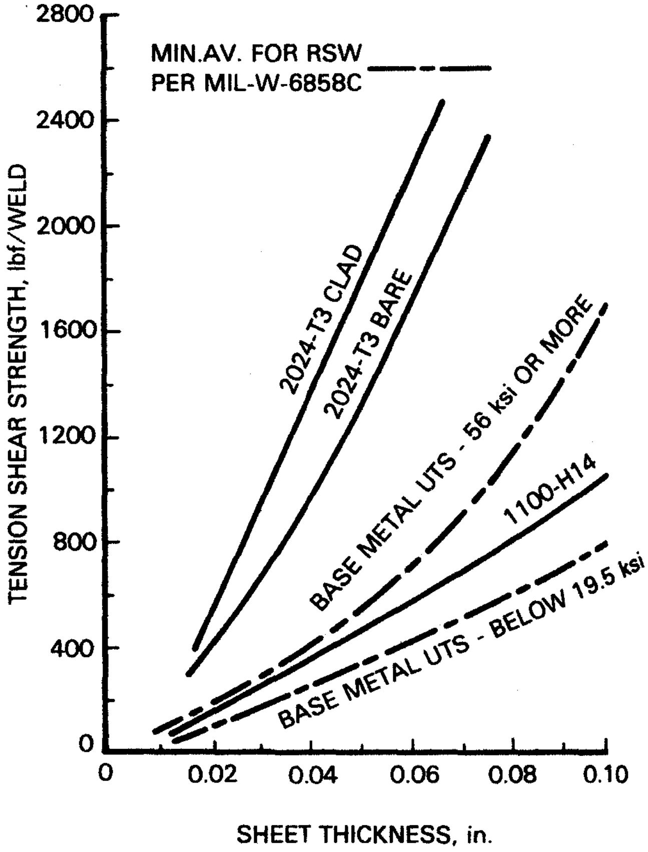


Figure 25.23–Typical Shear Strengths of Ultrasonic Spot Welds in Aluminum Alloy Sheet

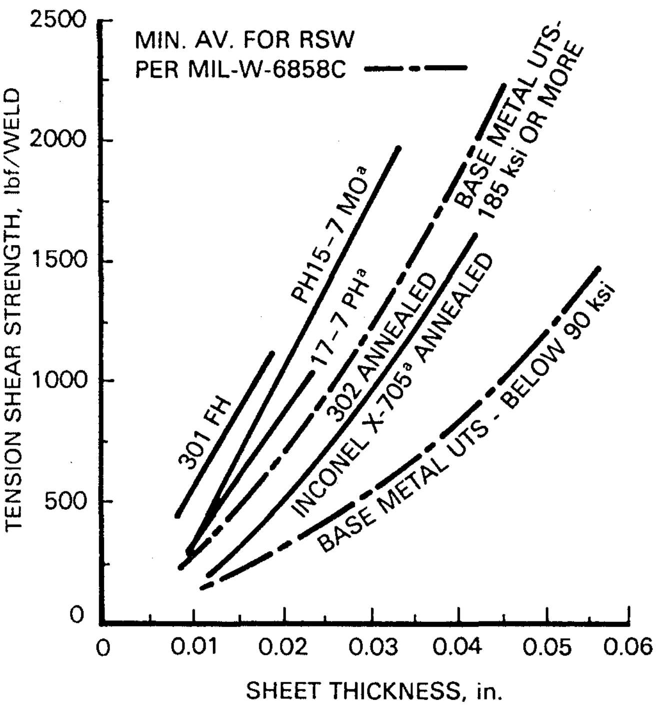
Tensile Strength

TENSILE TESTS ON welds in selected metals indicate tensile strengths usually within the range of 20 to 40 percent of the shear strength. With resistance welds, the ratio of direct tension to shear strength is usually taken as a criterion of weld ductility. The significance of this ratio for ultrasonic welds has not been established.

CORROSION RESISTANCE

THE CAST NUGGET of a resistance spot weld is frequently the site of localized corrosion attack when the weldment is exposed to an unfavorable environment. This is not true of ultrasonic welds. Weld specimens in aluminum alloys and stainless steels that have been exposed in boiling water, sodium chloride solutions, and other corrosive materials have shown no preferential attack in the weld.

However, when dissimilar metals are welded, the possibility of galvanic corrosion at the weld nugget must be recognized.



^{a}TRADE NAME

Figure 25.24—Typical Shear Strengths of Ultrasonic Spot Welds in Stainless Steel and Nickel-Base Alloys

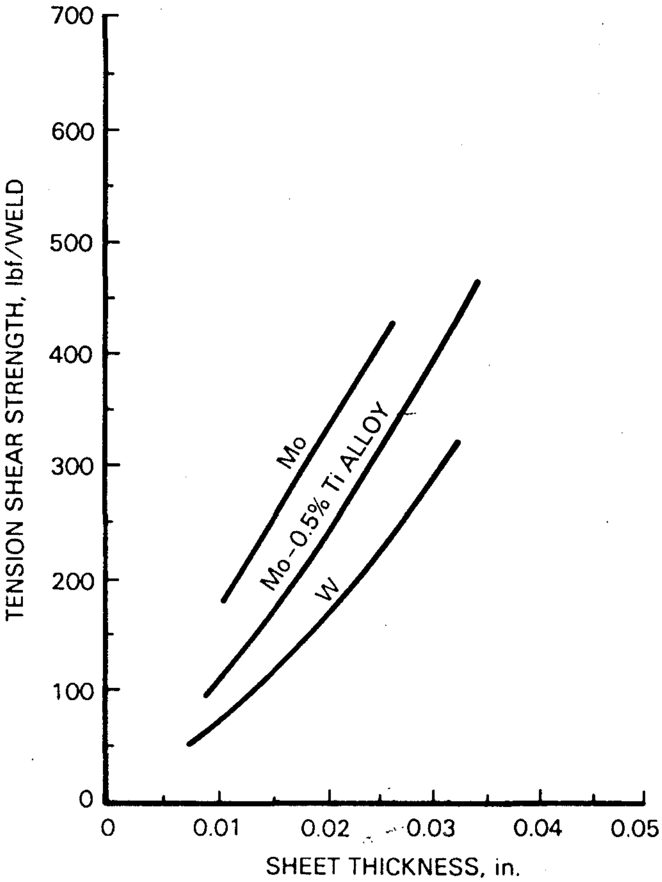


Figure 25.25—Typical Shear Strengths of Ultrasonic Spot Welds in Several Refractory Metals and Alloys

QUALITY CONTROL

Nondestructive Evaluation

THE WELD POWER monitor, discussed previously, provides an effective means of monitoring weld quality at the time the weld is made. The operator can immediately detect an improper cycle and reject the part, or logic may be provided for automatic rejection of a part that is made at an unsatisfactory level.

A number of postweld nondestructive techniques are also available. Ultrasound, radiography, and infrared radiation techniques may be used in specific applications. If hermetic sealing is the primary requirement of the weld, helium leak tests are effective.

Destructive Testing

AN APPROACH USED for some applications involves destructive testing of randomly selected specimens during a production run. For relatively thin ductile sheet, a peel test will indicate adequate weld strength if failure occurs by nugget tear-out or fracture of the base metal. Metallographic sectioning for examination provides a reliable indication of weld quality, but it is slow and expensive.

For most applications, shear testing is the most practical destructive test. Figure 25.26 shows typical variations in shear strength of random spot weld samples in 0.040-in. (1.0 mm) Type 2024-T3 aluminum alloy, produced with a specific machine setting for a number of days at different times of the day. The maximum, average, and minimum-strength values for each set of weld samples are shown. The horizontal lines indicate the mean value and standard deviation range for the entire group. The process began to show poor control on the seventh and eighth days. Control was restored on the ninth day by making the appropriate amplitude adjustments.

Table 25.3
Typical Shear Strengths of Ultrasonic Spot Welds in Several Alloys

Metal	Alloy or Type	Sheet Thickness, in.	Mean Shear Strength With 90% Confidence Interval, lbf
Aluminum	2020-T6	0.040	1240 ± 50
	3003-H14	0.040	730 ± 40
	5052-H34	0.040	750 ± 30
	6061-T6	0.040	800 ± 40
	7075-T6	0.050	1540 ± 90
Copper	Electrolytic	0.045	850 ± 20
Nickel	Inconel X-750 (*)	0.032	1520 ± 100
	Monel K-500 (*)	0.032	900 ± 60
	Rene 41 (*)	0.020	380
	Thoria dispersed	0.025	910
Steel	AISI 1020	0.025	500 ± 20
	A-286	0.015	680 ± 70
	AM-350	0.008	310 ± 20
	AM-355	0.008	380 ± 70
Titanium	8% Mn	0.032	1730 ± 200
	5% Al-2.5% Sn	0.028	1950 ± 120
	6% Al-4% V	0.040	2260 ± 180

* Trade Names

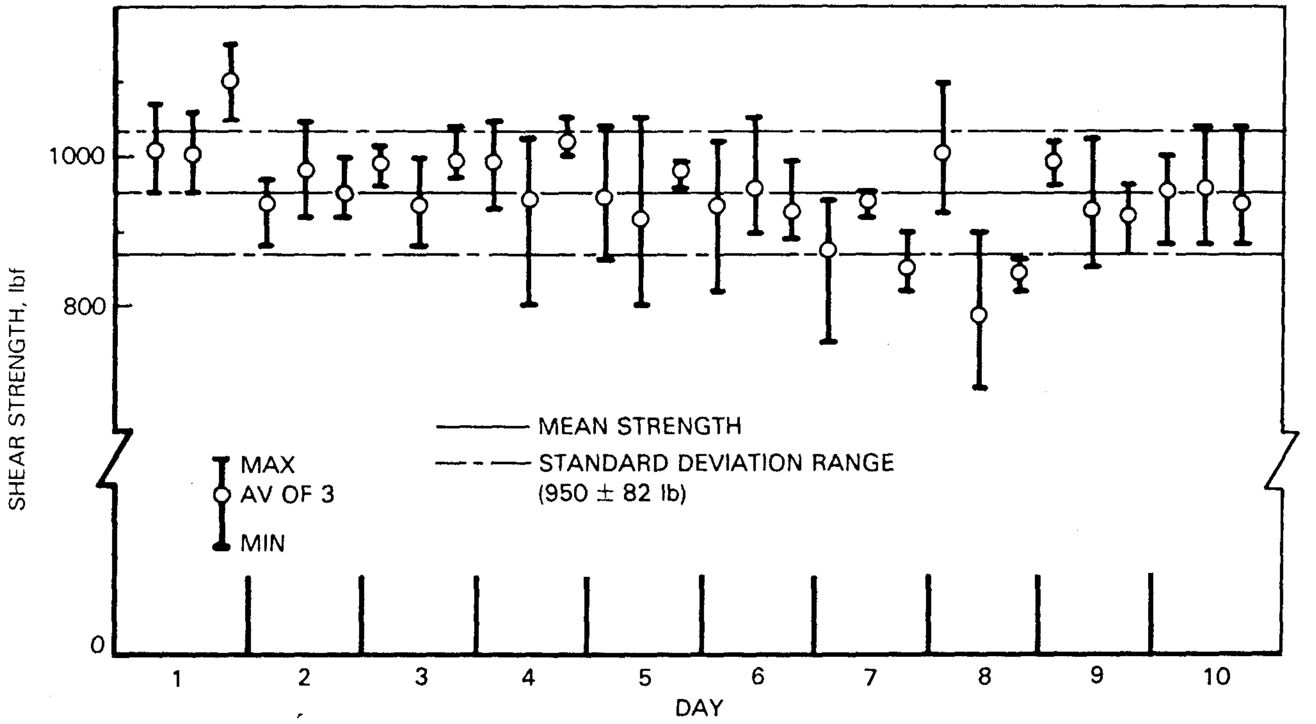


Figure 25.26–Typical Variance in Ultrasonic Weld Shear Strength in 0.040 in. Type 2024-T3 Aluminum Alloy

SAFETY

THE INTENT OF this section is to outline any probable hazards specifically associated with operating ultrasonic welding equipment. Thus, no attempt will be made here to discuss all of the potential hazards associated with welding and cutting processes in general, which are covered in detail in ANSI/ASC Z49.1 (latest edition), *Safety In Welding and Cutting*, nor all the OSHA regulations established to protect personnel working on (or around) various forms of industrial machinery and welding equipment. Strict conformance to the general requirements outlined in such applicable documents should be adhered to at all times.

The operator may require both eye and ear protection, depending on the specific application and equipment. Safety glasses are recommended for all workplace environments. Sound levels in the work area should be monitored to determine if a need for ear protection exists.

Most ultrasonic welding equipment is designed with interlocks and other safety devices to prevent operation under unsafe conditions. Nevertheless, consideration must be given to the health and safety of the operators, maintenance personnel, and other personnel in the area of the welding operations. Good engineering practice must be followed in the design, construction, installation, operation, and maintenance of equipment, controls, power supplies, and tooling to assure conformance to Federal safety laws (OSHA), state safety laws, and safety standards of the using company.

With high-power equipment, high voltages are present in the frequency converter, the welding head, and the coaxial cable connecting these components. Consequently, the equipment should never be operated with the doors open or housing covers removed. Door interlocks are usually installed to prevent introduction of power to the equipment when the high-voltage circuitry is exposed. The cables are shielded fully and present no hazard when properly connected and maintained.

Because of hazards associated with application of clamping force, the operator should never place hands or arms in the vicinity of the welding tip when the equipment is energized. For manual operation, the equipment is usually activated by dual palm buttons that meet the requirements of the Occupational Safety and Health Administration (OSHA). Both buttons must be pressed simultaneously to actuate a weld cycle, and both must be released before the next cycle is initiated. For automated systems in which the weld cycle is sequenced with other operations, guards should be installed for operator protection. Such hazards can be further minimized by setting the welding stroke to the minimum that is compatible with workpiece clearance.

Ring welding machines may be used for closure of containers filled with detonable materials. While no instance is known of premature ignition of such materials during ultrasonic welding, adequate provisions should always be made for remote operation by placing the welding machine either in a separate room from the control station or behind an explosion-proof barrier.

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CHAPTER 26

DIFFUSION WELDING AND BRAZING

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CHAPTER 26

DIFFUSION WELDING AND BRAZING

FUNDAMENTALS OF THE PROCESSES

DEFINITIONS AND GENERAL DESCRIPTIONS

DIFFUSION WELDING (DFW) is a solid state welding process that produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the workpieces. A filler metal may be inserted between the faying surfaces. Terms which are sometimes used synonymously with diffusion welding include diffusion bonding, solid-state bonding, pressure bonding, isostatic bonding, hot press bonding, forge welding, and hot pressure welding.

Several kinds of metal combinations can be joined by diffusion welding:

(1) Similar metals may be joined directly to form a solid-state weld. In this situation, required pressures, temperatures, and times are dependent only upon the characteristics of the base metals and their surface preparation.

(2) Similar metals can be joined with a filler metal in the form of a thin layer of a different metal between them. In this case, the filler metal may promote more rapid diffusion or permit increased microdeformation at the joint to provide more complete contact between the surfaces. This filler metal may be diffused into the base metal by suitable heat treatment until it no longer remains a separate layer.

(3) Two dissimilar metals may be joined directly where diffusion-controlled phenomena occur to form a metallic bond. The mechanisms are similar to those in category (1) above, with the added effects that dissimilar metals create.

(4) Dissimilar metals may be joined with a third metal; i.e., a filler metal, between the faying surfaces to enhance weld formation either by accelerating diffusion or permitting more complete initial contact in a manner similar to category (2) above.

Diffusion brazing (DFB) is a process that forms liquid braze metal by diffusion between dissimilar base metals or between base metal and filler metal preplaced at the faying surfaces. The process is used with the application of pressure. The filler metal may be diffused into the base metal to the extent that a distinct layer of brazing filler metal does not exist in the joint after the diffusion brazing cycle is completed. The joint properties approach those of the base metal. The process is sometimes called liquid phase diffusion bonding, eutectic bonding, or activated diffusion bonding.

Diffusion welding and diffusion brazing are similar in that a filler metal may be used with both processes. However, melting takes place by diffusion at the faying surfaces during the early stage of diffusion brazing. If diffusion at the interface continues with sufficient time at elevated temperature, any distinct layer of filler metal will finally disappear. Then the joint properties are nearly the same as those of the base metal.

If a filler metal is used and it does not melt, or alloy with the base metal to form a liquid phase, the process is diffusion welding. The purpose of the filler metal is to aid metallic bonding, particularly during the first stage of diffusion welding. It helps to eliminate voids at the interface that result when two rough surfaces are mated together. By proper selection, the filler metal will soften at welding temperature and flow under pressure to fill the interface voids. Also, it will diffuse into the base metal and produce a joint with acceptable properties for the application. The filler metal may be a diffusion aid, but it is not a brazing filler metal.

DIFFUSION WELDING PRINCIPLES

AS ILLUSTRATED IN Figure 26.1, metal surfaces have several general characteristics:

(1) Roughness
(2) An oxidized or otherwise chemically reacted and adherent layer
(3) Other randomly distributed solid or liquid products such as oil, grease, and dirt
(4) Adsorbed gas or moisture, or both

Two necessary conditions must be met before a satisfactory diffusion weld can be made:

(1) Mechanical intimacy of faying surfaces.
(2) The disruption and dispersion of interfering surface contaminants to permit metallic bonding.

For conventional diffusion welding without a diffusion aid, a three-stage mechanistic model, shown in Figure 26.2, adequately describes weld formation. In the first stage, deformation of the contacting asperities occurs primarily by yielding and by creep deformation mechanisms to produce intimate contact over a large fraction of the interfacial area. At the end of this stage, the joint is essentially a grain boundary at the areas of contact with voids between these areas. During the second stage, diffusion becomes more important than deformation, and many of the voids disappear as grain boundary diffusion of atoms continues. Simultaneously, the interfacial grain boundary migrates to an equilibrium configuration away from the original weld interface, leaving many of the remaining voids within the grains. In the third stage, the remaining voids are eliminated by volume diffusion of atoms to the void surface (equivalent to diffusion of vacancies away from the void). The stages overlap, and mechanisms that may dominate one stage also operate to some extent during the other stages.

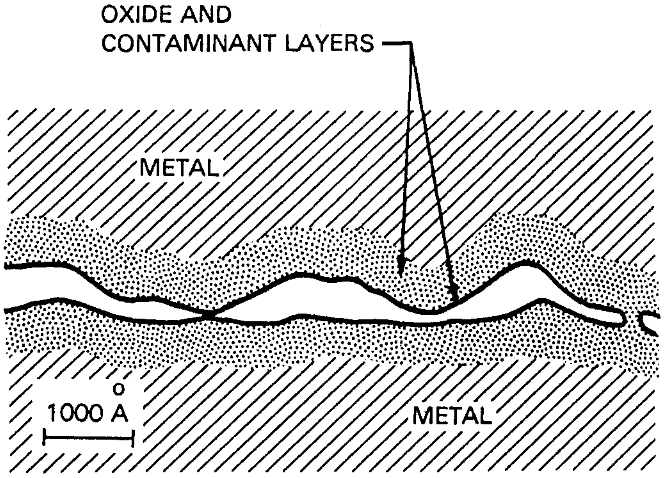

Figure 26.1–Characteristics of a Metal Surface Showing Roughness and Contaminants Present

This model is consistent with several experimentally observed trends:

(1) Temperature is the most influential variable since it, together with pressure, determines the extent of contact area during stage one and it alone determines the rate of diffusion that governs void elimination during the second and third stages of welding.

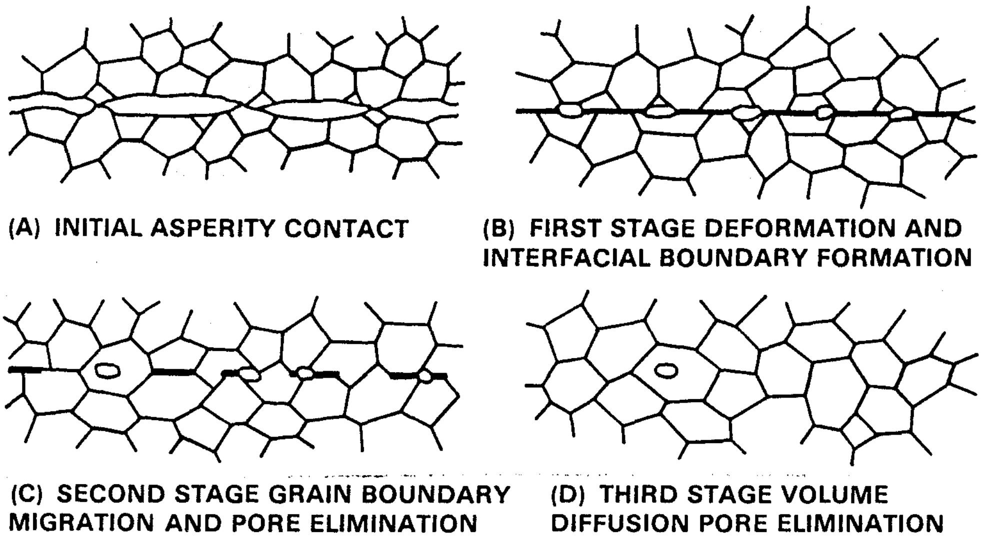

Figure 26.2–Three-Stage Mechanistic Model of Diffusion Welding

(2) Pressure is necessary only during the first stage of welding to produce a large area of contact at the welding temperature. Removal of pressure after this stage does not significantly affect joint formation. However, premature removal of pressure before completion of the first stage is detrimental to the process.

(3) Rough initial surface finishes generally adversely affect welding by impeding the first stage and leaving large voids that must be eliminated during the later stages of welding.

(4) The time required to form a joint depends upon the temperature and pressure used; time is not an independent variable.

This model is not applicable to diffusion brazing or hot pressure welding processes where intimate contact is achieved through the use of molten filler metal and bulk deformation, respectively.

At the same time that intimate contact is being achieved as described above, various intervening surface films must be disrupted and dispersed so that metallic bonds can form. During initial faying surface contact (stage 1), the films are locally disrupted and metal-to-metal contact begins at places where the surfaces move together under shear. The subsequent steps in the process involve thermally activated diffusion mechanisms that complete film dispersion and eliminate voids to achieve intimate metal contact (stages 2 and 3).

The barrier film is largely an oxide. Proper cleaning methods reduce the other components of film to negligible levels. Two actions tend to disrupt and disperse the oxide film. The first is solution of the oxide in the metal; the second is spheroidization or agglomeration of the film. Oxides decompose and the decomposition products are dissolved in titanium, tantalum, columbium, zirconium, and other metals in which interstitial elements are highly soluble. If the oxide is relatively insoluble in the metal, as is the case for aluminum, the disruption action for the trapped film is spheroidization. This leaves a few oxide particles along the weld interface. However, if the weld is properly made, these particles are no more detrimental than inclusions normally present in most metals and alloys.

Both decomposition and spheroidization of the oxides require diffusion. Decomposition results in the diffusion of interstitial atoms of oxygen into the metal and spheroidization by diffusion as a result of the excessive surface energy of the thin films. The time of solution of a film of thickness X is proportional to X^2/D, where D is the diffusion coefficient. The film must be kept very thin if diffusion welding times are to be within acceptable limits. Spheroidization occurs more rapidly if the oxide films are thin. Hence, control of the film thickness after cleaning and during heating to welding temperature is a critical factor in diffusion welding.

Once actual metal-to-metal contact is established, the atoms are within the attractive force fields of each other and a high-strength joint is generated. At this time, the joint resembles a grain boundary because the metal lattices on each side of the line have different orientations. However, the joint may differ slightly from an internal grain boundary because it may contain more impurities, inclusions, and voids that will remain if full asperity deformation has not occurred. (Stage 2 in the model for achieving intimate contact is not yet complete.) As the process is carried to completion, this boundary migrates to a more stable non-planar configuration, and any remaining interfacial voids are eliminated through vacancy diffusion.

An intermediate filler metal is of significant practical importance in many systems, although the mechanisms so far described do not consider its use. When a filler metal is used or dissimilar base metals are welded, the diffusion of each metal into the other must be considered to develop a complete understanding of the DFW process.

DIFFUSION BRAZING PRINCIPLES

DIFFUSION BRAZING PRODUCES joint properties that are significantly different from those of conventional brazed joints. The main objective of the process is to produce joints having mechanical properties approaching those of the base metal in applications where other joining processes are unacceptable. Some examples are the following:

(1) Cast nickel-base superalloys for high temperature service, and beryllium alloys

(2) Some dissimilar metal combinations

(3) Assemblies where a combination joining and heat treating cycle is desirable to minimize distortion

(4) Elevated temperature applications, such as high strength titanium alloys in aircraft

(5) Large, complicated assemblies where it is economical to produce many strong joints simultaneously

Two approaches to diffusion brazing are used. One utilizes a brazing filler metal that has a chemical composition approximately the same as the base metal but with a lower melting temperature. Melting temperature is suppressed by adding certain alloying elements to the base metal composition or to a similar alloy composition. For example, the melting temperature of a nickel-base high-temperature alloy can be lowered by a small addition of silicon or boron. In this case, the brazing filler metal melts and wets the base metal faying surfaces during the brazing cycle. This approach is sometimes called activated diffusion bonding or transient liquid phase bonding.

The second approach uses a filler metal that will alloy with the base metal to form one or more eutectic or peritectic compositions. When the brazing temperature is slightly higher than the eutectic or peritectic temperature, the filler metal and base metal will alloy to produce a low-melting composition. The filler metal itself does not melt, but a low-melting alloy is formed *in situ*. This method is also known as eutectic brazing. An example is the diffusion brazing of titanium alloys with copper.

With either approach, the assembly is held at brazing temperature for a sufficient time for diffusion to produce a nearly uniform alloy composition across the joint. As this takes place, the melting temperature of the braze metal and the strength of the joint increase. The brazing time depends upon the degree of homogeneity desired, the thickness of the initial filler metal layer, and the brazing temperature. The relationship of heating rate to brazing temperature may also be important. A low heating rate will allow more solid-state diffusion to take place, and more filler metal will be required to provide sufficient liquid to fill the joint. Conversely, if a large quantity of filler metal and fast heating are used, the molten metal may run out of the joint and erode the base metal. The thick joint so formed will require a longer diffusion time to achieve a suitable composition gradient across the joint.

The composition of the braze metal may be important with respect to response to subsequent heat treatment. This is particularly true for metals that undergo phase transformation during heating and cooling. Alloy composition will determine the transformation temperature and rate of transformation. Therefore, the phase morphology and mechanical properties of the joint can be controlled by the joint design and the brazing cycle.

ADVANTAGES AND LIMITATIONS

DIFFUSION WELDING AND brazing have a number of advantages over the more commonly used welding and brazing processes, as well as a number of distinct limitations on their applications. Some of the advantages of the two processes are as follows:

(1) Joints can be produced with properties and microstructures very similar to those of the base metal. This is particularly important for lightweight fabrications.

(2) Components can be joined with minimum distortion and without subsequent machining or forming.

(3) Dissimilar alloys can be joined that are not weldable by fusion processes or by processes requiring axial symmetry, such as friction welding.

(4) A large number of joints in an assembly can be made simultaneously.

(5) Members with limited access can be joined.

(6) Large joint members of base metals that would require extensive preheat for fusion welding can be more readily joined. An example is thick copper.

(7) Defects normally associated with fusion welding are not encountered.

Following are some important process limitations:

(1) The thermal cycle is normally longer than that of conventional welding and brazing processes.

(2) Equipment costs are usually high, and this can limit the maximum size of components that can be produced economically.

(3) The processes are not adaptable to a high production rate, although a number of assemblies may be joined simultaneously.

(4) Adequate nondestructive inspection techniques for quality assurance are not available, particularly those that assure design properties in the joint.

(5) Suitable filler metals and procedures have not yet been developed for all structural alloys.

(6) The faying surfaces and the fit of joint members generally require greater care in preparation than for conventional hot pressure welding or brazing processes. Surface smoothness may be an important factor in quality control in the case of diffusion brazing.

(7) The need to simultaneously apply heat and a high compressive force in the restrictive environment of a vacuum or protective atmosphere is a major equipment problem with diffusion welding.

SURFACE PREPARATION

THE FAYING SURFACES of joint members to be diffusion welded or diffusion brazed must be carefully prepared before assembly. Surface preparation involves more than cleanliness. It also includes (1) the generation of an acceptable finish or smoothness, (2) the removal of chemically combined films (oxides), and (3) the cleansing of gaseous, aqueous, or organic surface films. The primary surface finish is obtained ordinarily by machining, abrading, grinding, or polishing.

One property of a correctly prepared surface is its flatness and smoothness. A certain minimum degree of flatness and smoothness is required to assure uniform contact. Conventional metal cutting, grinding, and abrasive polishing methods are usually adequate to produce the needed surface flatness and smoothness. A secondary effect of machining or abrading is the cold work introduced into the surface. Recrystallization of the cold worked surfaces increases the diffusion rate across the weld or braze interface.

Chemical etching (pickling), commonly used as a form of preweld preparation, has two effects: the first is the favorable removal of nonmetallic surface films, usually oxides; the second is the removal of part or all of the cold worked layer that forms during machining. The need for oxide removal is apparent because it prevents metal-to-metal contact.

Degreasing is a universal part of any procedure for surface cleaning. Alcohol, acetone, detergents, and many other cleaning agents may be used. Frequently, the recommended degreasing technique is intricate and may include multiple rinse-wash-etch cycles using several solutions. Because some of these cleaning solvents are toxic or flammable, proper safety precautions should always be followed.

Heating in vacuum may also be used to obtain clean surfaces. The usefulness of this method depends to a large extent upon the type of metal and the nature of its surface films. Organic, aqueous, or gaseous adsorbed layers can be removed by vacuum heat treatment at elevated temperature. Most oxides do not dissociate during a vacuum heat treatment, but it may be possible to dissolve adherent oxides in some metals at elevated temperature. Some metals that may dissociate oxides and dissolve the resulting oxygen, at an elevated temperature, are zirconium, titanium, tantalum, and columbium. Cleaning in vacuum usually requires subsequent vacuum or inert atmosphere storage and careful handling to avoid the recurrence of surface contamination.

Many factors enter into selecting the faying surface treatment. In addition to those already mentioned, the specific welding or brazing conditions may affect the selection. With higher temperature or pressure, it becomes less important to obtain extremely clean surfaces. Increased atomic mobility, surface asperity deformation, and solubility of impurity elements all contribute to the dispersion of surface contaminants. With lower temperature or pressure, better prepared and preserved surfaces are more important.

Preservation of the clean faying surface is necessary following the surface preparation. One requirement is the effective use of a protective environment during diffusion welding or brazing. A vacuum environment provides continued protection from contamination. A pure hydrogen atmosphere will minimize the amount of oxide formed and it will reduce existing surface oxides of many metals at elevated temperature. However, it will form hydrides with titanium, zirconium, columbium, and tantalum that may be detrimental. High-purity argon, helium, and sometimes nitrogen can be used to protect clean surfaces at elevated temperature. Many of the precautions and principles applicable to brazing atmospheres can be applied directly to diffusion brazing or welding.[1]

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[1] Brazing atmospheres are discussed in Chapter 12 of this volume.

DIFFUSION WELDING

PROCESS CONDITIONS

Temperature

TEMPERATURE IS AN important diffusion welding process condition for a number of reasons:

(1) It is readily controlled and measured.

(2) In any thermally activated process, an incremental change in temperature will cause the greatest change in process kinetics when compared to most other process conditions.

(3) Virtually all the mechanisms are temperature dependent.

(4) Elevated temperature physical and mechanical properties, critical temperatures, and phase transformations are important reference points.

(5) Temperature must be controlled to promote or avoid certain metallurgical factors, such as allotropic transformation, recrystallization, and solution of precipitates.

Kinetic theory provides a means for understanding the quantitative effects of temperature in diffusion welding. Diffusivity can be expressed as a function of temperature as:

$$D = D_0 e^{-Q/kT} \tag{26.1}$$

where

D = diffusion coefficient at temperature T
D_0 = a constant of proportionality
Q = activation energy for diffusion
T = absolute temperature
k = Boltzmann's constant

From this, it is apparent that the diffusion-controlled processes vary exponentially with temperature. Thus, relatively small changes in temperature produce significantly large changes in process kinetics.

In general, the temperature at which diffusion welding will take place is above 0.5 *Tm*, where *Tm* is the melting temperature of the metal in degrees Kelvin or degrees Rankine. Many metals and alloys can best be diffusion welded at temperatures between 0.6 and 0.8 *Tm*. For any specific application the temperature, pressure, time, and faying surface preparation are interrelated.

Time

TIME IS CLOSELY related to temperature in that most diffusion controlled reaction rates vary with time. The diffusion length, x, is the average distance traveled by migrating atoms during diffusion. It can be approximated as:

$$x = C(Dt)^{1/2} \tag{26.2}$$

where

x = diffusion length
D = diffusion coefficient at T
t = time
C = a constant

Thus, diffusion reactions progress with the square root of time (longer times become less and less effective), whereas they progress exponentially with temperature, as was previously shown.

Experience indicates that increasing both the time and the pressure at welding temperature increases joint strength up to a limit. Beyond this point no further gains are achieved. This illustrates that time is not a quantitatively simple condition. The simple relationship that describes the average distance traveled by an atom does not reflect the more complex changes in micro structure that result in the formation of a diffusion weld. Although atom motion continues indefinitely, micro structural changes tend to approach equilibrium. An example of similar behavior is the recrystallization of metals.

In a practical sense, time may vary over a very broad range, from seconds to hours. Production factors influence the practical time for diffusion welding. An example is the time necessary to provide the heat and pressure.

When the welding equipment has thermal and mechanical (or hydrostatic) inertia, welding times are long because of the impracticality of suddenly changing the conditions. When there are no inertial problems, welding time may be as short as 0.3 min, as is the case when joining thoria-dispersed nickel to itself. On the other hand, it may be as long as 4 hours, as when joining columbium to itself with zirconium as a filler metal.

Pressure

PRESSURE IS AN important factor. It is more difficult to deal with as a quantitative value than either temperature or time. Pressure affects several aspects of the process. The initial phase of metallic bond formation is certainly affected by the amount of deformation induced by the pressure applied. This is the most obvious single effect and probably the most frequently and thoroughly considered. Higher pressure invariably produces better joints when the other variables are fixed, within the limits of the welding range. The most apparent reasons for this effect are the greater faying surface deformation and asperity collapse. The greater deformation may also lower recrystallization temperature and accelerate the process of recrystallization at the welding temperature.

The welding equipment and the joint geometry place practical limitations on the magnitude of welding pressure. The pressure needed to achieve a good weld is closely related to the temperature and time. Pressure has additional significance when dissimilar metal combinations are considered. From economic and manufacturing aspects, low welding pressure is desirable. High pressure requires more costly equipment, better controls, and generally involves more complex production procedures.

The pressures and temperatures employed are largely interdependent, but the pressure need not exceed the yield stress of the base metal or filler metal at the welding temperature. Thus, unless retaining dies are used, the pressure is usually kept slightly below the yield stress at the welding temperature. The temperature and pressure are normally selected to produce a weld in an acceptable time.

Metallurgical Factors

IN ADDITION TO the process conditions, there are a number of metallurgically important factors to be considered. Two factors of particular importance with similar metal welds are phase transformation and microstructural factors that tend to modify diffusion rates. Phase transformation (allotropic transformation) occurs in some metals and alloys. Steels are the most familiar of these, but titanium, zirconium, and cobalt also undergo phase transformation. During phase transformation, the metal is very plastic, and this promotes rapid faying surface deformation at lower pressures. Diffusion rates are generally higher during transformation, and also during recrystallization.

Another means of increasing diffusion is alloying or, more specifically, introducing elements with high diffusivity at the faying surfaces. The function of a high-diffusivity element is to accelerate void elimination. In addition to simple diffusion acceleration, these alloying elements may have secondary effects. The elements should have reasonable solubility in the base metal, but should not form stable compounds. Alloying should not promote melting at the weld interface.

When using a diffusion activator, it is desirable to hold the weldment at the diffusion temperature either during or after the welding process to reduce the high concentration of the element at the weld interface. If this is not done, the high concentration may produce metallurgically unstable microstructures. This is particularly important for joints that will be exposed to elevated temperature service.

It is sometimes advantageous to use some form of filler metal between the faying surfaces. One purpose of a filler metal is to provide a layer of soft metal between the faying surfaces. A soft metal layer permits plastic flow to take place at lower pressures than would be required without it during the first stage of welding. See Figure 26.2. After the joint is formed, the diffusion of alloying elements from the base metal into the filler metal reduces the compositional gradient across the joint.

Filler metals may be necessary or advantageous in certain applications in order to:

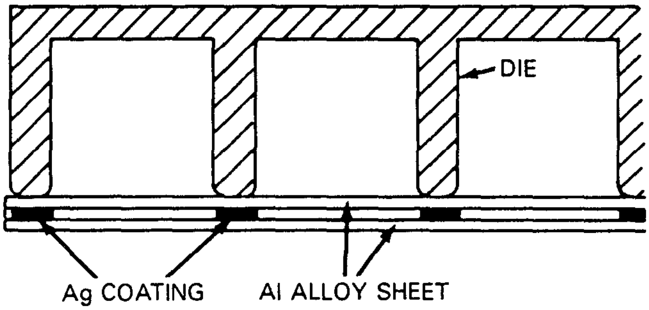
(1) Reduce welding temperature
(2) Reduce welding pressure
(3) Reduce process time
(4) Increase diffusivity
(5) Scavenge undesirable elements

Filler metals can be applied in many forms. They can be electroplated, condensed, or sputtered onto the faying surface, or they can be in the form of foil inserts or powder. The thickness of the filler metal should not exceed 0.010 in. (0.25 mm).

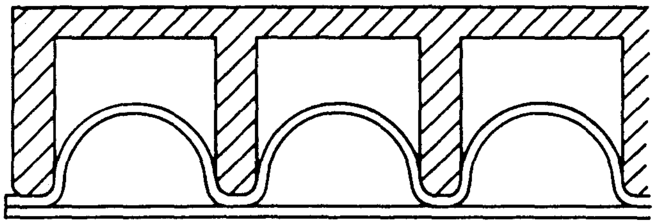
Generally, the filler metal is a purer version of the base metal. For example, unalloyed titanium often is used as an filler metal with titanium alloys, and nickel is sometimes used with nickel-alloys. An exception to this rule is the use of silver as filler metal in the diffusion welding of aluminum.

Aluminum alloys are among the most difficult metals to diffusion weld, because of the rapid formation of a stable oxide film on bare aluminum surfaces. Most aluminum diffusion welding is done at high temperatures. Lower temperature is required if foil interlayers or electroplated coatings are used as filler metals, and still lower pressures and deformations are needed in the presence of a transient liquid phase. However, these methods must be controlled, otherwise they can produce brittle intermetallic phases and low weld strengths. Significant quantities of silver can dissolve in aluminum at 896-986°F (480-530°C), and silver oxides are unstable above 392°F (200°C). Thus, if the diffusion temperature is 896-968°F (480-530°C), silver oxides will not form, and the silver will dissolve in the aluminum base metal.

A diffusion welding application of aluminum is illustrated in Figure 26.3. Any aluminum alloy can be welded by combining a silver coating on a surface clad with aluminum, and in practice this could have the advantage of a single welding procedure for all aluminum alloys.



(A) SETUP PRIOR TO DIFFUSION WELDING



(B) ASSEMBLY AFTER WELDING AND FORMING

Figure 26.3–Fabrication of Diffusion Welded Aluminum Assembly Using Silver as a Filler Metal

Filler metals containing rapidly diffusable elements can also can be used. For example, beryllium can be used with nickel alloys to decrease diffusion time. A properly selected diffusion aid will not melt at welding temperature or form a low melting eutectic with the base metal. An improperly chosen diffusion aid can:

(1) Decrease the temperature capability of the joint
(2) Decrease the strength of the joint
(3) Cause microstructural degradation
(4) Result in corrosion problems at the joint

PROCESS VARIATIONS

Conventional Diffusion Welding

CONVENTIONAL DIFFUSION WELDING involves the application of pressure and heat to accomplish a weld along the entire length of one or more joints simultaneously. Filler metal may or may not be used. Pressure may be applied using gas pressure or a press (mechanical or hydraulic). Heat may be applied by any convenient means but electrical resistance heaters are the most common source. Forming parts to shape is done prior to or after welding using equipment designed for that purpose.

Continuous Seam Diffusion Welding

CONTINUOUS SEAM DIFFUSION welding (CSDW) joins components by "yield-controlled diffusion welding." With this process variation, the parts are positioned with tooling and then fed through a machine with four rollers. The top and bottom rollers are made of molybdenum and function much like resistance seam welding wheels. The two side rollers are used to maintain the shape of the components. The wheels and parts are heated to the desired temperature by electrical resistance. A special control system monitors part temperature. Welding temperature is usually between 1800 and 2000°F (982 and 1090°C) for titanium and between 2000 and 2200°F (1090 and 1200°C) for nickel-base superalloys. The hot wheels apply pressure in the range of 1 to 20 ksi (7 TO 138 MPa) on the seam. The actual pressure depends upon the metal being joined, the joint design, the temperature, and the welding speed. An application of this process could be the joining of two flanges to a web to form a structural beam.

Combined Forming and Welding

TWO PROCESS VARIATIONS take advantage of the superplastic properties of certain metals or alloys. Some alloys can deform or flow significantly at elevated temperatures under very small applied loads without necking or fracture. Titanium and its alloys exhibit this superplastic behavior in the temperature range of 1400 to 1700°F (760 to 925°C). Complex shapes can be formed using moderate gas pressures; then the shapes can be diffusion welded, or vice versa.

One of these process variations is called creep isostatic pressing (CRISP). It is a two-step process combining creep or superplastic forming of titanium sheet structures with hot isostatic pressing to produce a diffusion welded structure.

Inherent in the CRISP process variation is the mating of two external skins. First, one skin is creep formed by gas pressure to the contour of a die. Then shaped inserts are located on the skin and a second skin is creep formed by gas pressure over the first skin and inserts. Diffusion welding of the formed sheets and inserts is achieved by hot isostatic pressing in an autoclave. This method eliminates the need for precision machined die sets and close dimensional tolerances in parts.

Another process variation takes advantage of the same properties of titanium and its alloys described previously; however, the welding is performed under low pressure conditions. This variation is called "superplastic forming diffusion welding" (SPF/DW). Since superplastic forming and diffusion welding of selected titanium alloys can be accomplished using the same temperature, the two operations can be combined in a single fabrication cycle. The welding is accomplished under low pressure conditions.

For titanium alloys that exhibit superplastic properties, SPF/DW considerably extends the range of low cost and structurally efficient titanium aerospace components that can be manufactured. SPF/DW titanium parts may be substituted for conventionally fabricated aluminum alloy components.

Recent developments in the SPF/DW of high strength aluminums and metal matrix composites have stimulated work in the field of diffusion welding of aluminum.

The superplastic forming of the sheet may be done first, followed by welding, or the steps can be reversed. The order depends upon the design of the component. Forming is done first if this is required to bring the faying surfaces of the joint together for welding. If the faying surfaces are in contact, welding is the first process and then the part is formed to final shape. A suitable nonmetallic agent may be used to prevent welding in selected areas.

Superplastic forming of Ti-6%Al-4%V alloy sheet can be done by the application of low pressure argon at 1700°F (925°C) in a sealed die. Gas pressure of about 150 psi (1035 kPa) is used for both forming and welding. Preparation of titanium alloy sheets is usually limited to degreasing and acid etch.

EQUIPMENT AND TOOLING

A WIDE VARIETY of equipment and tooling is employed for diffusion welding. The only basic requirement is that pressure and temperature must be applied and maintained in a controlled environment. Various types of equipment have been developed, each with its special advantages and disadvantages. There are numerous variations of a given type of equipment or approach depending upon the specific application. A general description of three types of diffusion welding equipment follows.

Isostatic Gas Pressure

THE PRESSURE FOR welding can be applied uniformly to all joints in an assembly using gas pressure. It is important that all air be removed from the assembly prior to welding. The assembly itself may be evacuated and sealed by fusion welding, if this is possible. Otherwise, the assembly must be sealed in a thin, gas-tight envelope which is evacuated and sealed. Electron beam welding in vacuum is a convenient process for evacuating and sealing in one operation.

Gas pressure is applied externally against the evacuated assembly at welding temperature. Very high pressures can be applied using an autoclave, but the assembly must be capable of withstanding the applied pressure without macrodeformation. Some designs may require internal support tooling with provisions for removing it after welding.

The primary component of hot isostatic equipment is a cold wall autoclave, which can be designed for gas pressures up to 150 ksi (1035 MPa) and for part temperature in excess of 3000°F (1650°C). A typical autoclave is shown in Figure 26.4. Work to be welded is placed in the heated cavity. Internal water cooling is usually provided to maintain a low wall temperature. Openings on each end provide access to the vessel cavity. Utilities and instrumentation are brought into the vessel through high pressure fittings located in the end closures. The high temperatures are produced with an internal heater. Resistance heaters of various designs are used. Alumina or silica insulation is used to reduce heat losses to the cold wall. Temperature is monitored and controlled by thermocouples located throughout the furnace and vessel. Pressurization is achieved by pumping inert gas into the autoclave with a multiple-stage piston-type compressor. Temperature and pressure are controlled independently, and any combination of heating and pressurizing rates can be programmed. Autoclaves are pressure vessels and should be designed to meet applicable code requirements.

The most important consideration is the gas-tight envelope or container in which the workpieces are contained. If a leak develops in the container, pressure cannot be applied to or maintained on the joint. Sufficient gas pressure is applied so that local plastic flow will occur at the faying surface and all void space will be filled as a result of local deformation. With proper conditions, essentially no macrodeformation or changes in part dimensions will occur during welding.

The chief advantage of this technique is the ability to handle complex shapes. It is also well suited to batch operations where large quantities of relatively small assemblies can be welded simultaneously. The major drawbacks are the capital equipment costs and the size limitations imposed by the internal dimensions of the autoclave. Opera-

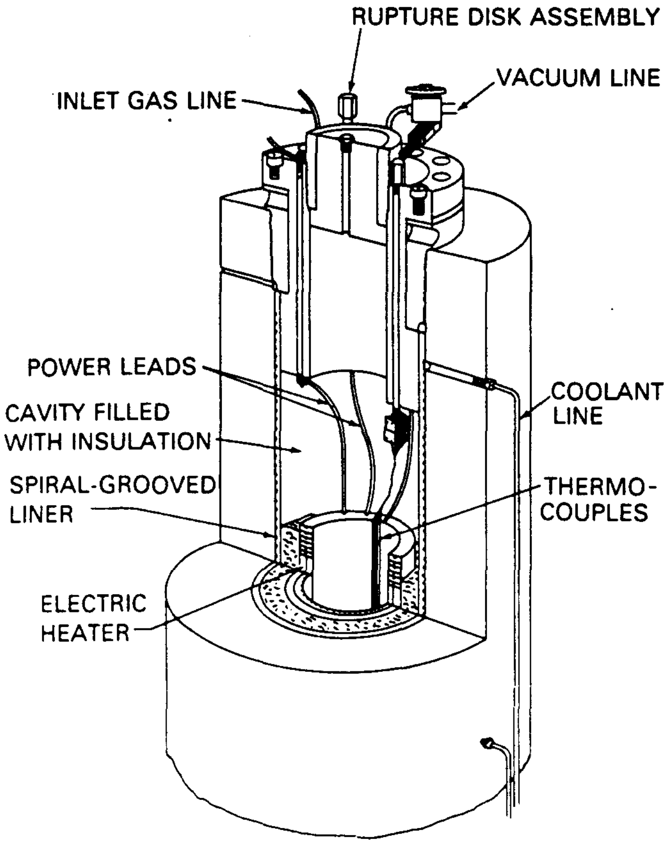


Figure 26.4–A Typical High Temperature, Cold-Wall Autoclave

tional equipment ranges up to 36 in. (92 cm) inside diameter and inside lengths of up to 108 in. (275 cm).

The gas pressure process variables are selected to suit the base metals. Usually joints are made at the highest possible pressure to minimize the temperature needed. This method is well suited for welding brittle metals or metals to ceramics and cermets because the isostatic pressure eliminates tensile stresses in the materials.

Presses

A COMMON APPROACH for diffusion welding employs a mechanical or hydraulic press. The basic requirements for the press are (1) sufficient load and size capacity, (2) an available means for heating, and (3) the maintenance of uniform pressure for the required time. It is often necessary to provide a protective atmosphere chamber around the weldment. Press equipment that can be adapted to diffusion welding applications, as shown in Figure 26.5, is often available in a manufacturing or development organization.

There is no standard press design for diffusion welding. Some units provide a vacuum or an inert atmosphere around the parts. Radiant, induction, and resistance types of heating are used. One advantage of a press is the ease of operation and the excellent process control available. One disadvantage is the practical limitation of press size when large weldments are considered. Presses do not lend themselves to high production rates, or batch operations.

Some of the limitations on size can be overcome by operating in a large forming or forging press without an inert atmosphere chamber. Heated platens apply both heat and pressure to the components. The platens may be metallic or ceramic, depending upon the temperature and pressure employed. Castable ceramics are particularly useful because contours can easily be accommodated without extensive machining. Heating elements can be cast into a ceramic die to provide uniform heat during welding. Close tolerances must be maintained between the die and the part so that uniform pressure will be applied to the joint. This is a major problem with press type equipment. It is difficult to maintain uniform pressure on the joint, and variations in weld quality can result.

Tooling requirements vary with application. If no lateral restraint is provided, excessive upsetting may occur during welding. In such cases, lower pressure or temperature is usually required. Heated dies are required and die materials can be a problem. The die must be able to withstand both the temperature and the pressure and must be compatible with the base metal. Interaction between the part and the die can be controlled by stopoff agents and sometimes by oxidizing the die surface. Atmosphere protection is often achieved by sealing the parts in evacuated metal cans that are designed to conform to the die shape.

Retorts can be used in conjunction with presses for diffusion welding of titanium. Tooling blocks and spacers of Type 22-4-9 stainless steel may be used to fill any voids between the titanium workpieces to maintain their shapes. Presses with side and end restraining jacks can exert up to 2 ksi (13.8 MPa) pressure on the retort in all directions. In actual production, the completed assembly pack (retort, heating pads, and insulation) is heated before it is placed in the press. Large structures may require a preheat of as long as 40 hours. Several packs may be in assembly and preheat at one time. The actual time in the press will vary from 2 to 12 hours, depending upon the shape of the structure and the mass of titanium. The assembly pack is cooled to room temperature, dismantled, and the retort is then cut open. This approach is quite slow and is not readily adapted to high production rates.

Resistance Welding Machines

RESISTANCE WELDING EQUIPMENT may be used to produce diffusion spot welds between sheet metal parts. In general, modification of standard equipment is not necessary to achieve successful diffusion welds. The interface is resis-

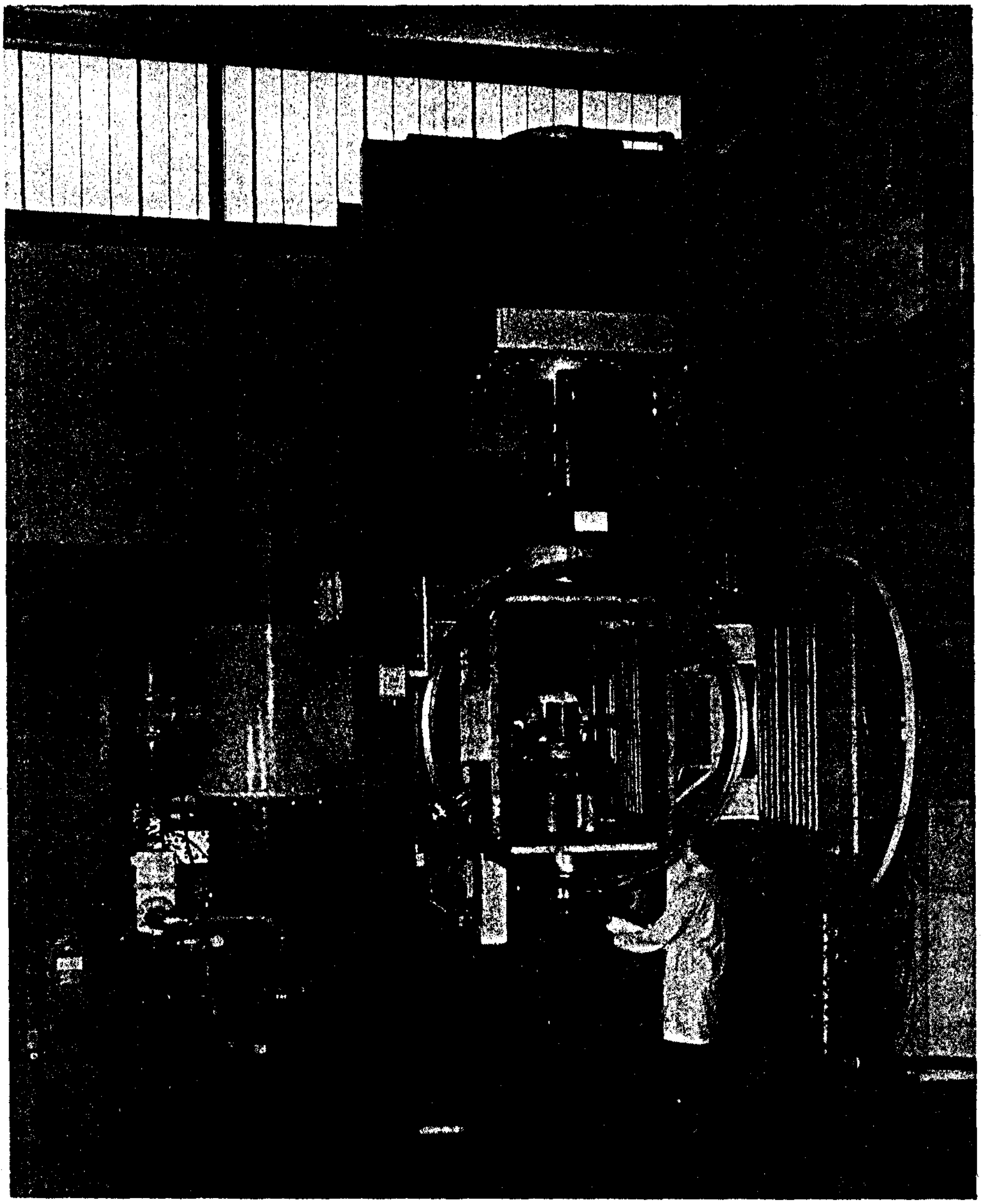


Figure 26.5—Diffusion Welding Vacuum Hot Press

tance heated under pressure with this equipment. The cycle is designed to avoid melting of metal at the interface. Weld times are generally less than 1 second.

As in standard resistance welding, selection of a suitable electrode material is important. The electrodes must be electrical conductors, possess high strength at welding temperatures, resist thermal shock, and resist sticking to the parts. There is no universal electrode material because of potential interaction with the workpiece. Therefore, each combination must be carefully evaluated from a metallurgical compatibility standpoint.

In some applications, a small chamber surrounding the electrodes is used to provide an inert atmosphere or vacuum during welding.

One advantage of this type of equipment is the speed at which diffusion welds can be made. Each weld is made in a very short time; however, only a small area is welded in each cycle and many welds are needed to join a large area.

Tooling

A NUMBER OF important considerations must be observed when selecting tooling materials. The main criteria are the following:

(1) Ease of operation
(2) Reproducibility of the welding cycle
(3) Operational maintenance
(4) Weld cycle time
(5) Capital cost

Furthermore, the materials must be capable of maintaining their proper positions and shapes throughout the heating cycle.

Suitable fixture materials are limited when welding temperatures are above 2400°F (1320°C). Only the refractory metals and certain nonmetallic materials have sufficient creep strength at such high temperatures. For example, only tantalum and graphite may be suitable fixturing for diffusion welding of tungsten. Ceramic materials are suitable for fixtures provided they are completely outgassed prior to welding.

Fixtures can be designed to take advantage of the difference in thermal expansion between the base metals and the fixture material. It is possible to generate some, if not all, of the pressure required for welding by appropriate selection of the fixture material, base metal and the clearances between the fixture and part. These principles have been used to join Type 2219 aluminum alloy tubing to Type 321 stainless steel. A precise method was devised to apply the correct welding pressure to the tubular assembly. The reproducible uniform welding pressure was developed by taking advantage of the difference in the thermal expansions of low alloy steel and stainless steel.

DIFFUSION BRAZING

PROCESS VARIABLES

DIFFUSION BRAZING IS similar to conventional brazing. Various methods of heating, atmospheres, joint designs, and equipment can generally be used interchangeably. With diffusion brazing, the filler metal, the brazing temperature, and the brazing time are selected to produce a joint with physical and mechanical properties almost identical to those of the base metal. To do this, it is necessary to completely diffuse the braze metal into the base metal.

Temperature and Heating Rate

THE TEMPERATURE CYCLE used for diffusion brazing depends upon the base metal and the design of the brazing system. When the filler metal composition is similar to that of the base metal, the assembly must be heated to the melting temperature of the filler metal as in conventional brazing. As the brazing alloy melts, it wets the base metal and fills the voids in the joint; then the temperature can be maintained or reduced to solidify the braze metal.

Diffusion brazing forms a filler metal *in situ* during brazing. The metals are generally selected to form a molten eutectic that flows and fills the voids in the joint at brazing temperature. The brazing temperature is somewhat higher than the eutectic that flows and fills the voids in the joint at brazing temperature. The brazing temperature is somewhat higher than the eutectic temperature. For example, a plating of copper on a silver base metal faying surface will form a eutectic when heated to 1500°F (815°C). The eutectic melting temperature is 1435°F (780°C).

In systems where several eutectic and peritectic reactions take place at different temperatures, both the brazing temperature and the heating rate are important. Although a liquid phase can form at the lowest eutectic temperature, diffusion rates will be faster at higher temperatures. The heating rate will determine whether a molten eutectic is formed. If the heating rate is too low, solid-state diffusion will prevent the formation of a molten eutectic. The voids at the faying surface will not be filled by the braze metal.

The maximum brazing temperature may be established by the characteristics of the base metal: for example, incipient melting in most metals is not desirable. Brazing temperature may also be limited by the effect of temperature on the final metallurgical structure or by the heat treatment requirements for the weldment.

After brazing is completed and the braze metal solidified, a high temperature is maintained while solid state diffusion takes place.

Time

THE DURATION OF the diffusion brazing cycle will depend on (1) the brazing temperature, (2) the diffusion rates of the filler metal and the base metal at brazing temperature, and (3) the maximum concentration of filler metal permissible at the joint. The alloy composition at the joint may influence the response to heat treatment or the resulting mechanical properties of the joint. Therefore, the joint must be held at high temperature for some minimum time to reduce the concentration of filler metal to an acceptable value.

Pressure

CONVENTIONAL BRAZING REQUIRES little or no pressure across the joint. In some cases, fixturing may be necessary to avoid excessive pressure. This is particularly so when the molten filler metal is to flow into the joint by capillary action. When the filler metal is placed in the joint before brazing, excessive pressure may force low melting constituents to flow out of the joint before brazing temperature is achieved. In that case, the molten filler metal may not be sufficiently fluid to fill interface voids.

Metallurgical Factors

THE METALLURGICAL EVENTS that transpire during diffusion brazing are similar to those that occur during diffusion welding. An additional factor is the variation in chemical composition across the joint. Compositional variations can significantly affect the response of a particular alloy to heat treatment. For metals that exhibit an allotropic transformation, the chemical composition affects both the transformation temperature and the rate of transformation. Thus, the response to heat treatment across a diffusion brazed joint varies with the local chemical composition. For example, copper stabilizes the beta phase in titanium and decreases the beta-to-alpha transition temperature.

Filler Metals

THE FILLER METAL is a metal that will alloy with the base metal to form a molten alloy at some elevated temperature. A eutectic must form that melts at a temperature compatible with the metallurgy and properties of the base metal. The filler metal may be in powder, foil, or wire form, or it may be plated onto the surface of the base metal. Close control of the amount of filler metal in the joint is essential for consistent results.

Application of pure metals and simple alloys by electroplating or vapor deposition can be accurately controlled. Films of desired thickness can be deposited on the faying surfaces. However, these processes are not always economical. Metal foil or wire formed into suitable shapes are better for many applications.

In the case of nickel- and cobalt-base alloys, elements commonly added to brazing filler metal to depress the melting temperature also increase alloy hardness and brittleness. Consequently, these filler metals can only be produced as powders. Powders are a problem when precise amounts of filler metal are required. Boron in the range of 2.0 to 3.5 percent is used in nickel-base filler metals. Boron can be diffused into the surfaces of nickel alloy foil or wire shapes to produce filler metal preforms. These preforms provide good control of filler metal placement for diffusion brazing applications.

EQUIPMENT AND TOOLING

THE EQUIPMENT AND tooling used for diffusion brazing are essentially the same as those used for conventional brazing. If furnace brazing is used, the entire cycle can be done in the same equipment or in a dedicated furnace. In some cases it may be more economical and convenient to braze with one piece of equipment and then follow with a diffusion heat treatment with other equipment. For example, the brazing could be done with resistance welding or induction heating equipment, and the diffusion heat treatment could be performed in a furnace.

APPLICATIONS

A WIDE VARIETY of similar and dissimilar metal combinations may be successfully joined by diffusion welding and brazing. Most applications involve titanium, nickel, and aluminum alloys, as well as several dissimilar metal combinations. The mechanical properties of the joint depend on the characteristics of the base metals. For example, the relatively low creep strength and the solubility of oxygen at elevated temperature contribute to the excellent properties of titanium alloy diffusion weldments.

Nickel-base heat-resistant alloys are difficult to join because their creep strengths are high, requiring high pressures for diffusion welding. In addition, a thin, stable oxide film interferes with metal to metal contact because, unlike titanium, the oxygen is not soluble in the nickel. These factors contribute to poor solid-state weldability of these nickel-base heat-resistant alloys. This problem can be overcome by the use of a relatively soft filler metal that provides more intimate contact.

Base metals strengthened by cold working will be irreversibly softened by the joining heat treatment. However, heat treatable alloys may be rehardened during the joining heat treatment or may be hardened with a postweld heat treatment.

TITANIUM ALLOYS

MANY DIFFUSION WELDING and brazing applications involve titanium alloy components, the majority of which are Ti-6%Al-4%V alloy.[2] The popularity of the processes with titanium alloys stems from the following factors:

(1) Titanium is readily joined by both processes without special surface preparation or unusual process controls.

(2) Diffusion welded or brazed joints may have better properties for some applications than fusion welded joints.

(3) Most titanium structures or components are used principally in aerospace applications where weight savings or advanced designs, or both, are more important than manufacturing costs, within limits.

A number of well-established diffusion welding and brazing methods are available for joining titanium alloys. Welding can be accomplished using pressures in the range of several hundred to several thousand psi. High pressures are used in conjunction with low welding temperatures and when the assembly is welded in a retort. Inserts may be used to maintain the required dimensions. When welding at higher temperatures without an enclosure surrounding the joint members, maximum pressure is usually limited by the allowable deformation in the weldment, and this pressure must be determined empirically. Pressures of 300 to 500 psi (2070 to 3450 kPa) work well in many cases. In some applications, total weldment deformation and deformation rate instead of pressure are used for process control during welding.

Titanium Diffusion Welding

WELDING TEMPERATURE IS probably the most influential condition in determining weld quality; it is set as high as possible without causing irreversible damage to the base metal. For the commonly used alpha-beta type titanium alloys, this temperature is about 75 to 100°F (24 to 38°C) below the beta transus temperature. Thus, Ti-6%Al-4%V alloy with a beta transus of approximately 1825°F (996°C) is normally diffusion welded between 1700 and 1750°F (925 and 955°C).

The time required to achieve high weld strength can vary considerably with other factors, such as mating surface roughness, welding temperature, and pressure. Welding times of 30 to 60 minutes should be considered a practical minimum, with 2 to 4 hours being more desirable.

Faying surface finish and preweld cleaning procedure are two other important considerations. Although the general rule that a smooth faying surface makes welding easier still applies, parts with relatively rough (milled or lathe-turned) faying surfaces can be successfully diffusion welded as long as welding temperature, time, and pressure are adjusted to accommodate such rough finishes. Freshly machined faying surfaces only need to be degreased with a suitable solvent prior to welding. Hydrocarbon and chlorinated solvents should not be used because of safety considerations. A preferred cleaning method is acid cleaning in a nitric and hydrofloric acid solution. Any residue remaining from cleaning must be removed by thorough rinsing.

Several industries have taken advantage of the benefits of the diffusion welding process, particularly the aerospace industry with its high usage of titanium alloys. The engine mount of the space shuttle vehicle was designed to have 28 diffusion welded titanium parts, ranging from large frames to interconnecting box tubes. This structure is capable of withstanding three million pounds of thrust. Eight-inch (203 mm) square tubes with 0.75 in. (19 mm) thick wall were fabricated by diffusion welding in lengths up to 180 in. (457 cm).

The use of diffusion welding in the gas turbine industry reached a milestone with the production application of a Ti-6%Al-4%V component for an advanced, high-thrust engine. This application marks the first production use of diffusion welding in a rotating engine component.

Titanium Diffusion Brazing

CONTINUOUS SEAM DIFFUSION brazing has been used to produce stiffened skins fabricated as an integral one-piece structure. An example is shown in Figure 26.6. One of the first applications of this method was the fabrication of curved Ti-6%Al-4%V alloy I-beams used as structural members to support boron-aluminum composite on a fighter airplane. These beams were made from 0.025 in. (0.64 mm) sheet.

Superplastic forming/diffusion brazing of titanium parts is also used. An augmentor flap fabricated by the process is shown in Figure 26.7.

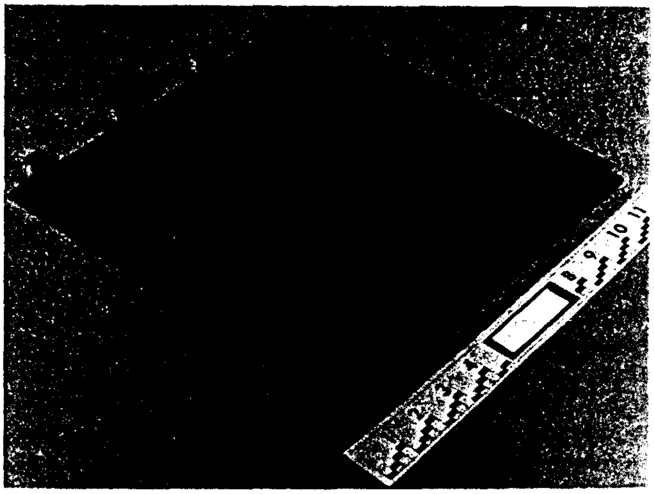


Figure 26.6–A Titanium Alloy Stiffened Sheet Structure Fabricated by Continuous Seam Diffusion

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[2] The weldability of titanium alloys is discussed in the *Welding Handbook*, Vol. 4, 7th Ed. 433-487.

Figure 26.7–Augmentor Flap for a Jet Engine Fabricated by Superplastic Forming/Diffusion Brazing of Titanium. (The structure features two and three sheet construction and weighs three pounds)

Conventional diffusion brazing techniques are also used for joining titanium alloys. Brazing times, temperatures, and preweld cleaning procedures are much the same as for diffusion welding. Pressure may just be sufficient to hold the joint members in contact, and faying surface finish requirements are not as stringent.

The faying surfaces of the titanium alloy are electrolytically plated with a thin film of either pure copper or a series of elements, such as copper and nickel. When heated to the brazing temperature of 1650 to 1700°F (900 to 925°C), the copper layer reacts with the titanium alloy to form a molten eutectic at the braze interface. The brazement is then held at the brazing temperature for at least 1.5 hours. The assembly may also be given a subsequent heat treatment at the brazing temperature for several hours, to reduce the composition gradient in the braze metal. Diffusion brazed joints made with a copper filler metal and a cycle of 1700°F (925°C) for 4 hours exhibited tensile, shear, unnotched fatigue, and stress corrosion properties equal to those of the base metal. However, they had slightly lower notch fatigue and corrosion fatigue properties, and significantly lower fracture toughness. A typical photomicrograph of a diffusion brazed T-joint between Ti-6%Al-4%V and Ti-3%Al-2.5%V alloys is shown in Figure 26.8. A Widmanstatten structure formed at the braze interface because the plated filler metal stabilized the beta phase.

Diffusion brazing is being used to fabricate light-weight cylindrical cases of titanium alloys for jet engines. In this application, the titanium core is plated with a very thin layer of copper and nickel that reacts with the titanium to form a eutectic. During brazing in a vacuum of 10^{-5} torr, a eutectic liquid forms at 1650°F (900°C). This liquid performs the function of a brazing filler metal between the core and face sheets. The eutectic quickly solidifies due to rapid diffusion at the braze interface.

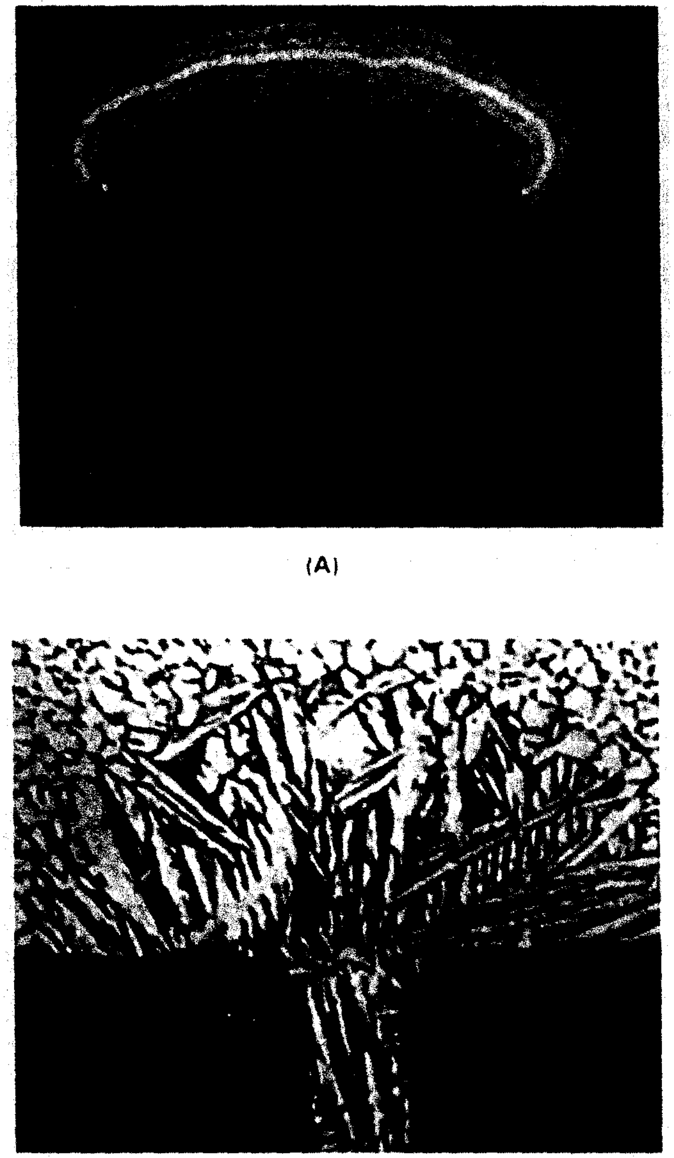
In the past, the copper-nickel filler metal was electrodeposited on the edge of the core in a lamellar fashion. Currently joints are produced using a homogeneous, thin copper-nickel foil as the filler metal. The use of foil has the advantage of allowing more precise control of the filler metal thickness and composition. In addition, the use of foil eliminates several complicated steps that are required in the plating process. Finally, as the foil is a homogeneous layer, it produces its available liquid all at once as soon as the ternary eutectic point is reached. This situation is an improvement over the stepwise formation of liquid that is produced from the electro- plated method.

Diffusion brazed assemblies are held at the brazing temperatures for one to four hours to reduce the composition gradient at the braze interface by diffusion. A typical diffusion brazed titanium alloy honeycomb structure is shown in Figure 26.9.

NICKEL ALLOYS

Diffusion Welding of Nickel Alloys

MANY NICKEL ALLOYS, specifically the high-strength heat-resistant alloys, are more difficult to diffusion weld than most other metals. These alloys must be welded at temperatures close to their melting temperatures, and because of their high-temperature strengths, relatively high pressures are required. In addition, extra care must be taken in preparing the faying surfaces to be welded to ensure cleanliness and mutual conformity. Surface oxides that form on these alloys are stable at high temperatures and will not dissolve or diffuse into the base metal. During welding, the ambient atmosphere must be carefully controlled to prevent faying surface contamination.



(A)

(B)

Figure 26.8–A Diffusion Brazed T-Joint Between Ti-6%Al-4%V and Ti3%Al-2.5%V Alloys

Pure nickel or a soft nickel alloy is commonly used as filler metal when diffusion welding nickel alloys. These filler metals, generally from 0.0001 to 0.001 in. (2.5 to 25 µm) thick, serve several functions. Their relatively low yield strength allows surface conformity to take place at relatively low welding pressures. More important, they are used during welding to prevent the formation of stable precipitates, such as oxides, carbides, or carbonitrides, at the weld interface. The diffusion welding time must be adequate to allow sufficient interdiffusion to occur at the weld interface.

Welding conditions for some diffusion welded nickel base heat-resistant alloys are shown in Table 26.1.

The pressure required for satisfactory welding is influenced strongly by the geometry of the joint members. Therefore, the required pressure for each application must be determined empirically.

The significance of filler metal and its composition was demonstrated by a series of diffusion welds in a wrought and cast proprietary nickel alloy. Welds were made without filler metal and then with 0.0002 in. (5 µm) both pure nickel and Ni-35%Co alloy. The welding conditions were the same as those listed for this alloy in Table 26.1.

The microstructure of the welds in wrought proprietary alloy are shown in Figure 26.10. With no filler metal, fine Ti (C,N) and $NiTiO_3$ precipitates formed at the weld interface during welding and pinned the interfacial boundary, causing very poor weld mechancial properties. The nickel filler metal consisted of an electroplated layer on each surface. These layers probably welded together early in the cycle, and no precipitates were present to interfere with welding. Subsequent diffusion and grain boundary movement resulted in much improved mechanical properties. The pure nickel filler metals, however, resulted in preferential diffusion of aluminum and titanium into the nickel. This led to the formation of excessive amounts of the strengthening precipitate $Ni_3(Al, Ti)$ in the joint. The use of a nickel- 35% cobalt alloy filler metal prevented the diffusion of aluminum and titanium and resulted in a homogeneous joint.

Diffusion Brazing of Nickel Alloys

NICKEL-BASE HEAT RESISTANT alloys can be diffusion brazed using two variations of the process. The variations differ primarily in the thermal cycle to accomplish diffusion. Both methods produce high-strength joints that resemble the base metal in both structure and mechanical properties.

The First Variation With the first variation, a filler metal of 0.001 to 0.004 in. (0.025 to 0.1 mm) thickness, is used. The joint members are held together under slight pressure [under 10 psi (69 kPa)] and heated to the brazing temperature [typically 2000 to 2200°F (1090 to 1200°C)] in vacuum or an argon atmosphere. At brazing temperature, the filler metal melts, filling the voids between the faying surfaces with a thin, molten layer. While the parts are held at the brazing temperature, rapid diffusion of alloying elements occurs between the braze metal and the base metal. This change of composition at the braze interface causes the braze metal to isothermally solidify, thus forming solid braze metal while still at the brazing temperature. After isothermal solidification occurs, the joint microstructure generally resembles that of the base metal except for some compositional and structural variations.

Figure 26.9—Diffusion Brazed Titanium Alloy Honeycomb Structure (81 in. long, 6 lb total weight)

Two single crystál components can be joined together by diffusion brazing to form a joint without grain boundaries and with the same crystal orientation as the base material. The two components have to have the same crystal orientation. A braze alloy of essentially the same composition as the base metals to be joined but with melting point depressents is required. The assembly is then heated to a temperature above the liquidus of the braze alloy and held at this temperature to allow the melting point depressent to diffuse from the filler metal into the base alloy. The base metal then solidifies isothermally. The solidification grows epitaxially from the base metal surfaces, and because the base metals are single crystal with the same orientation, the solidifying braze grows as a single crystal with the same orientation as the base metal.

A diffusion brazed joint between two single crystals is shown in Figure 26.11. This joint was brazed with B-Ni2 foil (Ni-7%Cr-3%Fe-4.5%Si-3.2%B) for 16 hours at 2100°F (1150°C) followed by 12 hours at 2275°F (1245°C). Notice the absence of grain boundaries in the joint area. The fractured surface of a similarly brazed joint is shown in Figure 26.12(A). The microstructure across the fracture of the tensile specimen is shown in Figure 26.12 (B). The joint was brazed using a nickel base foil containing 15% Cr and 4% B at 2150°F (1175°C) for 16 hours plus 2275°F (1245°C) for 22 hours. The tensile strength at 2000°F (1095°C) was 46.6 ksi (321 MPa). The reduction in area was 12.5%.

At this stage the joint has good properties, although not fully equivalent to those of the base metal. By permitting the brazement to remain at the brazing temperature for a longer time, the braze metal can be homogenized both in composition and structure until it is essentially equivalent to the base metal.

The Second Variation The second variation involves joining nickel-base components with a specially designed brazing filler metal that completely melts at some elevated temperature below the incipient melting point of the base metal. Subsequent to this, the brazed component is given a diffusion heat treatment to homogenize the brazing filler with the base metal. This is followed by an appropriate aging heat treatment designed for the base metal.

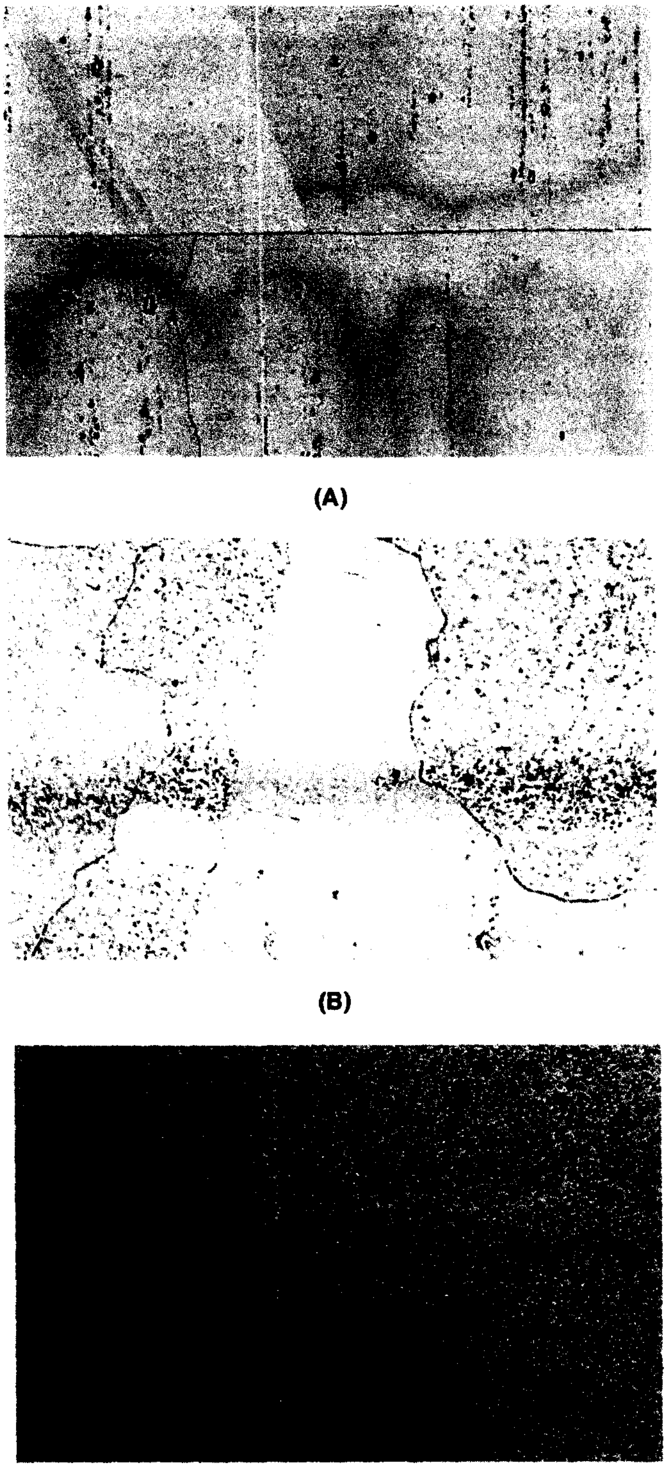
A brazing filler metal contains melting point depressants, such as silicon, boron, manganese, aluminum, titanium, and columbium. The filler metal contains sufficient amounts of depressants so that the resultant alloy is molten at a temperature that does not impair the properties of the base metal. Ideally, brazing is accomplished at the normal solution heat treating temperature for a given base metal. Figure 26.13 shows a diffusion brazed joint made in a wrought proprietary nickel alloy using the first procedure described. A filler metal of 0.003 in. (0.08 mm) thick Ni-15%Cr-15%Co-5%Mo-3%Be was used in the joint with a processing cycle of 2140°F (1170°C) for 24 hours in vacuum. A microprobe chemical analysis across a joint showed a uniform chemical composition, essentially that of the base metal. Stress rupture tests at 1600 and 1800°F (870 and 980°C) showed that the diffusion brazed joints had essentially the same properties as the base metal.

Diffusion brazed joints produced at lower temperatures and with shorter time may not be uniform in composition. As a result, some elevated temperature mechanical properties of the joints may be lower than those of the base metal, particularly under stress-rupture conditions.

Table 26.1
Typical Diffusion Welding Conditions for Some Nickel-Base Alloys

Base Metal*	Filler Metal	Welding Temp.		Pressure,		Time, h
		°F	°C	psi	kPa	
Inconel 600	Ni	2000	1090	100-500	690-3450	0.5
Hastelloy X	Ni	2050	1120	100-500	690-3450	4
Wrought Udimet 700	Ni-35%Co	2140	1170	1000	6900	4
Cast Udimet 700	Ni-35%Co	2175	1190	1200	8275	4
Rene 41	Ni-Be	2150	1180	1550	10690	2
Mar-M 200	Ni-25%Co	2200	1205	1000-2000	6900-13800	2

* Tradenames



(A)

(B)

(C)

Figure 26.10–Diffusion Welds in a Wrought Alloy with (A) No Interlayer, (B) A Nickel Interlayer, and (C) A Ni-35% Co Alloy Interlayer (x250)

ALUMINUM ALLOYS

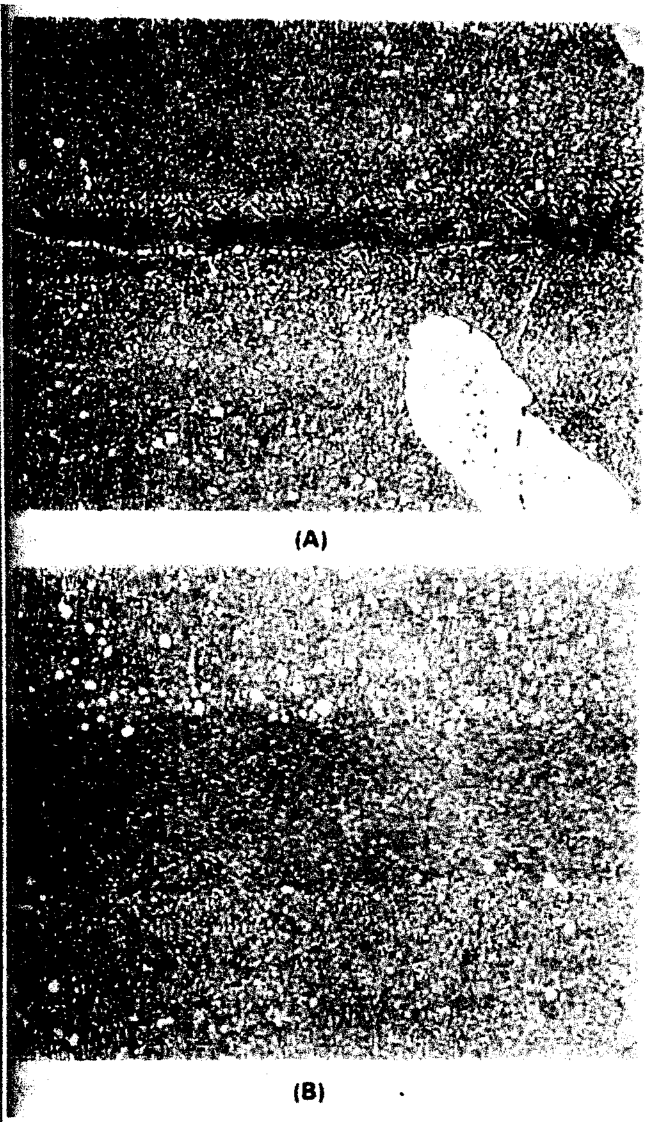
ALUMINUM ALLOYS CAN be successfully diffusion welded as long as some means is employed to avoid, disrupt, or dissolve the tenacious surface oxide. A wide range of temperatures, pressures, and times may be utilized: for example, with Type 6061 aluminum alloy, welding conditions as divergent as 725°F (385°C) and a pressure of 3800 psi (26 MPa) for several hours or 1000°F (538°C) and a pressure of 1000 psi (7 MPa) for one hour have been satisfactory. However, the main boundary condition is the melting point of the base metal. Welding is normally carried out in vacuum or inert gas although aluminum-boron fiber composites can be diffusion welded in air. If no local deformation of the parts can be tolerated, the faying surfaces should be coated with a thin layer of silver or gold-copper alloy by electrolytic or vapor deposition. The coating will prevent surface oxidation during welding.

Aluminum and aluminum alloys can be diffusion brazed using a copper filler metal. Sound, strong joints can be produced in aluminum by limiting the copper thickness to 2×10^{-5} in. (0.5 μm) and restricting the brazing temperature to between 1030 and 1060°F (554 and 571°C). The time at temperature should not exceed 15 minutes at the lower temperature limit or 7 minutes at the upper limit. Type A356.0 aluminum-7% silicon casting alloy can be diffusion brazed by electroplating one of the joint members with copper that will form a eutectic with the aluminum and silicon in the casting alloy when heated to 975°F (524°C).

To ensure optimum joint properties, copper thickness, brazing temperature, and brazing time must be selected to promote isothermal solidification during brazing and thereby prevent the formation of the compound $CuAl_2$. Proper balancing of these conditions results in strong joints that can withstand quenching from the solution temperature required for heat treating Type A356.0 alloy to the T61 condition. Electroplating the cover sheets with 1.5 to 2.0×10^{-5} in. (0.38 to 0.5 μm) of copper and holding between 980 and 1000°F (527 and 538°C) for one hour are satisfactory conditions. After quenching and aging, the joint strength will equal that of the casting itself. Microstructurally, the brazed joint will be indistinguishable from the casting.

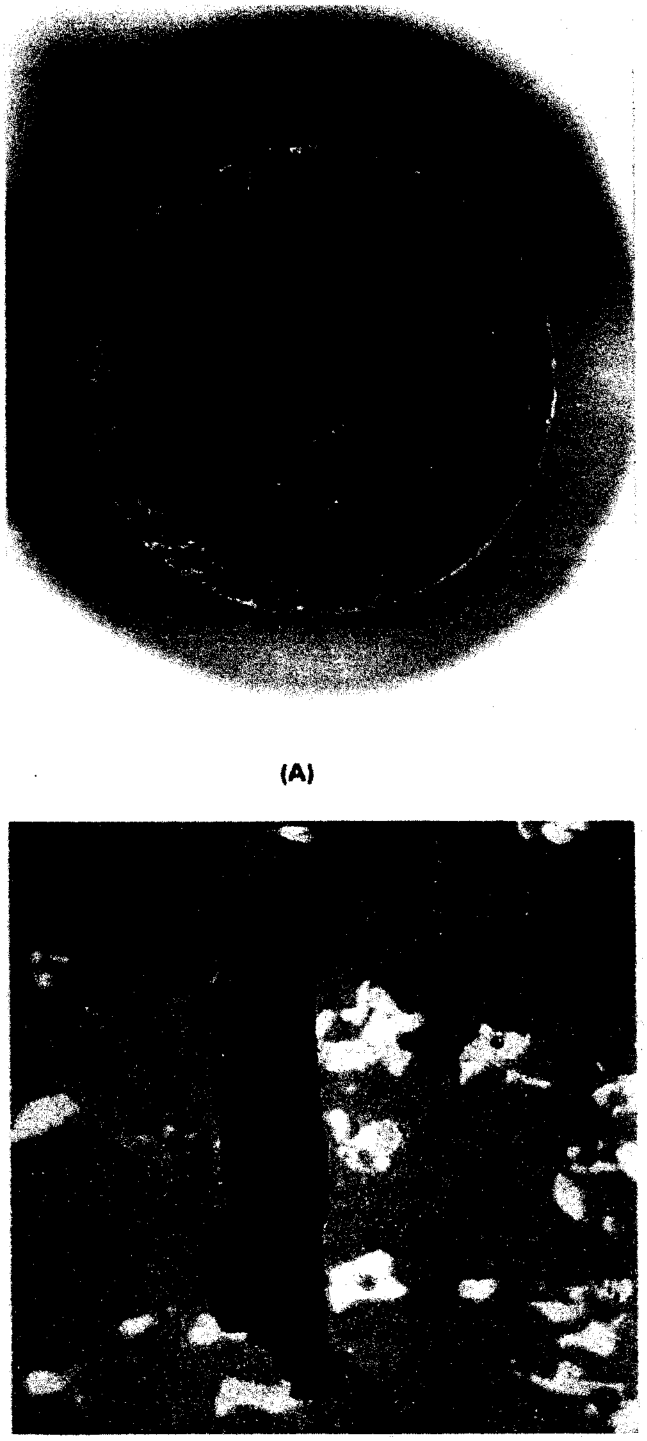
STEELS

STEELS ARE NOT normally diffusion welded because they are more easily joined by conventional brazing or fusion welding processes for most applications. Diffusion welding may be utilized successfully for specialized applications


(A)

(B)

Figure 26.11–Diffusion Brazed Single Crystal. (Brazing Temperature was 16 Hours at 2100°F Followed by a Diffusion Heat Treatment of 22 Hours at 2275°F)


(A)

(B)

Figure 26.12–Fracture Surface (8X) (A) and Microstructure (100X) (B) of Single Crystal Brazement

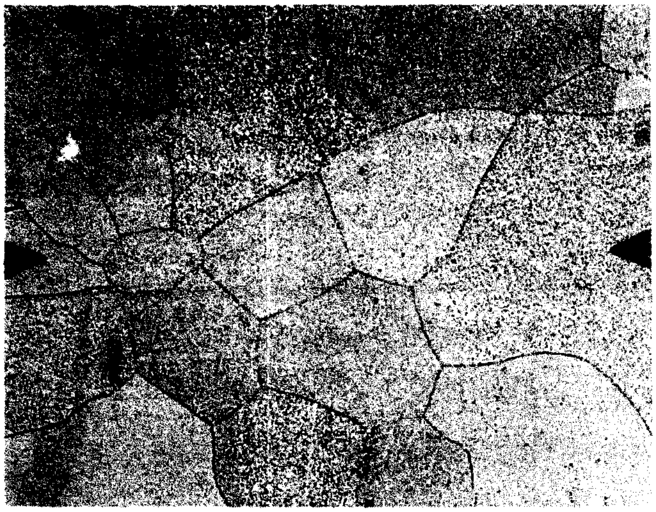


Figure 26.13–A Diffusion Brazed Joint in Wrought Nickel Alloy

where high-quality joints are required between large, flat surfaces. For example, low carbon steels have been welded without a filler metal over a wide range of conditions. Two sets of conditions that produced excellent welds in AISI 1020 steel are 1800 to 2200°F (982 to 1204°C) with a pressure of 1 ksi (7 MPa) for 1 to 15 minutes and 2000 to 2200°F (1093 to 1204°C) with a pressure of 5 psi (35 kPa) for 2 hours. Welding can be accomplished either in a protective atmosphere or in air, provided the joint is first seal welded around the periphery to exclude air.

Stainless steels can be diffusion welded using conditions similar to those used for carbon steel; however these steels are normally covered by a thin adherent oxide that must be removed prior to welding. This can be accomplished either by welding at high temperatures in dry hydrogen or by copper plating the faying surfaces after anodic cleaning. Copper oxide on the plating is relatively easy to reduce in hydrogen during heating to welding temperature. For illustrative purposes, sound welds were made in AMS 5630 martensitic stainless steel at 2000°F (1093°C) with a pressure of 100 psi (690 kPa) for 1.5 hour using a 0.0001 in. (2.5 µm) thick copper filler metal.

DISSIMILAR METAL COMBINATIONS

DIFFUSION WELDING IS particularly well suited for joining many dissimilar metal combinations, especially when the melting points of the two base metals differ widely or when they are not metallurgically compatible. In such cases, conventional fusion welding is not practical because it would either result in excessive melting of one of the metals or in the formation of a brittle weld metal. Diffusion welding is also suitable when the high temperatures of fusion welding would cause an alloy to become brittle or lower its strength drastically, as is the case with some refractory metal alloys. Filler metals are sometimes used to prevent the formation of brittle intermetallic phases between certain metal combinations.

When determining conditions and filler metal requirements for diffusion welding a particular dissimilar metal combination, the effects of interdiffusion between the two base metals must be considered. Interdiffusion can cause certain problems as a result of the following metallurgical phenomena:

(1) An intermediate phase or a brittle intermetallic compound may form at the weld interface. Selection of an appropriate filler metal can usually prevent such problems.

(2) Low melting phases may form. Sometimes this effect is beneficial.

(3) Porosity may form due to unequal rates of metal transfer by diffusion in the region adjacent to the weld interface. This is known as Kirkendall porosity. Proper welding conditions or the use of an appropriate filler metal, or both, may prevent this problem.

One problem that often exists and that is not unique to diffusion welding is the difference in the thermal expansion characteristics of the two base metals. Simply stated, any combination of dissimilar metals that is heated and cooled during welding or brazing will develop shear stresses in the joint if the coefficients of thermal expansion are not identical. The severity of the problem will vary depending upon the temperature span, the difference between the expansion coefficients, the size and shape of the joint members, and the nature of the weld formed between them. This becomes a design problem, in part, since distortion can result. Cracking can result when the joint strength or ductility, or both, are low and the stresses are high.

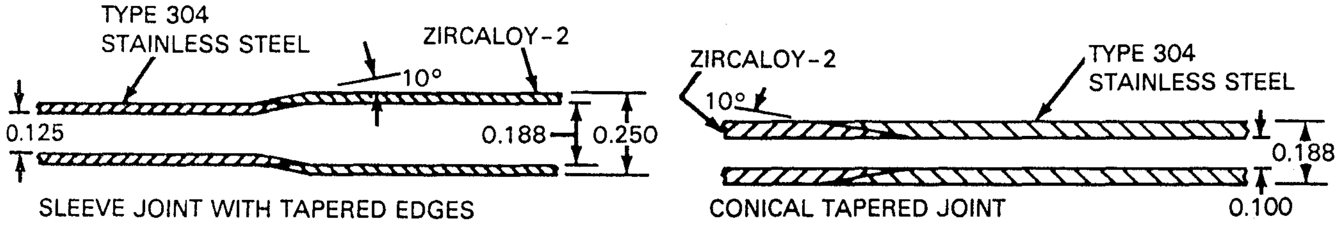
Many dissimilar combinations can be formed but result in brittle intermetallic phases, and in some cases the reaction proceeds very rapidly due to the formation of a liquid phase at the welding temperature. Although these combinations are brittle, useful joints can be attained by allowing for it in the component design. A combination of Zircaloy 2 with type 304 stainless steel is a good example of the situation where a strong useful joint can be made despite the presence of brittle phases. Figure 26.14 shows the joint designs employed for joining type 304 stainless tube to Zircaloy 2.

The conical tapered joint shown in Figure 26.14(A) uses the differential expansion of the two materials to provide the required pressure. The joint shown in Figure 26.14(B) requires a longitudinal force to maintain pressure during the diffusion welding process.

Joints between stainless steel and Zircaloy 2 tubing of 7/8 in. (22.2 mm) diameter and 1/8 in. (3.2 mm) wall can withstand from 12 000 to 17 000 psi (83 to 117 MPa) internal pressure when tested hydraulically. The fracture initiates by longitudinal splitting of the Zircaloy tube. Similar joints have withstood 100 pressure cycles between 100 and 3500 psi (690 to 24 000 kPa) at 500°F (260°C) and 200 temperature cycles between 100 and 600°F (38 and 316°C) without failure.

Representative conditions used for diffusion welding some dissimilar metal combinations are presented in Table 26.2. Often the temperature and the time used for a particular combination are selected as part of the necessary heat treatment for one of the alloys to develop design properties for a specific application.

Several recent Japanese successes are shown in Table 26.3



(A) BONDING PRESSURE IS APPLIED BY EXPANSION OF THE STAINLESS STEEL AGAINST THE ZIRCALOY.

(B) BONDING PRESSURE IS APPLIED BY AN AXIAL COMPRESSIVE FORCE FROM AN INTERNAL BAR.

Figure 26.14–Joint Design Used to Overcome Existence of Brittle Phases

Table 26.2
Diffusion Welding Conditions for Some Dissimilar Metal Combinations

Base Metal Combinations	Filler Metal	Temperature, °F	°C	Time,h	Pressure[a], ksi	MPa	Atmosphere
Cu to Al	—	950	510	0.25	1	7	Vacuum
Cu to 316 Stainless Steel	Cu	1800	982	2	a		Vacuum
Cu to Ti	—	1560	849	0.25	0.7	5	Vacuum
Cu to Cb-1%Zr	Cb-1%Zr	1800	982	4	a		Vacuum
Cu-10%Zn to Ti-6%Al-6%V-2%Sn	—	900	482	8	a		Vacuum
4340 Steel[c] to Inconel 718[b]	—	1730	943	4	29	200	Vacuum
Nickel 200 to Inconel 600[b]	—	1700	927	3	1	7	Not Reported
Pyromet X-15[b] to T-111 Ta alloy	Au-Cu	1100	593	4	30	207	Not Reported
Cb-1%Zr to 316 Stainless Steel	Cb-1%Zr	1800	982	4	a		Vacuum
Zircaloy-2 to 304 Stainless Steel	—	1870-1900	1021-1038	0.5	a		Vacuum

a. Pressure is applied with differential thermal expansion tooling.

b. Tradenames

c. Outgassing of the 4340 steel at 10(-5) torr (130 mPa) and 1850°F (1010°C) for 24 hours prior to welding was critical to the formation of satisfactory welds.

Table 26.3
Recent Applications of Diffusion Joining in Japanese Industries

Products	Materials	Reason for Adoption	Previous Method	Product Records
F-15 Fighter Fitting	Ti-6Al-4V	Cost reduction	Machining from forging or plate	more than 1000 parts
Impeller for Liquid Fuel Rocket	Ti-5Al-2.5Sn	Higher quality	—	100 parts
Jewelry	18K gold alloy	Higher quality	Brazing	400 million yen per year
Electrode	Cu-316L stainless steel	New type only possible by DJ	—	2200 parts
Tube sheet	Cupro Ni-mild steel-316L ss	Cost reduction	Rolling or explosive bonding	1000 parts
Chock liner for steel rolling mill	Brass-mild steel	Cost reduction	Solid Cu alloy	100 parts
Cooling plate for cyclotron accelerator	Cu-316Lss	New type only possible by DJ	—	50 parts
Continuous casting mold	wear resistant material - Cu alloy - 304 ss	New type only possible by DJ	—	20 parts

INSPECTION

ESTABLISHING THE QUALITY of a diffusion welded or brazed joint is difficult with current nondestructive examination procedures. This is due to the nature of the joints. Usually, little or no porosity exists if the joint is made with properly developed procedures. The main defect in a diffusion weld is lack of grain growth across the original interface. Efforts to distinguish intimate contact without grain growth across the interface from a perfect bond have not been successful.

Radiography, eddy current, and thermal methods are relatively unsatisfactory for inspection of most applications. Dye penetrant methods have been found useful for edge inspections.

Ultrasonic examination has proved the most useful for internal inspection, especially if a hairline separation exists. The sensitivity varies with the metal being tested, the ultrasonic frequency, the skill of the operator, and the degree of sophistication of the equipment. In general, defects of less than 0.1 in. (2.5 mm) diameter are difficult to locate and a practical limit of about 0.04 in. (1.0 mm) exists. With special methods and very sophisticated equipment, it has been reported that defects equivalent to 0.005 in. (0.13 mm) diameter can be detected in some metals. These testing approaches cannot be considered routine and they only work under special conditions.

Various types of diffusion weld defects representing possible production defects for superplastic forming/diffusion brazing processes have been evaluated in numerous titanium specimens. These specimens were used to evaluate ultrasonic techniques with regard to defect resolution. Table 26.4 summarizes the results. Higher frequency, focusing probes appear to produce the best results, but investigations are continuing.

Ultrasonic inspection cannot differentiate between complete intimate contact and an actual diffusion weld. Only metallographic examination can assure complete welding or brazing. Because this is a destructive test, it cannot always be performed on the part in question. Fortunately, diffusion welding and brazing are reproducible when good process control is exercised. Random destructive sampling coupled with ultrasonic examination will provide a high confidence level. This approach has been successfully used in production.

A reliable nondestructive examination method for inspection of diffusion welded structures is desireable. However, the present conventional nondestructive examination procedures and equipment do not adequately differentiate between acceptable and unacceptable diffusion welded or brazed joints. Therefore it is necessary to supplement the nondestructive tests with destructive tests. Conventional radiography is not suitable for detecting the extremely small defects involved in diffusion welding, but use of x-ray micro-focus techniques coupled with digital image enhancement offer an improvement in resolution.

Table 26.4
Detectability of Diffusion Brazing Defects with Various Ultrasonic Testing Methods

Diffusion Brazing Defects	Ultrasonic Testing Methods			
	Transmission-focussing, non-focussing probes 5 and 10 MHz	Pulse/echo, non-focussing probes 10 up to 20 MHz	Pulse/echo non-focussing probes 30 up to 110 MHz	Pulse/echo point-focussing probes $>$ 30 MHz
Course-dispersive macro defects (single defect size $w = 200\mu m$; $\varphi = 3$ mm)	D	WD	WD	WD
Course-dispersive macro defects (single defect size $w = 5\mu m$; $\varphi > 5$ mm)	PD	D	WD	WD
Fine-dispersive macro defects (single defect size $w = 3\mu m$; $0{,}1 < \varphi < 5$ mm)	PD	PD	WD	WD
Micro defect configurations (single defect size $w = 1\mu m$; $\varphi < 15\mu m$)	ND	ND	PD	D

ND not detected
PD partially detected
D detected
WD well detected

SAFE PRACTICES

HAZARDS ENCOUNTERED WITH diffusion welding and brazing are similar to those associated with other welding and cutting processes. Personnel must be protected against hot materials, gases, fumes, electrical shock, and chemicals.

The operation and maintenance of diffusion welding and brazing equipment should conform to the provisions of American National Standard Z49.1, Safety in Welding and Cutting. This standard provides detailed procedures and instructions for safe practices which will protect personnel from injury or illness, and property and equipment from damage by fire or explosion arising from diffusion welding.

It is essential that adequate ventilation be provided so that personnel will not inhale gases and fumes generated while diffusion welding and brazing. Some filler metals and base metals contain toxic materials such as cadmium, beryllium, zinc, mercury, or lead, which are vaporized during brazing.

Solvents such as chlorinated hydrocarbons, and cleaning compounds such as acids and alkalies, may be toxic or flammable or cause chemical burn when present in the brazing environment.

Requirements for the purging of furnaces or retorts that will contain a flammable atmosphere are also given in the standard. In addition, to avoid suffocation, care must be taken with atmosphere furnaces to insure that the furnace is purged with air before personnel enter it.

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CHAPTER 27

ADHESIVE BONDING OF METALS

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CHAPTER 27

ADHESIVE BONDING OF METALS

FUNDAMENTALS OF THE PROCESS

DEFINITIONS AND GENERAL DESCRIPTION

ADHESIVE BONDING IS a materials joining process in which a nonmetallic adhesive material is placed between the faying surfaces of the parts or bodies, called *adherends*. The adhesive then solidifies or hardens by physical or chemical property changes to produce a bonded joint with useful strength between the adherends. During some stage of processing, the adhesive must become sufficiently fluid to wet the faying surfaces of the adherends.

Adhesive[1] is a general term that includes such materials as cement, glue, mucilage, and paste. Although natural organic and inorganic adhesives are available, synthetic organic polymers are usually used to join metal assemblies. Various descriptive adjectives are applied to the term adhesive to indicate certain characteristics, as follows:

(1) Physical form: liquid adhesive, tape adhesive

(2) Chemical type: silicate adhesive, epoxy adhesive, phenolic adhesive

(3) Materials bonded: paper adhesive, metal-plastic adhesive, can label adhesive

(4) Application method: hot-setting adhesive, sprayable adhesive

Although adhesive bonding is used to join many nonmetallic materials, only the bonding of metals to themselves or to nonmetallic structural materials is covered in this chapter.

Adhesive bonding is similar to soldering and brazing of metals in some respects but a metallurgical bond does not take place. The surfaces being joined are not melted, although they may be heated. An adhesive in the form of a liquid, paste, or tacky solid is placed between the faying surfaces of the joint. After the faying surfaces are mated with the adhesive in between, heat or pressure, or both, are applied to accomplish the bond.

An adhesive system must have the following characteristics:

(1) At the time the bond is formed, the adhesive must become fluid so that it wets and comes into close contact with the surface of the metal adherends.

(2) In general, the adhesive cures, cools, dries, or otherwise hardens during the time the bond is formed or soon thereafter.

(3) The adhesive must have good mutual attraction with the metal surfaces, and have adequate strength and toughness to resist failure along the adhesive-to-metal interface under service conditions.

(4) As the adhesive cures, cools, or dries, it must not shrink excessively. Otherwise, undesirable internal stresses may develop in the joint.

(5) To develop a strong bond, the metal surfaces must be clean and free of dust, loose oxides, oil, grease, or other foreign materials.

(6) Air, moisture, solvents, and other gases which may tend to be trapped at the interface between the adhesive and metal must have a way of escaping from the joint.

(7) The joint design and cured adhesive must be suitable to withstand the intended service.

PRINCIPLES OF OPERATION

FOR WETTING TO occur, the surface free energy of the adherend must be greater than that of the adhesive. This is usually the case for metallic adherends and polymeric adhesives; however, contaminants adsorbed on the metal can lower the surface free energy and prevent the formation of a good adhesive bond. Contaminants can be removed from

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[1] Terms relating to adhesives are defined in ANSI/ASTM D907.

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the surface by washing with solvent or by abrasion. The latter treatment, using grit blasting, abrasive paper, or abrasive pads, is frequently used to prepare metal surfaces before bonding.

In addition to the surface energetics, an adhesive must have low viscosity during the bond forming process in order to spread readily over the adherend surface. The higher the viscosity, the greater the probability that the adhesive will not completely wet the surface and will entrap gases, liquids, or vapors in the bondline. This tendency can be reduced by the application of pressure during the cure process.

PROCESS ADVANTAGES

ADHESIVE BONDING HAS several advantages for metals joining when compared to resistance spot welding, brazing, soldering, or mechanical fasteners such as rivets or screws.

Bonding Dissimilar Materials

IT IS POSSIBLE to bond dissimilar metals with minimal galvanic corrosion in service, provided the adhesive layer maintains electrical isolation between the metals. Many types of adhesive formulations are flexible enough to permit the bonding of dissimilar metals with widely different coefficients of thermal expansion. Such possibilities depend, of course, upon the size of the pieces and the degree of joint strength required. A single adhesiv
for joining a number of dissimilar metal cor
single assembly.

Adhesive bonding also makes it possible
to nonmetallic materials such as various ty
Figure 27.1 shows the bonding of rigid ure
sheet steel with a free-flowing, room-temp
epoxy adhesive in the fabrication of insula

Bonding Thin Gage Metals

VERY THIN METALS parts can be adhesively
examples of this are: (1) multiple layers of th
can be bonded together to form electric m
(2) various metal foils can be joined to th
other materials; and (3) thin-gage metal shee
as sandwich panel skins.

Low Processing Temperatures

THE TEMPERATURES USED for the heat curing
sives are between 150 and 350°F (65 and 17
tures that are below the normal soldering
temperature-curing formulations are availab
sturdy structural bonds for service tempe
180°F (82°C) under humidity conditions t
ceed 70 percent relative humidity. High
room-temperature-curing epoxy adhesives

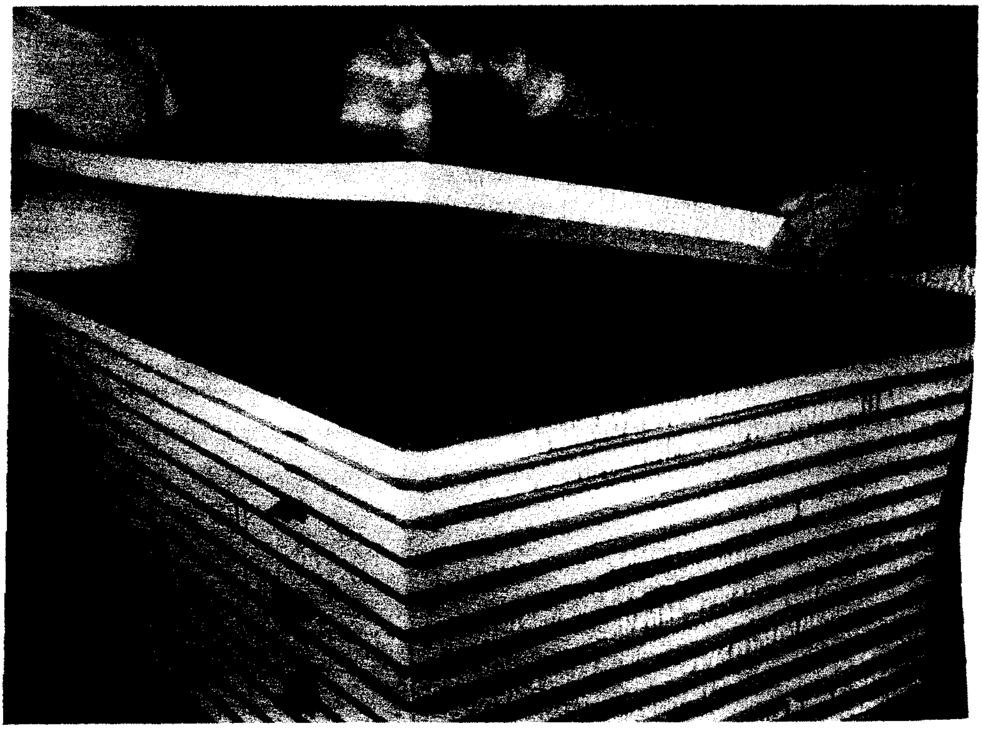

Figure 27.1—Rigid Urethane Foam Bonded to Sheet Metal

that maintain good strength up to 300°F (150°C). They can be used to join heat-sensitive components without damage. Adhesive bonding should be considered when high temperature joining operations would cause metallurgical or structural damage to the parts.

Many adhesives provide suitable performance at temperatures above their curing temperature, which is not the case with metal solders.

Combination Bonding and Sealing

THE ADHESIVE THAT bonds the components may also serve as a sealant or coating to provide protection from oils, chemicals, moisture, or a combination of these. In Figure 27.2, a room-temperature-curing adhesive is being applied to seal the ends of an antenna circuit in the handle of a marine radio. The same adhesive is also used to bond neoprene tubing and plastic-coated lead-in wires to aluminum at three points within the radio housing.

Thermal and Electrical Insulation

ADHESIVES CAN PROVIDE thermal or electrical insulating layers between the two surfaces being joined. For example, almost all mass-produced printed circuits use adhesive bonding. In this application, the adhesive used to bond the copper conductor to the base material has electrical characteristics similar to those of the base material. An adhesive may also serve as an insulator between adjacent conductors.

The addition of certain metallic or carbon fillers to adhesive formulations can make them electrically conductive. Some testing before acceptance should be done under simulated service conditions because corrosion may occur in some metal structures bonded with electrically conductive adhesives that are exposed to moisture. Metal powder additives can improve the thermal conductivity of adhesives.

Uniform Stress Distribution

JOINTS CAN BE designed to distribute the load over a relatively large bonded area to minimize stress concentrations. In wall panel construction, for example, metal skin sheets are bonded to metal or paper honeycombs, foamed polystyrene, or other core materials.

Smooth Surface Appearance

ADHESIVES CAN ENSURE smooth, unbroken surfaces without protrusions, gaps, or holes. A typical example is the vinyl-to-metal laminate widely used in the production of television cabinets, housing for electronic equipment, and automotive trim. Figure 27.3 shows adhesive-bonded truck

Figure 27.2—Application of an Epoxy Adhesive to Seal the End of a Marine Radio Antenna

door panels where broad, smooth areas are required. Hood and roof stiffeners on automobiles are adhesive bonded rather than resistance spot welded to the panels to avoid marks that would be susceptible to rusting and might require filling, grinding, and polishing prior to painting.

Good Vibration and Sound Damping

THE ABILITY OF FLEXIBLE adhesives to absorb shock and vibration gives the joints good fatigue life and sound-dampening properties. The use of adhesives rather than rivets has increased joint fatigue life by a factor of ten or more in some applications. A specific example is the improved fatigue life of adhesive bonded helicopter rotor blades.

A combination of adhesives and rivets for joints in very large aircraft structures has increased the fatigue life of joints from 2 x 10^5 cycles for rivets alone to more than 1.5 x 10^6 cycles for the bonded and riveted joints. The large bonded area also dampens vibration and sound.

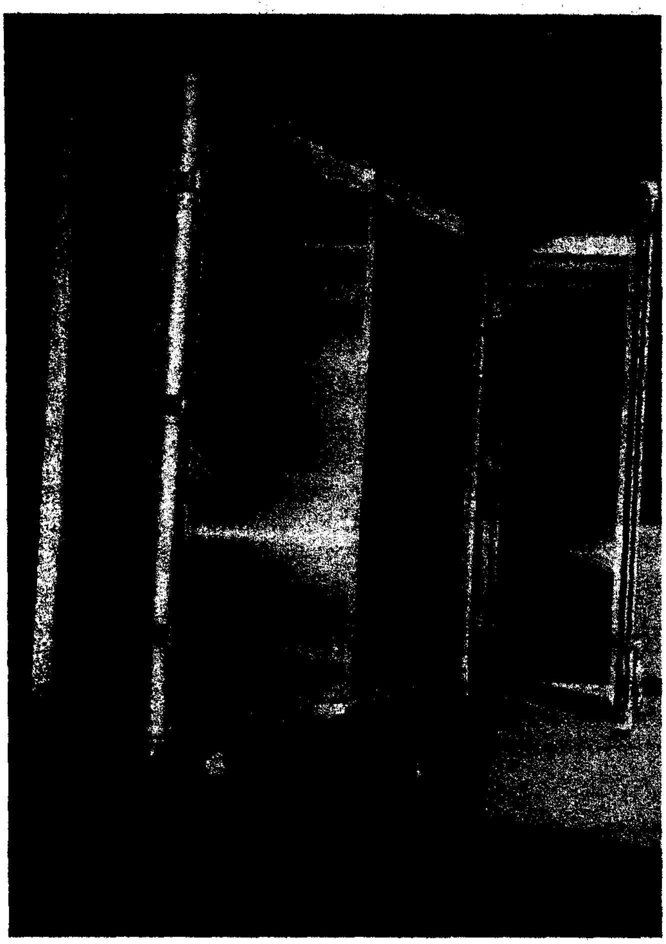

Figure 27.3–Truck Door Panels of Aluminum Adhesive Bonded to Chipboard

Weight Savings

ADHESIVE BONDING MAY permit significant weight savings in the finished product by utilizing lightweight fabrications. Honeycomb panel assemblies, used extensively in the aircraft industry and the construction field, are excellent examples of lightweight fabrications. Typical panels are shown in Figure 27.4. Not only is the honeycomb core material bonded to the metal face sheets, the honeycomb core itself is generally adhesive bonded. Although weight reduction can be important in the function of the product, it may also provide considerable cost savings in packing, shipping, and installation labor.

Simplification of Design

ADHESIVES OFTEN PERMIT design simplification. In Figure 27.5, aluminum die cast pump sections have been adhesive bonded to a steel core. Previously, the part was cast as one piece of steel, but blow holes in the casting resulted in an excessive number of rejects. Redesigning to an adhesive-bonded assembly reduced the number of rejects to near zero.

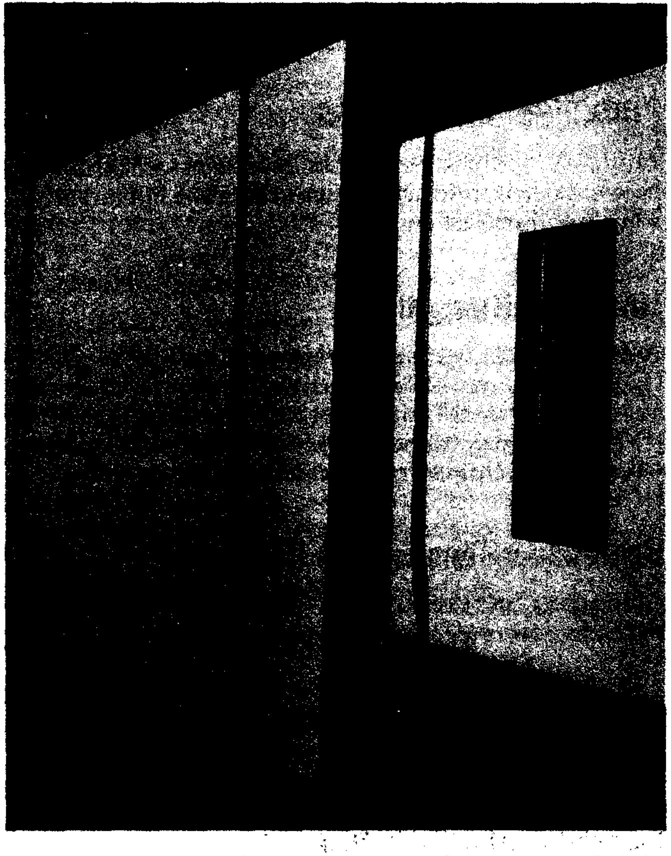

Figure 27.4–Adhesive Bonded Honeycomb Panels

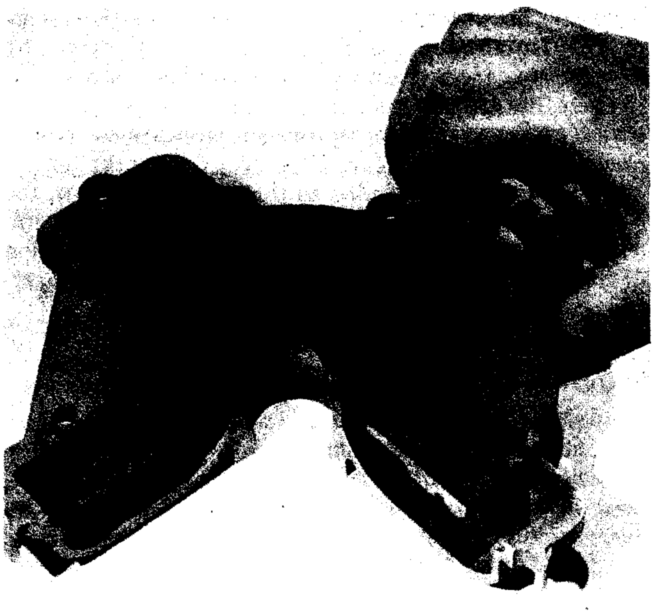

Figure 27.5–Aluminum Die Cast Pump Sections Adhesive Bonded to a Steel Core

PROCESS LIMITATIONS

ADHESIVE BONDING HAS certain limitations which should be considered in its applications, the most important of which are listed below.

Low Peel Strength

ADHESIVES WILL NOT support high peel loads above 250°F (120°C), not even those adhesives that have high tensile and shear strengths at temperatures as high as 300°F (150°C). For applications where high peel strength is essential, some mechanical reinforcement may be necessary.

Operational Temperature Ceiling

ADHESIVES, INCLUDING EPOXY-PHENOLICS that are designed for low creep at elevated temperatures, have an operational temperature ceiling of about 500°F (260°C). Some new high temperature adhesives derived from heat stable polyamides, polybenzimidazoles, and related compounds show promise for use at temperatures up to 700°F (371°C), but they are costly and difficult to process.

Equipment and Processing Costs

CAPITAL INVESTMENT FOR equipment and tooling to process components may be high when large bonding areas and special service requirements are involved. The benefits of an adhesive-bonded joint must be balanced against the cost of autoclaves, presses, tooling, and other special equipment needed to perform the bonding operation.

Process control costs may be higher than those for other joining processes. Surfaces must be properly cleaned, treated, and protected from contamination prior to bonding if the best bond durability is required. Surface preparation can range from a simple solvent wipe to multi-step cleaning, etching, anodizing, rinsing, and drying procedures which must be very carefully followed in critical structural bonding applications. Control of ambient temperature and humidity may also be necessary.

Curing Time

TO DEVELOP FULL strength, joints must be fixtured and cured at temperature for some time. On the other hand, mechanical fasteners provide design strength immediately and usually do not require extensive fixturing.

Bond Testing Procedures

NONDESTRUCTIVE INSPECTION METHODS normally used for other joining methods are not generally applicable to the evaluation of adhesive bonds. Both destructive and nondestructive testing must be used with process controls to establish the quality and reliability of bonded joints.

Limited Service Conditions

SERVICE CONDITIONS MAY be restrictive. Many adhesive systems degrade rapidly when the joint is both highly stressed and exposed to a hot, humid environment.

ADHESIVES

GENERAL DESCRIPTION

ADHESIVES MAY BE either thermosetting or thermoplastic. The principal ingredients in most adhesive formulations following are:

(1) A synthetic resin system
(2) An elastomer or flexibilizer
(3) Inorganic materials

Thermosetting Adhesives

THERMOSETTING RESINS ARE the most important materials on which metal adhesive formulations are based. Their properties can be modified for specific applications by the addition of modifying agents and fillers. Thermosetting adhesives harden or cure by chemical reactions that occur with the addition of a hardener or catalyst. Heat, pressure, radiation, or other energy can accelerate the curing rate. Once they cure, these adhesives cannot be remelted, and a broken joint cannot be rebonded by heating. Depending upon composition, thermosetting adhesives may soften or weaken at high temperature and ultimately decompose. Thermosetting resins, or adhesives, are frequently referred to as *structural adhesives*.

Thermoplastic Adhesives

THERMOPLASTIC RESINS ARE long chain molecular compounds that soften upon heating and harden upon cooling. They undergo no chemical change upon heating, so the cycle can be repeated. However, they will oxidize and decompose at excessively high temperatures. Many thermoplastic resins can also be softened at room temperature with organic solvents. They harden again as the solvent evaporates. Limited resistance to heat, solvents, and load-induced stresses makes thermoplastic resins generally unsuitable as structural adhesives. However, some thermoplastic resins or elastomers are combined with thermosetting resins such as epoxies and phenolics for improved flexibility, peel strength, and impact resistance.

Flexibilizers or elastomers are added to adhesive formulations to add resiliency, improve peel strength, and increase resistance to shock and vibration.

Inorganic materials are added as fillers to improve the mechanical and physical properties of the adhesives. Fillers can add greatly to the stability of bonded joints by reducing shrinkage and thermal expansion and by increasing the modulus of elasticity of the adhesive.

TYPES OF ADHESIVES

THE TYPES OF polymeric adhesives used to bond metals are listed in Table 27.1.

Table 27.1
Types of polymeric adhesives used to bond metals

Solvent	
	Neoprene
	Nitrile
	Urethane (thermoplastic)
	Block copolymer
	Styrene-butadiene
Hot Melt	
	Ethylene vinyl acetate
	Block copolymer
	Polyester
	Polyamide
Pressure Sensitive	
	Block Copolymer
	Acrylic
Chemically Reactive	
	Epoxy
	Phenolic
	Structural Acrylic
	Anaerobic
	Cyanoacrylate
	Urethane

Solvent Type Adhesives

THE SOLVENT TYPE contact adhesives are predominantly elastomeric thermoplastics produced as solutions. They achieve their bond strength upon removal of the solvent. The liquid adhesive is applied to the adherend surfaces and, for metal adherends, time is allowed for the solvent to evaporate. The adhesive-coated surfaces are then joined under contact pressure. Sometimes heat is applied to fuse the coated surfaces after drying.

Hot-Melt Adhesives

THE HOT-MELT ADHESIVES are thermoplastics. After the adherends have been coated with adhesive and mated, heat and pressure are applied to the assembly. The joint is then cooled to solidify the adhesive and achieve a bond. These adhesives are not normally used for structural applications.

Pressure Sensitive Adhesives

PRESSURE SENSITIVE ADHESIVES are formulations that instantly provide a relatively low-strength bond upon the brief application of pressure. They may be applied to any clean, dry surface. Since they are capable of sustaining only very light loads because of retention of their flow characteristics, they are not considered structural adhesives. However, in recent years a number of pressure sensitive transfer tapes and double sided tapes have become available that exhibit high shear strengths. They are used in the construction of trucks and trailers.

Chemically Reactive Adhesives

THE CHEMICALLY REACTIVE adhesives consist primarily of thermosetting resins in liquid and solid forms, including films and tapes. They are activated either by the addition of a catalyst or hardener, or by the application of heat. Bond strength is achieved from the chemical reaction that takes place during the cure. Catalysts or hardeners may be incorporated by the adhesive manufacturer or may be added by the user just prior to application. Such formulations generally must be used within a prescribed period of time after mixing to avoid premature setting.

STRUCTURAL ADHESIVES

THE ULTIMATE OBJECTIVE of a structural adhesive is to create a bond that is as strong as the materials it joins. Since this goal is not always attainable, a structural adhesive can be defined as one that is used to transfer required loads between adherends in a structure for its life expectancy when exposed to its service environment.

Although structural bonding has been successfully used for many aerospace applications since the 1950's, concerns about the long-term durability of structural adhesive bonds have limited the widespread use of this joining method. The combination of stress, even as low as 20 percent of the initial adhesive strength, and exposure to hot, humid environments, can cause significant degradation of bond performance, sometimes leading to failure. Many of the factors affecting the durability of adhesive joints are known and include the type of adhesive, the nature of the adherends, the surface preparation before bonding, and the service conditions.

There are several mechanisms by which the performance of an adhesive can be affected by the presence of moisture. The mechanical properties can change as water is absorbed due to the plasticizing action of water. Swelling stresses can lead to the formation of crazes and microcracks. In unfavorable situations, hydrolysis of the adhesive can occur. Water can also displace the adhesive from the metal surface and thus induce interfacial disbonding. Finally, water may hydrate and weaken the metal oxide surface layer of the adherend. The relative importance of each of these factors is, in general, unknown, as are the details of the various mechanisms. For these reasons it is not usually possible to predict the durability of a given adhesive joint.

Phenolic Resins

PHENOLIC RESINS ARE modified with thermoplastics or elastomers for structural adhesive applications. These modified phenolics are available as solutions in organic solvents and also as films, both supported and unsupported. Such adhesives feature high peel strengths, and tensile and shear strengths in the range of 3000 to 5000 psi (20 to 34 MPa).[2]

Epoxy Resins

THE EPOXY RESINS combine the properties of excellent wetting action, low shrinkage, high tensile strength, toughness, and chemical inertness to produce adhesives noted for their strength and versatility. Unlike phenolic adhesives, epoxies do not form volatile products during curing. They can be applied in liquid form without a solvent carrier. Because of this, volatile entrapment is minimized. Only low pressure is necessary to maintain intimate contact between the adherends during bonding, resulting in greatly simplified equipment requirements.

Epoxy adhesives are available as free-flowing liquids, films, powders, stocks, pellets, and mastics. This variety of forms permits considerable latitude in the selection of application technique and equipment. Fillers or plasticizers may be added to minimize stresses that can develop when the adhesive and adherends have different coefficients of thermal expansion.

The wide choice of hardeners available for epoxy formulations offers curing cycles ranging from a few seconds at elevated temperatures to several minutes or hours at room temperature. However, the heat-resistant formulations require high temperature cures.

Unmodified epoxy-based adhesives show high shear and tensile strengths, but tend to be brittle and thus perform poorly in cleavage and peel. High peel strength can be obtained by flexibilizing the epoxy resin, but this reduces the modulus of the adhesive. Specially formulated "toughened" epoxy adhesives, in which a modifying rubber is present as a distinct phase evenly distributed throughout the cured adhesive, are now available. These adhesives have high shear strengths together with high peel strength and impact resistance. The phase-separated structure imparts high fracture toughness, or resistance to crack propagation, to the adhesive.

Anaerobic Adhesives

ANAEROBIC ADHESIVES ARE shelf-stable, ready-to-use formulations that cure at room temperature. Their cure is inhibited by the presence of air (oxygen) in the package and during application. Once the joint is assembled and air excluded from the liquid adhesive, curing begins. The major use of these adhesives is for sealing and securing threaded fasteners, although formulations are available for applications requiring high bond strength.

Cyanoacrylate Adhesives

CYANOACRYLATE ADHESIVES ARE also shelf-stable and cure rapidly at room temperature when placed in contact with most surfaces. The cure is catalyzed by traces of basic compounds present on the surface. Water, which is adsorbed on most materials, often acts as the effective catalyst. Cyanoacrylates work best when the surfaces are well matched, so that a controlled, even bond is possible. Until recently these adhesives found only limited use in industrial applications because of their relatively poor moisture and heat resistance. However, some of the newer adhesives appear to perform better in these respects.

Acrylic Adhesives

ACRYLIC STRUCTURAL ADHESIVES cure by a chain-growth free- radical mechanism that allows cure times from about one minute to a few hours. The adhesives are generally

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[2] The mechanical properties stated for these adhesive systems pertain to bonded structures which have not been stressed prior to testing and are stored in a low or normal relative humidity condition; i.e., less than 70 percent relative humidity.

supplied as two components that are mixed just prior to the assembly of the joint. Some formulations are available that require no mixing; cure is initiated on contact of the adhesive with a surface that has been coated with a special primer/activator.

Acrylics adhere well to a variety of metals and engineering plastics and are tolerant of surface contamination. Formulations are available that form strong bonds to metals whose surfaces have not been cleaned of mill oils and drawing compounds. However, the most durable bonds are produced when clean surfaces are used.

An epoxy-phenolic resin cured with dicyandiamide is an adhesive that performs well in the 400 to 500°F (205 to 260°C) temperature range. It will produce a bond having good shear and creep properties at 500°F (260°C), but relatively poor peel resistance when cured in a representative cycle of 2 hours at 350°F (177°C) and 150 psi (1 MPa) pressure. Better "all-around" strength properties are often obtained by using this adhesive in conjunction with a specially formulated primer having a high peel strength. The elastomer-modified phenolics, which require curing at temperatures from 300 to 350°F (149 to 177°C) and pressures up to 100 psi (690 kPa), offer good resistance to heat and water in service.

Other classes of high-temperature resistant polymers have been evaluated as high-temperature adhesives. Of these the polyamides are available as structural adhesives; however, applications for such adhesives are limited at present owing to the difficult processing conditions.

FORMS AND APPLICATION METHODS

INDUSTRIAL ADHESIVES ARE available in a number of forms:

(1) Liquids, ranging in viscosity from free-flowing to thick syrups
(2) Pastes
(3) Mastics
(4) Solids
(5) Powders
(6) Supported and unsupported films

The method used for application of a particular adhesive should be selected after careful consideration of these factors:

(1) Available forms of the selected adhesive
(2) Methods available for applying the various forms
(3) Joint designs and order of assembly
(4) Production rate requirements
(5) Equipment costs

Adhesives may be applied with rollers, brushes, caulking guns, trowels, spray guns, or by dipping. The form of the adhesive and method of application must be compatible.

Liquid Adhesives

FOR SMALL ASSEMBLY work, liquid adhesives are commonly applied by brush, short-napped paint roller, or dipping. The more viscous liquids are often applied by trowel, extrusion gun, or plastic squeeze bottle. Polyethylene nozzles of bottle or tube containers should not be rubbed across prepared surfaces such as etched aluminum. This action may deposit a waxlike coating to which the adhesive will not adhere. Small applicators, resembling a ballpoint pen or a hypodermic needle, may be used to deposit very narrow glue lines for spot application. The silk screen process is also useful for applying an adhesive to selected areas. Automatic dispensing machines, which simplify the proportioning and the mixing of many two-component formulations, are also available.

For large areas such as curtain wall panels, liquid adhesive may be applied by spraying, flow coating, roller coating, or troweling. Depending upon the application method, consideration must be given to the viscosity and working (pot) life of the adhesive formulation.

Paste and Mastic Adhesives

PASTE AND MASTIC adhesives may be applied with a smooth or serrated trowel, knife roller, or an extrusion device.

Some paste formulations contain a thixotropic additive that inhibits sag or flow during application and cure. This feature permits their use on vertical or overhead surfaces and may eliminate or significantly reduce the need for special cleanup operations.

Solid Adhesives

ONE METHOD FOR applying a solid adhesive is to first heat the substrate to a temperature slightly above the melting point of the adhesive and then add the adhesive to the hot surface as it melts. Some rod and powder forms of epoxy adhesives are applied in this manner. Specially developed flame spray guns can also be used, but this method may require powders with a particle size within narrow tolerances. Also, care must be taken to avoid overheating the adhesive during application.

Film Adhesives

ADHESIVES IN FILM or tape form are extremely simple to use and produce a bond line having relatively constant thickness and coating weight per unit area. These are important factors in most bonding applications. Films made from adhesives that are thermoplastic, thermosetting, or pressure sensitive are supplied in rolls or sheets that can be blanked or cut to the required shape with scissors. Film adhesives are particularly useful for bonding large areas such as honeycomb sandwich panels. Special films are available for use as adhesive backing on items such as nameplates and decals.

Generally, the film adhesive is placed in position between the adherends and activated with heat or solvent. In the case of pressure-sensitive film, pressure is applied to accomplish bonding. For applications demanding high strength at elevated temperatures, the films usually require both heat and pressure to create the bond.

Solvent reactive and pressure sensitive films are intended primarily for bonding large sheets where only nominal pressure is required. These types of films do not need special heating equipment. They are particularly useful for short-run production and for bonding parts at room temperature.

Duplex bonding films, which combine the properties of elastomeric adhesives and epoxies, are sometimes used for honeycomb sandwich constructions. The elastomeric side, usually a nitrile phenolic, is bonded to the facing to provide peel resistance. The epoxy side forms fillets around the cell walls, and this increases the effective bonding area and the resulting joint strength.

PRIMERS

CERTAIN SERVICE CONDITIONS may require the use of a primer for improved corrosion resistance, flexibility, shock resistance, or peel resistance of the adhesive bond. Primers may also be used to wet or penetrate the substrate or to protect a treated surface of a substrate prior to the application of adhesive.

Most primers are low-viscosity solutions commonly applied by spraying. Brush applications may be satisfactory when relatively small areas are to be coated. In some cases, roll coating or dipping may be employed. Several primer coats may be required to build up the desired thickness, particularly if the adherends are porous. Air drying and full or partial curing are generally necessary prior to further processing.

ADHESIVE SELECTION

THE SELECTION OF the proper adhesive for production depends basically upon the answers to four key questions:

(1) What materials are being joined?
(2) What are the service requirements?
(3) What method of adhesive application is most suitable?
(4) Are bonding costs competitive with other joining methods?

The service requirements of the completed assembly must be studied thoroughly. Several factors to be considered in describing the bonding application:

(1) Type of loading
(2) Operating temperature range
(3) Chemical resistance
(4) Weather and environmental resistance
(5) Flexibility
(6) Differences in thermal expansion rates
(7) Odor or toxicity problems
(8) Color match

Once the service requirements are known, adhesive systems with good durability potential can be selected. The desired form of the adhesive and method of application can then be chosen based on availability of production equipment and scheduling requirements.

In adhesive selection, the tendency to over-design must be avoided. Requirements for higher strength or greater heat resistance than is actually required for the specific application may exclude from consideration many formulations that are adequate for the job, and perhaps less costly or easier to handle in production.

In adhesive selection for a specific application, there are certain physical properties of the adhesive itself and mechanical properties of bonded joints that should be considered. These properties pertain to the behavior of an adhesive from the time that it is made until the bond is accomplished, as well as its performance in service. Table 27.2 lists some of the properties and the applicable ASTM Standards.

For most applications several candidate adhesives will usually be selected based on the above considerations. The final choice is generally made after a test program to determine the suitability of the adhesives for the particular application. Testing may involve various laboratory specimens or a prototype of the complete assembly. In either case, testing should include some estimate of the long-term durability of the adhesive bond in the service environment. The adhesive supplier will generally provide help in the selection and evaluation of adhesives.

Table 27.2
ASTM Standards for Determining Adhesive Properties

Property	ASTM Designation(s)
Physical	
Aging	D1151, D1183, D2918, D2919, D3236, D3762
Chemical	D896
Corrosivity	D3310, D3482
Curing rate	D1144
Flow properties	D2183
Storage life	D1337
Viscosity	D1084
Volume resistivity	D2739
Mechanical	
Cleavage strength	D1062, D3433
Creep	D1780, D2293, D2294
Fatigue	D3166
Flexural strength	D1184
Impact strength	D950
Peel	D903, D1781, D1876, D2918, D3167
Shear	D1002, D2182, D2295, D2919, D3528, D3983
Tensile	D897, D1344, D2095

JOINT DESIGN

TO INCORPORATE AS many of the advantages of adhesive bonding as possible, joint design should be a part of the early stages of product planning. If bonding is being considered as part of a redesign program, structural adhesives should not be substituted directly for other joining methods. The joint should be redesigned to take advantage of adhesive bonding.

Although the primary objective is a strong assembly capable of meeting service requirements, proper joint design can often lead to other cost-saving benefits. Through good design, it may be possible to achieve satisfactory results with an economical adhesive formulation, to utilize a simple bonding process, and to minimize the quality control steps needed to ensure reliability.

Joint design often influences the form and characteristics of the bond line. The design must provide space for sufficient adhesive and a means of getting the adhesive into the joint area.

When considering a new design or a redesign for adhesive bonding, three rules should be observed:

(1) The design loading should produce shear or tensile loading on the joint; cleavage or peel loading should be minimized.

(2) The joint design should ensure that the static loads do not exceed the adhesive-plastic strain capacity.

(3) If it is anticipated that the joint will be exposed to low cyclic loads, the joint overlap should be increased sufficiently to minimize the possibility of creep in the adhesive.

These rules may be difficult to achieve in practice. Some stress concentrations are unavoidable, and it is difficult to design a joint that will be stressed in one mode only.

The four main types of loading are illustrated in Figure 27.6. An adhesive bonded joint performs best when loaded in shear: that is, when the direction of loading is parallel to the plane of the faying surfaces. With thin-gage metal bonds, joint designs can provide large bond areas in relation to the metal cross-sectional area. This makes it possible to produce joints that are as strong as the metal adherends.

The relationship between joint strength and overlap length for a double-lap shear joint is shown in Figure 27.7. The joint strength and overlap distance are proportional up to some limit (point A on Figure 27.7). Then the unit increase in strength decreases as the overlap distance increases. Beyond some overlap (point B), the failure load does not change significantly with overlap distance.

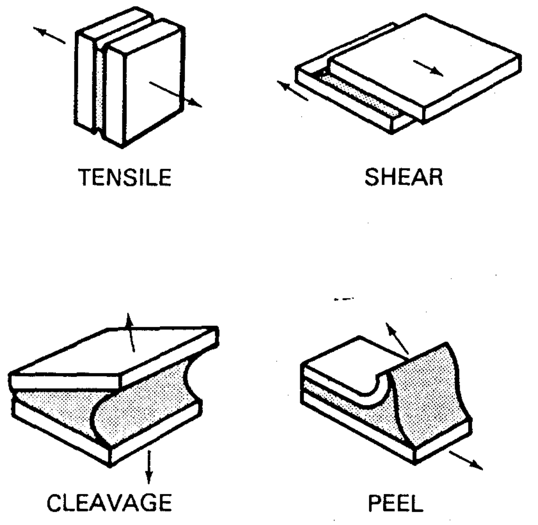


Figure 27.6–Four Principal Types of Loading

SHEAR LOADING

FIGURE 27.8 INDICATES the shear stress distribution across lap joints caused by load P with short, medium, and long overlaps. With short overlap, Figure 27.8(A), the shear stress is uniform along the joint. In this case, the joint can creep under load with time and failure may occur prematurely. When the overlap exceeds some value, the adhesive at the ends of the joint carries a larger portion of the load than the adhesive at the center. Therefore the shear stress at the center is lower, as shown in Figure 27.8(B), and the likelihood of creep is decreased. With long overlap, Figure 27.8(C), the portion of the joint overlap that sees low shear stress is a greater percentage of the total, and creep poten-

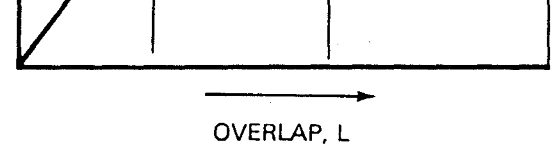
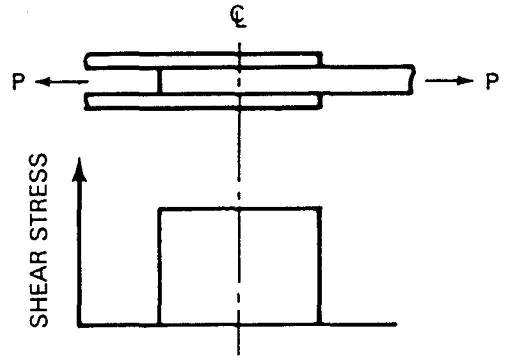
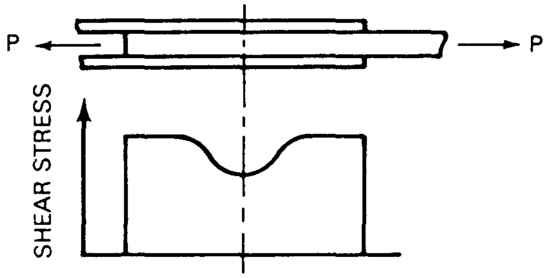


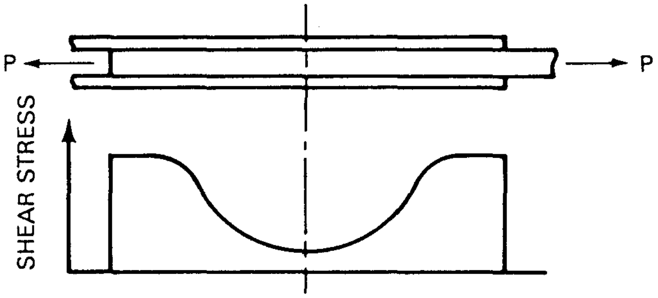
Figure 27.7–Relationship Between Joint Strength and Overlap in Shear



(A) SHORT OVERLAP (PLASTIC ZONE)



(B) MEDIUM OVERLAP (TRANSITION ZONE)



(C) LONG OVERLAP (CONSTANT LOAD ZONE)

Figure 27.8–Change in Shear Stress Distribution with Overlap for Constant Load, P

tial is minimized. The joint overlap for minimum creep will depend upon the mechanical properties of the base metal, the adhesive properties and thickness, the type of loading, and the service environment.

PEEL LOADING

DIFFICULTIES MAY ARISE when cleavage or peel-type loading is present. Cleavage loading produces nonuniform stress across the joint, and this causes failure to initiate at the edge of the adhesive. Obviously, such a joint is considerably weaker than the same bonded area under uniform shear or tensile stress.

The situation is even more critical when the adhesive is subject to peel-type loading. A very narrow line of adhesive at one edge of the joint must withstand the load. Peel loading produces failure at only a fraction of the tensile load needed to rupture a bond of the same area.

As noted earlier, undirectional loading is rarely accomplished. Most joints are subjected to loads which combine cleavage or peel loading with tension or shear stress in the bond. One example is a straight butt joint that is designed to be stressed strictly in tension but is subjected to a slight bending moment that creates a cleavage load. Another example is a single lap joint that is designed to withstand expected shear stress but sees cleavage or peel loads when the joint rotates slightly as the load forces tend to align, as shown in Figure 27.9. These problems can usually be minimized by selecting an adhesive designed to carry the type of loading expected and by employing the proper joint design.

Several of the more common types of joints for sheet metal are shown in Figure 27.10. A butt joint design, shown in Figure 27.10(A), is not recommended. Cleavage loading may develop if the applied loading is eccentric. A scarf joint [Figure 27.10(B)] is a better design because the bonded area can be greater than with a butt joint. Cleavage stress concentrations at the edges are minimized by the tapered edges of the adherends. Although widely used in wood bonding, this configuration is difficult to make in metals with regard to alignment and pressure application during curing.

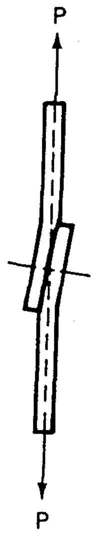


Figure 27.9–Lap Joint Rotation as a Result of Loading

The single lap joint, Figure 27.10(G), is probably the most commonly used type and is adequate for many applications. The beveled lap joint, Figure 27.10(H), has less stress concentration at the edges of the bond because of the beveled edges. The thin edges of the adherends deform as the joint rotates under load, and this minimizes peel action.

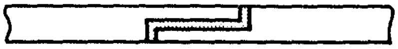
If joint strength is critical and the components are thin enough to bend under load, a joggle lap joint, Figure 27.10 (I), is better, The load is aligned across the joint and parallel with the bond plane, thus minimizing the possibility of cleavage loading.

If sections to be bonded are too thin to permit edge tapering, a double-strap joint, Figure 27.10(E), will give good results. The best design is the beveled double-strap joint, Figure 27.10(F), with its tapered straps.

Adhesive bonding can be used to advantage on extruded, cast, or machined components. The butt joints shown in Figure 27.11 can easily be incorporated into machined or extruded shapes that are to be assembled by adhesive bonding. The tongue and groove joint not only aligns the load-bearing interfaces with the plane of shear stress but also provides good resistance to bending. The landed-scarf tongue and groove joint offers production advantages. Its configuration automatically aligns the parts to be mated, controls the length of joint, and establishes the thickness of the glue line. It is a good design for an assembly that will see high compressive forces, and it offers a clean appearance.

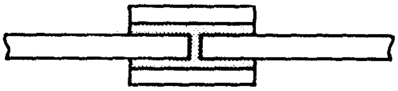
(A) BUTT—POOR

(B) SCARF—FAIR



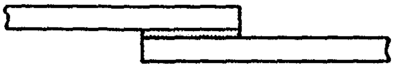
(C) DOUBLE BUTT LAP—EXCELLENT

(D) SINGLE STRAP — FAIR

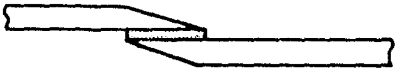


(E) DOUBLE STRAP—GOOD

(F) BEVELED DOUBLE STRAP—EXCELLENT

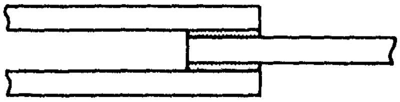


(G) SINGLE LAP—GOOD



(H) BEVELED LAP—VERY GOOD

(I) JOGGLE LAP—GOOD



(J) DOUBLE LAP—GOOD

Figure 27.10–Adhesive Bonded Joint Designs for Sheet Metal

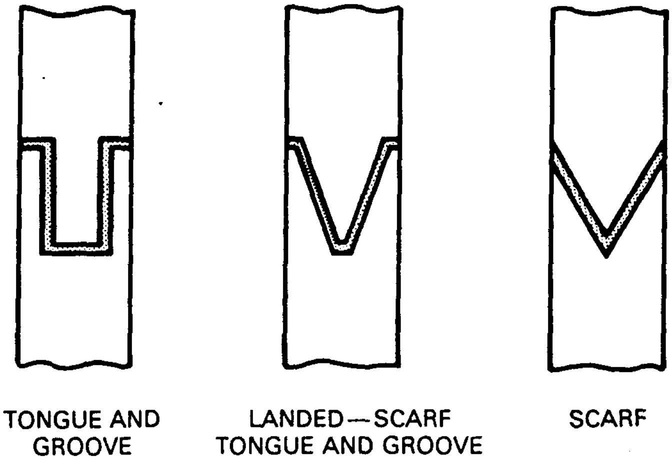


Figure 27.11–Adhesive Bonded Butt Joint Designs for Machined or Extruded Shapes

Corner and T-joint designs are shown in Figure 27.12. The use of beveled or tapered reinforcing members requires a cost analysis to determine if the improved joint properties are justifiable. Joints requiring machined slots or complex corner fittings are seldom of interest in sheet metal designs.

Adhesive bonding is also useful for tube joints, examples of which are shown in Figure 27.13. Large bonded areas give very strong joints with clean appearance. Processing may be complicated with some designs. During assembly of designs shown in Figures 27.13(A) and (B), the adhesive may be pushed out of the joint. The design shown in Figure 27.13(C) partially overcomes this problem. Adhesive in the corners is forced into the joint by a positive pressure filling action during assembly. Tapered or scarfed tubular joint designs as illustrated in Figures 27.13(D), (E), and (F), will produce a positive pressure on the adhesive during assembly to completely fill the gap, but they are costly to produce. The design pictured in Figure 27.13(G) shows a tubular sleeve joint that can be filled by injecting the adhesive under a positive pressure through a hole in the sleeve. This technique results in completely filled and bonded joints at reasonable fabrication costs.

With the availability of computers and the development of analytical mathematical models, it is now possible to optimize joint design by taking into account the geometry of the adherends and the properties of the adhesive. The thick adherend shear test (ASTM D 3983) provides the shear modulus, the elastic shear stress limit, and the asymptotic shear stress of the adhesive which are useful in this respect.

It may be possible to eventually include the effects of environmental exposure into the mathematical modeling of joint performance. This will allow the durability of adhesively bonded structures to be predicted.

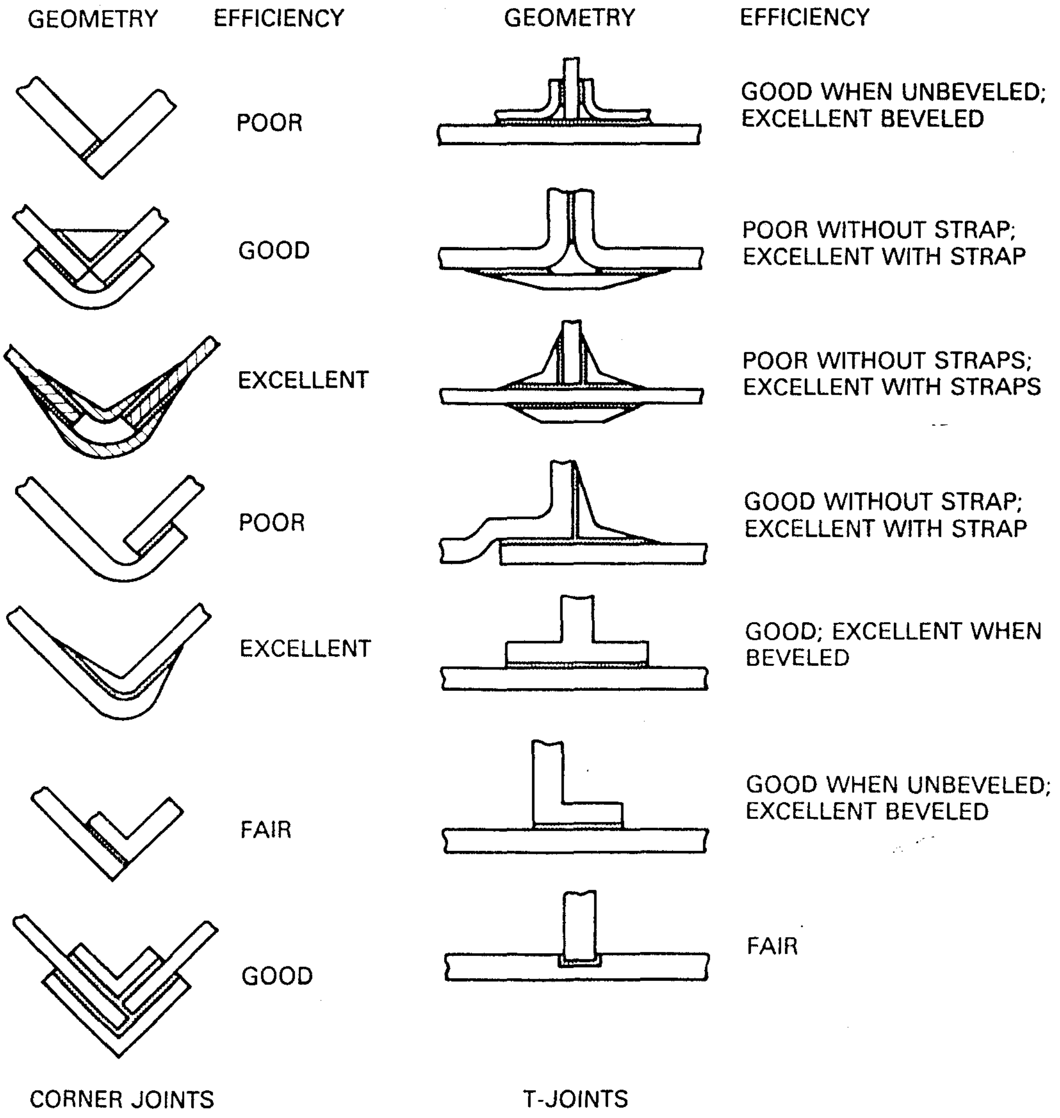


Figure 27.12–Corner and T-Joint Designs for Adhesive Bonding

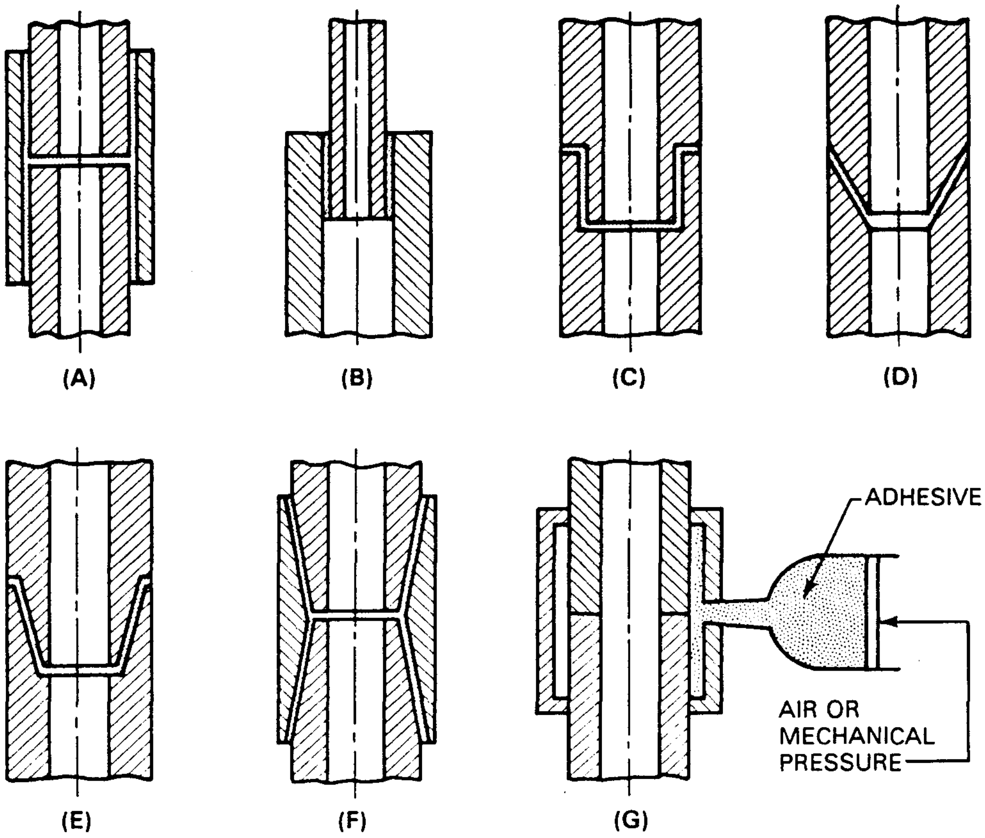


Figure 27.13–Tubular Joint Designs for Adhesive Bonding

SANDWICH CONSTRUCTION

A MAJOR USE of structural adhesive bonding is in sandwich construction. First used in the aircraft industry to meet the demand for a high stiffness-to-weight ratio, sandwich panels are now widely used throughout industry. Their characteristics make them equally valuable in the fabrication of walls, truck bodies, refrigerators, cargo pallets, and a great many other commercial applications

The sandwich skins, or facings, behave approximately as membranes stabilized by a lightweight core material that transmits shear between the skins. Basically, a high stiffness-to-weight ratio is achieved by placing the two load carrying skins as far from the neutral axis as possible with the lightweight core bonded to them. In a sense, the face sheets perform the same functions as the flanges of an I-beam, and the core performs as the beam web.

The selection of skin and core materials for sandwich construction is dictated by service requirements and economic considerations, including the cost of fabrication and materials. Many different skin and core materials may be used as sandwich components. Sheets of metal, plastic, wood, and fire-resistant inorganics are all commonly used as skin materials. Core materials are of the following three basic types:

(1) Solid types such as hardwood, balsa, or metal

(2) Honeycomb or corrugated types made of various materials, typically metal foils, resin-impregnated paper, or reinforced plastics

(3) Open- or closed-cell foamed materials such as polystyrene, polyurethane, polyisocyanurate, and glass

Metal foil honeycomb cores are available with and without perforations in the cell walls. The perforations permit equalization of pressure in the completed panel and also vent gases produced by some types of adhesives during bonding. Cores are also available in truss and waffle configurations that are produced by corrugating and folding or by pressing the material to shape between matched dies.

Expanded plastic cores may be supplied in a preformed state that requires a separate bonding step, or the plastic may be foamed in place and thus simultaneously formed and bonded to the skins of the sandwich.

Special consideration should be given to selecting the material combination that will produce the optimum composite structure for a specific application. For example, a honeycomb core between thin metal skins can provide high strength and low weight; or a foamed plastic core can be used to assure high thermal insulation with almost any skin material.

Several basic types of adhesives with very similar properties are used in sandwich manufacture. These basic formulations are modified to meet specific environmental conditions. A careful study of the design, environmental factors, and material properties should be made before selecting the adhesive.

SURFACE PREPARATION

FREQUENTLY, THE WEAKEST link in an adhesive-bonded joint is the interfacial bond between the adhesive and the adherents. Exactly the right adhesive may have been selected for the job, the joints may have been designed properly, and correct application and cure procedures and equipment used. However, if the adherents are not properly cleaned and prepared to receive the adhesive, the bond will show less than optimum performance and the environmental resistance will usually be significantly reduced. Surfaces should be cleaned by procedures that ensure that the bond between the adhesive and metal surfaces is as strong as the adhesive itself. Failure should occur in the adhesive rather than at the bond line when the joint is tested under simulated service conditions.

The degree of surface preparation depends chiefly upon the nature of the material and, to some extent, on the service requirements, bonding cycle, and the probable nature of contaminants. For some less critical applications, a solvent wipe or washing in a detergent solution may prove to be adequate. Care should be taken, however, to remove all cleaning agents from the surface by rinsing and drying thoroughly prior to the application of the adhesive. However, for the best joint performance, the surfaces must be prepared using procedures that will provide the best bond between the adhesive and adherent.

It is equally important to avoid recontamination of the clean surfaces during processing. Components should be handled with clean gloves, tongs, or hooks, and all contact with the bonding area should be avoided. Priming, bonding, or a combination of these should be accomplished as soon after surface cleaning as possible. In the interim, parts should be stored in a clean, dry place.

METAL PREPARATION

METAL SURFACES MAY be cleaned by chemical means or mechanical abrasion. These are the two basic methods, but some variation in procedures is advised by various adhesive manufacturers. Metal faying surfaces should be free from oxide scale, deep scratches, burrs, and other irregularities. Cleaning should be done after machining, heat treating, welding, sand-blasting, abrading, deburring, polishing, or similar treatment that might leave foreign material on the metal surface.

The surface preparation procedure should be reproducible, easily controlled, and production oriented if it is to be economical. In addition, it should satisfy the following requirements:

(1) Remove all contaminants from the surface
(2) Make the surface chemically receptive to the adhesive or primer and give satisfactory wetting characteristics
(3) Prevent poorly adhering or low-strength compounds from forming on the adherents
(4) Remove minimum amounts of metal
(5) Avoid embrittlement or corrosion, or forming a surface prone to environmental attack

Surface preparation methods for aluminum alloys, stainless steels, carbon steels, magnesium alloys, titanium alloys, and copper alloys are given in ASTM D2651, *Standard Recommended Practice for Preparation of Metal Surfaces for Adhesive Bonding.* The best corrosion-resistant surface preparation for aluminum alloys is stated in SAE *Aerospace Recommended Practice* (ARP) No. 1524.

To obtain optimum strength characteristics on aluminum, surface preparation is usually done in steps that include:

(1) Vapor degreasing
(2) Drying
(3) Chemical cleaning such as an alkaline precleaning and rinse followed by an acid etch
(4) Anodizing
(5) Careful rinsing in clean water
(6) Air drying, forced drying, or a combination of these

The vapor degreasing solution should be checked periodically for oily contaminants and decomposition products, and the solvent changed when necessary. Solvent degreasing is rarely recommended, but if it is used, the adherents should only be wiped with clean cloths or disposable tissues.

The recommended composition of the bath for chemical cleaning varies from one manufacturer to another. It depends upon the kind of metal being treated. Forced drying in an oven after water rinsing is preferred since this reduces the possibility of recontamination from dust and impurities when air drying at room temperature. Forced drying temperatures must be selected judiciously. Temperatures that are too high can adversely affect the surface condition.

Mechanical abrading is sometimes used to clean metal surfaces and increase the effective bonding area by roughening. Grinding, filing, wire brushing, sanding, and abrasive blasting are some methods. Abrasive cleaning is not usually as effective as chemical treatment, but it may be adequate in certain applications. It is best to clean the surface with solvent before abrading so that any contaminants are not ground into the surface. It is also desirable to clean the surface with solvent after the abrading to remove contaminants and debris.

For magnesium, one of the corrosion-inhibiting pretreatments developed specifically for this metal should be used. It is possible to clean magnesium mechanically, but care must be taken to prevent the exposure of any magnesium dust to an open flame.

Mechanical pretreatments should not be used for structural magnesium joints or for joints that will be subjected to severe environments. Some treatments for magnesium have been found to be effective only with certain adhesives. Certain corrosion-inhibiting pretreatments produce a weak surface layer that fails before the adhesive; these are not satisfactory for structural applications. If such pretreatments are used, the joints should be reinforced with mechanical fasteners.

A thorough check of treating solution composition should be made periodically. Special consideration should be given to the rate of metal processing over a given period of time. Failure to control the concentration of strong acid or alkali solutions may result in excessive metal loss. Aluminum and magnesium alloys are more reactive than stainless steel and titanium alloys, and exposure of these metals to high concentrations of acid or alkali may affect adhesion characteristics with certain kinds of adhesives. The time between composition checks depends upon the rate of exhaustion of the treating solution.

PREPARATION OF OTHER MATERIALS

RIGID PLASTICS CAN be lightly sanded to reduce gloss and remove mold-release compounds. Then they should be wiped and flushed with an oil-free solvent. Certain types of plastics, such as fluorocarbon isomer and polyethylene, are difficult to bond and may require chemical treatment.

Glass is easily cleaned by wiping with a suitable solvent. Joint durability can be greatly enhanced, particularly in moist environments, by first cleaning with a laboratory glassware cleaning solution or with a 30 percent hydrogen peroxide solution and then priming the surfaces with a silane finish.

INSPECTION OF PREPARED SURFACES

THE AFFINITY OF a clean metal surface for water is the most common test for a chemically clean surface. It is called the *water-break test.* If clean water from the rinse bath spreads smoothly over the metal surface as it runs off, it indicates that the surface is clean. If it collects in droplets, there is probably a thin film of oil on the surface. The oil should be removed completely, and the water-break test repeated.

If water drops placed on a flat, dry, treated surface spread rapidly and uniformily, this indicates that the surface is free of oil or grease. If the contact angle of the water drop is low (10 degrees or less), the surface has been cleaned adequately to remove greases, oils, and other nonpolar contaminants. When contact angle measurement is used as a quality control device for cleanliness, inspection should be made immediately after the metal has been dried. If the water remains in droplet form, the surface has not been suitably prepared.

ASSEMBLY AND CURE

THE PROCEDURES AND equipment used for assembly and cure of bonded components depend upon:

(1) The type of adhesive used
(2) The type, size, and configuration of the assembly
(3) The service requirements of the completed assembly

ASSEMBLY

DRYING TIME IS an important factor when solvent-dispersed adhesives are used. Since this time varies with different formulations, it is essential that the adhesive manufacturer's recommendations be followed. Solvent evaporation rate may be increased by moderate heating with infrared lamps, a hot-air oven, or other methods.

If there is sufficient porosity in one component to allow the solvent to escape, the parts may be mated during the drying time. In any case, the assembly must not be heated for curing until the solvent has evaporated. It is also essential that coated parts be mated before the tack range of the adhesive has expired.

Parts may be mated immediately after they are coated with chemically reactive adhesives. Mating may be delayed, but it must be done before the adhesive starts to "body" or thicken excessively.

FIXTURING

PROVISION SHOULD BE made for positioning the components for mating and holding them in place while the adhesive cures or sets. Assembly fixtures are frequently used for positioning. They may be simple jigs or self-contained equipment with provision for applying pressure or heat, or both. The fixture design depends upon the amount of heat and pressure needed to cure the adhesive and the size and configuration of the assembly.

Fixturing is particularly important when a contact adhesive is used. Care should be taken to align the parts accurately before they are mated since a strong bond is created instantly upon contact of the two coated surfaces. The use of release sheets, untreated kraft paper for example, is often helpful to avoid premature contact. Positioning may not be so critical with some formulations of less aggressive tack if the assembly can be slightly adjusted after mating without damage to the bond.

The fixture should properly position the parts to meet assembly tolerances and glue line thickness requirements. It should be lightweight for ease of handling and heat transfer. A heavy fixture presents a large heat sink which may retard heating and cooling rates. This may be detrimental for some adhesive systems. Nevertheless, the fixture must be strong enough to maintain dimensions under the curing conditions for the assembly. The expansion rate of the fixture material should nearly match that of the assembly to minimize part distortion and subsequent stressing of the adhesive.

Pressure-sensitive tape may be used to hold parts in position if it can withstand the curing temperature. Tapes are particularly useful with epoxy formulations that cure at room temperature or slightly warmer and require only moderate pressures.

Adhesive bonding may be combined with resistance welding or mechanical fasteners to improve the load carrying capacity of the joint. The adhesive is applied to the adherents first. Then the components are joined together with spot welds or mechanical fasteners to hold the joints rigid while the adhesive cures. Figure 27.14 illustrates typical design combinations. These techniques significantly reduce or eliminate fixturing requirements and decrease assembly time when compared to conventional adhesive bonding methods.

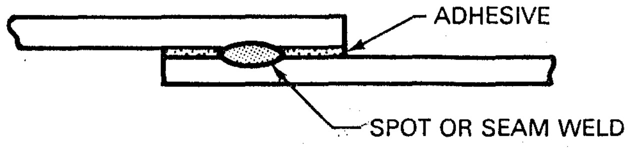
PRESSURE APPLICATION

WITH CERTAIN ADHESIVE formulations, it is necessary to apply and maintain adequate pressure during cure to:

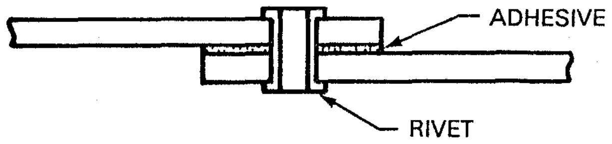
(1) Produce a uniformly thin glue line over the entire bonded area for optimum strength characteristics
(2) Facilitate flow or spreading of viscous adhesives
(3) Counteract any internal pressure caused by the release of volatiles
(4) Overcome minor imperfections in the faying surfaces
(5) Compensate for solvent loss and dimensional changes

Pressure may be applied to the joint by several methods which include the following:

(1) Dead weights such as bags of sand or shot
(2) Mechanical devices such as clamps, wedges, bolts, springs, and rollers
(3) Inflated tubes



WELDBONDING



RIVBONDING

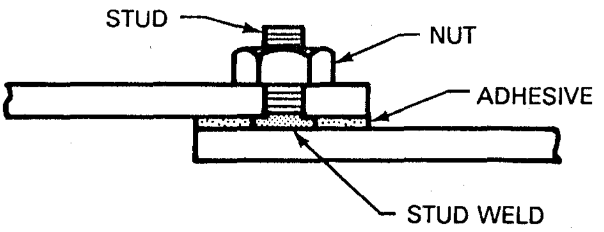


Figure 27.14–Adhesive Bonding in Combination with Resistance Welds and Mechanical Fasteners

(4) Air pressure bearing on the assembly located in a flexible, evacuated bag
(5) Mechanical or hydraulic presses
(6) Autoclaves

Inflated tubes are used in conjunction with a rigid backing fixture. When inflated, the tube presses uniformly along the bond line. Ambient air pressure is adequate for some applications. It is applied by enclosing the assembly in a thin, air-tight bag and then evacuating the bag. Autoclaves are used in a similar fashion in that the assembly is placed in a thin, gas-tight bag vented to ambient pressure. The bagged assembly is placed in an air-tight chamber which then is pressurized to several atmospheres. The pressure forces the bag to conform to the part and transmits the pressure to the assembly.

Phenolic-based adhesives generally require curing pressures in the 300 psi (2070 kPa) range, although adequate bonds may be attained with pressures as low as 50 psi (345 kPa).

Flat panels coated with a neoprene contact bond adhesive are generally mated by passing them through rollers under as much pressure as the components will withstand without crushing. A weighted hand roller or other pressure device can also be used.

For sandwich panel fabrication, the upper pressure limit is governed by the compressive strength of the core material. The lower limit depends upon the minimum requirements of the adhesive formulation. For sandwich panels containing solid inserts or edgings, special fixtures may be used to apply higher pressure at the specific locations.

Throughout the curing cycle, pressure should be as uniform and constant as possible over the entire bond area. If necessary, irregular surfaces can be built up with pads of compressible material. In some cases, soft rubber pads are used to compensate for variations in the dimensions of sheet material and fixtures. The mass of such materials should be minimized to avoid heat sink and insulating effects. Matched tooling is not often used for curved panels because of the high cost. A better method is to use a male or female tool in conjunction with the vacuum bag or autoclave technique.

CURING TEMPERATURE

SINCE VARIATIONS IN the thermal conductivity of the components influence the amount of heat transmitted to the adhesive layer, curing temperature should be measured at the glue line. Otherwise, the adhesive may not develop the desired properties for the application because of improper curing temperature.

Most phenolic-based structural adhesives require curing at elevated temperatures, generally from about 300 to 400°F (150 to 205°C), for periods ranging from 0.5 to 2 hours. Many one-part epoxy adhesives can be cured at temperatures as low as 250°F (120°C). A great number of two-component epoxy systems cure at room temperature; however, their properties are generally better when they are cured at elevated temperatures.

When neoprene contact-bond adhesives are used, the adhesive-coated surfaces are frequently heated during the drying cycle and mated under pressure while still warm. When design requirements are not so stringent, the adhesive may be dried and the components mated at room temperatures. Joint properties tend to be more variable, however, than those obtained when the hot contact bonding procedure is used.

As a general rule, curing time decreases as the curing temperature is increased within limits. Even the epoxies designed to cure at room temperature will cure faster when heated to moderately elevated temperatures. Curing time may be reduced from a number of hours to several minutes by heating. On the other hand, some room-temperature-curing adhesives will not cure properly below 60°F (16°C). This may be an important factor in field applications.

In some instances, longer curing times at elevated temperatures will improve the bond strength of the joint for service above room temperature. Post-curing of the bonded joint without pressure can also improve the heat resistance of the bond.

OVENS

OVENS ARE A widely used, inexpensive method for heat curing when only moderate pressure or simple positioning of the parts is required. They can be heated by gas, electricity, or steam. Adhesives that give off flammable vapor or solvent during cure should not be exposed to open flame or electrical elements. Ovens should be vented, temperature controlled, and fitted with an air circulating fan for uniformity of heat throughout. Infrared lamps and ovens are commonly used for contact-bond rapid-drying neoprene formulations.

HEATED PRESSES

HYDRAULIC PLATEN PRESSES are frequently used for applying heat and pressure to flat assemblies. These are usually heated by electric heating elements, high-pressure steam, hot water, or some other heat-exchanging fluid.

When the work is placed in the press at temperatures below about 150°F (73°C), it is called "cold entry". Entry at the adhesive curing temperature is known as "hot entry". In general, adhesives that release volatiles perform better when cold entry is employed. Certain adhesives are also affected by the rate of temperature rise or heat input. These factors influence the chemical reactions, the flow, and the density of cured adhesives of the volatile releasing types. For example, cold entry and a rate of temperature rise of less than 10°F (6°C) per minute result in better shear strength at elevated temperatures for certain nitrile-phenolic film adhesives. Other adhesives, such as epoxy-phenolics, require either stepped heat input or release of pressure (breathing) at specific temperatures to allow volatiles to escape. Nonvolatile adhesives, such as epoxies, are not affected to any great extent by entry temperature or by the rate of heat input.

Large autoclaves are used for bonding aircraft assemblies and other extremely large parts. The typical operating range of such autoclaves is 200 psi (1380 kPa) maximum pressure and 350°F (180°C) maximum temperature. Pressure is generally provided by compressed air, and curing temperature is achieved with steam heated tubes or electrical elements.

QUALITY CONTROL

TESTING

ADHESIVE BONDED JOINTS are inspected and tested to determine their quality and performance under the specific loading and environmental conditions they will see in service. Based on the test results, quality requirements can be established. Inspection methods and procedures can be specified to assure that quality. The advantages and limitations of inspection and testing procedures must be understood in order to apply them successfully. There are a number of military and industry standard specifications for testing adhesive bonded joints (Table 27.2).

Testing may also consist of accelerated, simulated, or actual use tests of the end product devised by the individual manufacturer or an industry group. For this reason, industry associations may be good sources of information on testing procedures.

If an adhesive is to be used with a metal for which no performance data exist, or if it is to be used in an unusual environment, it should be subjected to some testing. Single overlap shear specimens can be used to evaluate the compatibility of a metal surface condition with an adhesive system and to evaluate the effect of any unusual environmental exposure. If an adhesive is to be used in a structural joint under stress in a certain environment, test joints should be simultaneously subjected to both the stress and the environmental conditions expected in service.

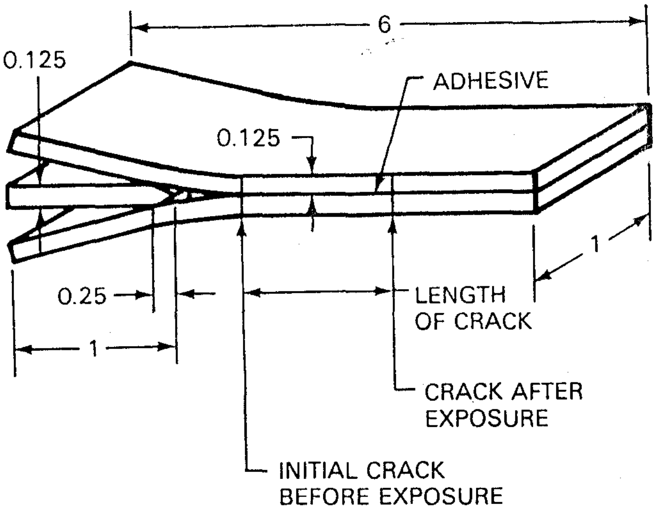
PROCESS CONTROL AND QUALITY ASSURANCE

GOOD PROCESS CONTROL usually requires inspection of all cleaning and processing equipment, evaluation of all materials, and control of storage time and conditions.

Adhesives and primers should be evaluated to assure conformance to the requirements of the design and the user's or adhesive manufacturer's specifications. Certified test reports from the manufacturer may be acceptable in lieu of actual performance tests.

Periodic tests should be performed to determine that cleaning, mixing, and bonding procedures are adequately controlled. Lap shear tests are generally satisfactory for control of mixing, priming, and bonding. Peel tests should be performed to ascertain the adequacy of cleaning procedures. The climbing drum method, described in ASTM D1781, as well as the crack extension (wedge) test, ASTM D3762, may also be used for this purpose.

The crack extension (wedge) test is designed for rapid screening of adhesive joint durability in a controlled humidity and temperature environment. The test specimen design for aluminum alloys is shown in Figure 27.15. One or more specimens are cut from an adhesive bonded panel. The wedge is forced between the adherents and bends them apart. This separates the adhesive and produces cleavage loading at the apex of the separation. The location of the apex of the sheet separation is recorded.



DIMENSIONS ARE IN INCHES

Figure 27.15–Crack Extension (Wedge) Specimen Designed for Aluminum Alloys

The wedged specimens are then exposed at 120°F (49°C) to an air environment of 95 to 100 percent relative humidity for 60 to 75 minutes. The water should contain less than 200 parts per million total solids. The distance that the apex moved during exposure is measured two hours after exposure.

The test is used for surface preparation process control by comparing test results with a maximum acceptable increase in adhesive crack length. It is also used for adhesive durability characteristics and surface preparation procedures. The test was originally designed for adhesive bonded aluminum. However, it may be suitable for other metals with design modifications to account for differences in stiffness and yield strength.

The frequency of testing will depend upon the volume of parts produced and the requirements for the application. However, many manufacturers who employ adhesive bonding in critical applications perform suitable quality control tests at least daily to ensure that the process is within specifications. Any production parts rejected for dimensional reasons or structural damage should be destructively inspected for joint quality.

EVALUATION OF FABRICATED PARTS

AFTER THE MECHANICAL and processing properties of an adhesive system have been determined through destructive laboratory testing, the ability of manufacturing departments to duplicate these properties should be established. Therefore, rather complete testing of the first part or the first few parts of the production run is recommended.

Test loads should be applied in the same manner in which the part will be loaded in use. However, actual loading conditions are often difficult to simulate. In cases involving multidirectional loads, design loads may be applied in each plane individually. The part can then be loaded to failure in the most critical load path to determine if it meets the minimum design strength.

When it is impractical to load a completed part for test because of geometry or difficulty in mounting, many companies fabricate test specimens that are either an integral part of the assembly or separate panels processed in the same manner as the part. Mechanical properties of such specimens closely represent the actual strength of the part. This procedure can provide close control over materials and processing equipment.

NONDESTRUCTIVE INSPECTION

THERE ARE SEVERAL nondestructive inspection methods other than visual that may apply to adhesive bonding:

(1) Ultrasonic
(2) Acoustic impact (tapping)
(3) Liquid crystals
(4) Birefringent coatings
(5) Radiography
(6) Holography
(7) Infrared
(8) Proof test
(9) Leak test

Methods which can be used for a specific application will depend upon one or more of the following factors:

(1) Design and configuration of the structure
(2) Materials of construction
(3) Types of joints
(4) Material thicknesses
(5) Type of adhesive
(6) Accessibility of the joints

In some cases, it may be necessary to incorporate features in the component design or the adhesive to utilize an inspection process. For example, a filler may be required in the adhesive to increase its thermal or electrical conductivity or its density. To determine the applicability of a particular inspection method, the manufacturers of the particular type of equipment should be consulted.

SAFE PRACTICES

ADEQUATE SAFETY PRECAUTIONS must be observed with adhesives. Corrosive materials, flammable liquids, and toxic substances are commonly used in adhesive bonding. Therefore, manufacturing operations should be carefully supervised to ensure that proper safety procedures, protective devices, and protective clothing are being used. All federal, state, and local regulations should be complied with, including OSHA Regulation 29CFR 1900.1000, *Air Contaminants*. The material safety data sheet of the adhesive should be carefully examined before the adhesive is handled to ensure that the appropriate safety precautions are being followed.

GENERAL REQUIREMENTS

Flammable Materials

ALL FLAMMABLE MATERIALS such as solvents should be stored in tightly sealed drums and issued in suitably labeled safety cans to prevent fires during storage and use. Solvents and flammable liquids should not be used in poorly ventilated, confined areas. When solvents are used in trays, safety lids should be provided. Flames, sparks, or spark-producing equipment must not be permitted in the area where flammable materials are being handled. Fire extinguishers should be readily available.

Toxic Materials

SEVERE ALLERGIC REACTIONS can result from direct contact, inhalation, or ingestion of phenolics and epoxies as well as most catalysts and accelerators. The eyes or skin may become sensitized over a long period of time even though no signs of irritation are visible. Once a worker is sensitized to a particular type of adhesive, allergic reactions may keep that individual from working close to it. Careless handling of adhesives by production workers may expose others to toxic materials if proper safety rules are not observed: for example, co-workers may touch tools, door knobs, light switches, or other objects contaminated by careless workers.

For the normal individual, proper handling methods that eliminate skin contact with the adhesive should be sufficient. It is mandatory that protective equipment, protective creams, or both be used to avoid skin contact with certain types of formulations.

Factors to be considered in determining the extent of precautionary measures to be taken include:

(1) The frequency and duration of exposure
(2) The degree of hazard associated with the specific adhesive
(3) The solvent or curing agent used
(4) The temperature at which the operations are performed
(5) The potential evaporation surface area exposed at the work station

All these elements should be evaluated in terms of the individual operation.

PRECAUTIONARY PROCEDURES

A NUMBER OF measures are recommended in the handling and use of adhesives and auxiliary materials.

Personal Hygiene

PERSONNEL SHOULD BE instructed in the proper procedures to prevent skin contact with solvents, curing agents, and uncured base adhesives. Showers, wash bowls, mild soaps, clean towels, refatting creams, and protective equipment should be provided.

Curing agents should be removed from the hands with soap and water. Resins should be removed with soap and water, alcohol, or a suitable solvent. Any solvent should be used sparingly and be followed by washing with soap and water. In case of allergic reaction or burning, prompt medical aid should be obtained.

Work Areas

AREAS IN WHICH adhesives are handled should be separated from other operations. These areas should contain the following facilities in addition to the proper fire equipment:

(1) A sink with running water
(2) An eye shower or rinse fountain
(3) First aid kit
(4) Ventilating facilities

Ovens, presses, and other curing equipment should be individually vented to remove gases and vapors. Vent hoods should be provided at mixing and application stations.

Protective Devices

PLASTIC OR RUBBER gloves should be worn at all times when working with potentially toxic adhesives. When contaminated, the gloves must not contact objects that others may touch with their bare hands. Contaminated gloves should be discarded or cleaned using procedures that will remove the particular adhesive. Cleaning may require solvents, soap and water, or both. Hands, arms, face, and neck should be coated with a commercial barrier ointment or cream. This type of material may provide short term protection and facilitate removal of adhesive components by washing.

Full face shields should be used for eye protection whenever the possibility of splashing exists, otherwise glasses or goggles should be worn. In case of irritation, the eyes should be immediately flushed with water and then promptly treated by a physician.

Protective clothing should be worn at all times by those who work with the adhesives. Shop coats, aprons, or coveralls may be suitable and they should be cleaned before reuse.

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CHAPTER 28

THERMAL SPRAYING

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CHAPTER 28

THERMAL SPRAYING

INTRODUCTION

GENERAL HISTORY

ALTHOUGH THERMAL SPRAYING has been in use since the early part of the 20th Century, many of the early applications were concerned mainly with reclamation. Since 1960, there has been a dramatic expansion in the number and diversity of thermal spraying processes, methods, and materials.

Technological advances in equipment, process variations, and materials and forms (wire, rod, cord, or powder) now available have resulted in a multiplicity of new and potential applications. Only the present range and scope of the process variations and applications are reviewed in this chapter. The information will be useful as a guide to the equipment and consumables available, and as a reference for selecting the process variation suitable for each application. Attention is paid to setting variables once thermal spraying is selected as the production or repair process.

PROCESS DESCRIPTION

THERMAL SPRAYING (THSP) is a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semimolten condition on a substrate to form a thermal spray deposit. The surfacing material may be in the form of wire, rod, cord, or powder. The spray material is heated to its plastic or molten state by an oxyfuel gas flame, electric arc, plasma, or by detonation of an explosive gas mixture. The hot material is propelled from the spray gun to the substrate in a gas stream. Most metals, cermets, oxides, and hard metallic compounds can be deposited by one or more of the process variations. The process is sometimes called "metallizing", "metal spraying", or "flame spraying". A schematic view of a wire flame spray system is shown in Figure 28.1.

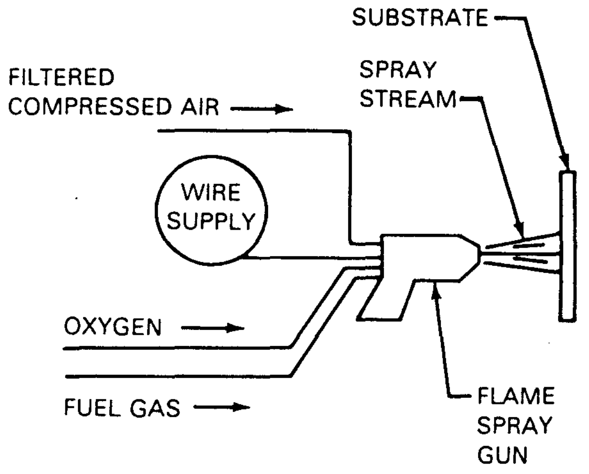

Figure 28.1–Schematic View of Wire Flame Spray System

The substrate is usually roughened before spraying, generally by grit blasting using aluminum oxide or chilled iron grit.

When the molten particles strike the substrate, they flatten and form thin platelets that conform to irregularities of the part geometry and to each other. The platelets rapidly cool and solidify. Successive layers are built up to the desired thickness by the impingement of particles upon the substrate, building up, particle by particle, into a lamellar structure, as shown in Figure 28.2.

The bond between the substrate and the coating material may be mechanical, metallurgical, chemical, or a combination of these. A post spray heat treatment of the coating may be required to increase the bond strength, by

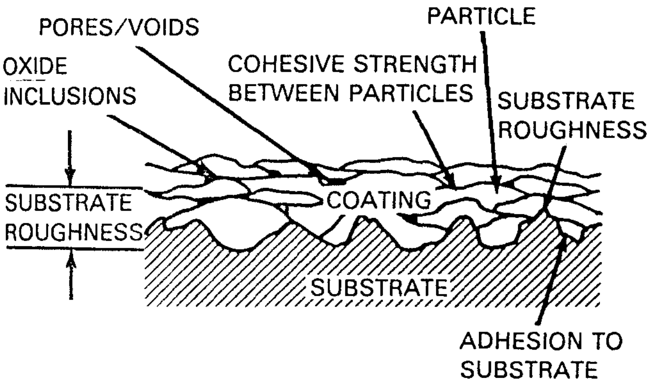

Figure 28.2–Typical Coating Cross Section to Illustrate Lamellar Structure of Oxides and Inclusions

diffusion or by chemical reaction between the spray deposit and the substrate.

The density of the coating deposit will depend upon the material type, method of deposition, the spraying conditions, and post spray processing. The density is generally 85 to 90+ percent of the filler metal density. The properties of the deposit depend upon such factors as porosity, the cohesion between deposited particles, adhesion to the substrate including interface integrity, and chemistry of the coating material.

PROCESS SELECTION

THE ANTICIPATED SERVICE conditions should be considered in choosing the thermal spray process, procedures, consumables, and quality requirements. This chapter covers basic knowledge about thermal spray processes and potential applications. Practical application procedures, to the extent that is possible, are also given. For more detailed information refer to the AWS publication *Thermal Spraying: Practice, Theory and Application.*

ADVANTAGES AND APPLICATIONS

THERMAL SPRAYING PROCESSES and procedures are specialized, yet find wide use in both manufacturing and maintenance applications. The nature of thermal spraying processes is inherently synergistic. Many components and variables are involved, which, when working together and properly applied, produce an effect far greater than they would individually. Yet each component and variable must be separately and jointly understood, to permit the selection and operation of a suitable process. The background of this chapter will help the user tailor that process to particular applications.

The end use of sprayed coatings determines the properties needed in the final coating, the type of consumable employed, and the kind of equipment needed.

Manufacturing

THERMAL SPRAYING IS used extensively in the manufacture of original equipment components. For example, the aerospace industry has developed hundreds of applications. In addition, marine, mining, food, automotive, petroleum, electrical power generation, thermal processing, chemical processing and electronic applications use thermally sprayed coatings to achieve results that no substrate by itself can provide.

Maintenance

EXISTING INDUSTRIAL FACILITIES save hundreds of millions of dollars annually through the use of thermal spraying for repair and maintenance. This includes not only in-plant but also on-site applications, to coat structures and equipment parts. Repair of components, where thermal spraying is applicable, is both economical and time saving. When corrosion or wear, or both, are encountered, thermal spraying should be considered. The use of sprayed coatings, often impregnated with sealers, has received worldwide acceptance by industry for such applications. In many cases, the thermal spray application ends up making the component better than new.

LIMITATIONS

APPLICATION ENGINEERS NEED to be aware of the nature of thermally sprayed coatings, as contrasted with fusion welding, and evaluate them accordingly. For example, thermally sprayed wear coatings usually should not be selected over welded overlays if high impact resistance or resistance to aggressive liquid corrosion is needed in the end-use of the component. For these applications, consideration should be given to fused coatings which have a true metallurgical bond. In addition, the engineer needs to consider the effect of part geometry on coating quality and buildup. In cases where fused coatings cannot be used, successful results have been obtained by applying sealers, selected for a specific environment, over a sprayed coating.

Thermal spraying embodies a group of processes, as does fusion welding, and selection should proceed in the normal fashion. For example, capital investment for plasma spraying equipment is 10 times more expensive than arc spraying. Careful consideration should to be given to equipment and process costs.

The heterogenous structure of sprayed deposits creates factors unique to thermal spraying:

(1) Microhardness is lower than that exhibited by the original spray consumable.

(2) Bond strength is mechanical, metallurgical, or a combination of these, and can be modified in a number of ways.

(3) Deposit densities are less than 100 percent.

(4) Shrinkage stresses may be a factor affecting coating bond strength in certain configurations and applications. Low shrinkage materials should be selected for difficult part geometries.

(5) Thermally sprayed deposits usually have some porosity, but sealers can be used to minimize coating penetration by corrosive media.

SPRAY CONSUMABLES

THE SPRAY MATERIALS are in the form of wire (both solid and cored), rod, cord (a continuous length of powder-filled plastic tubing), or powder. Cord spraying is primarily used in Europe. Many metals, oxides, ceramics, intermetallic compounds, some plastics, and certain types of glass can be deposited by one or more of the processes.

PROCESS VARIATIONS

THERMAL SPRAYING PROCESSES can be categorized under two basic groups, according to the methods of heat generation. Group I uses combustible gases as the heat source, while Group II uses electrical power. See Table 18.1. Additional heat is generated at impact during hypersonic flame spraying, as the spray material gives up its kinetic energy. This is discussed further in the section on Hypersonic Spraying.

GROUP I: COMBUSTION

Subsonic Flame Spraying

IN SUBSONIC FLAME spraying, the spray material is fed into and melted by an oxyfuel gas flame. Whether the material is in the form of wire, rod or powder, molten particles are propelled onto the substrate by the force of the flame.

A wide variety of materials in these forms can be sprayed with the flame. Materials that cannot be melted with an oxyfuel gas flame, and those that burn or become severely oxidized in the oxyfuel flame, cannot be flame sprayed.

Flame spray accessories in the form of air jets and air shrouds are available to change the flame characteristics. These accessories can be used to adjust the shape of the flame and the velocity of the sprayed materials.

Materials are deposited in multiple layers, each of which can be as thin as 0.0005 in. (130 μm) per pass. The total thickness of material deposited will depend upon several factors including the following:

(1) Type of surfacing material and its properties

(2) Condition of the workpiece material including geometry

(3) Service requirements of the coated product

(4) Postspray treatment of the coated product

Table 28.1
Basic Groups of Thermal Spraying

Group I Combustion	Group II Electrical
1. Flame	1. Arc
a. Subsonic	2. Plasma arc
b. Hypersonic	3. Induction coupled plasma

Hypersonic Flame Spraying

DETONATION AND CONTINUOUS flame guns are two types of hypersonic spray guns.

The detonation gun operates on principles significantly different from other flame spray methods. This method repeatedly heats and projects charges of powder onto a substrate by rapid successive detonations of an explosive mixture of oxygen and acetylene in the gun chamber.

The continuous flame hypersonic guns used in the United States use a propylene-oxygen flame. Overseas operators prefer ethylene, hydrogen, and propane as fuel gases. The powder is brought to the torch using a nitrogen carrier. The torch is designed to confine the powder in the center of the flame. The particles leave the gun at velocities generally in excess of mach 4. This speed is far greater than achieved in most other spray methods. The kinetic energy released by impingement upon the substrate contributes additional heat that promotes bonding, high density, and appreciable hardness values.

GROUP II: ELECTRIC

Arc Spraying

THE SPRAY MATERIALS used with arc spraying, commonly called "electric arc spraying", are metals and alloys in wire form, and powders contained in a metal sheath (cored wire). Two continuously fed wires are melted by an arc operating between them. The molten metal is atomized and propelled onto a substrate by a high-velocity gas jet, usually air. Recent work has been done using other gases.

This method is restricted to spraying consumables that can be produced in continuous wire form.

Plasma Spraying

PLASMA SPRAYING IS a thermal spraying process in which a nontransferred plasma arc gun is used to create an arc plasma that melts and propels the surfacing material to the substrate.

The term *nontransferred arc* means that the plasma arc is contained within the gun, and that the substrate is not part of the electric circuit. The arc is maintained between a tungsten cathode and a constricting nozzle which serves as the anode. An inert gas or a reducing gas, under pressure, enters the annular space between the anode and cathode, where it becomes ionized, producing temperatures up to 30 000°F (17 000°C). The hot plasma gas passes through the nozzle as a high velocity jet. The surfacing material, in powder form, is injected into the hot gas stream, where it becomes molten and is propelled onto the substrate.

Vacuum Plasma Spraying

VACUUM SPRAYING IS a variation of plasma spraying which is performed in a vacuum chamber. The advantage of the process is the elimination of oxides from the deposit. This is especially advantageous in aircraft engine applications. The cost of this apparatus is about ten times that of standard plasma spray equipment. Operating costs are also higher.

Induction Coupled Plasma Spraying

INDUCTION COUPLED PLASMA equipment is used to create an ultra high temperature arc region 2 in. (50 mm) in diameter by 6 in. (150 mm) long, into which powders are injected. The powder is heated along a substantially longer path than that within a comparable plasma spray gun. The longer powder residence time makes possible the use of larger particles, assures the melting of the particles, and results in a more consistent sprayed coating.

Because of the size of the equipment, this system has limited torch movement and portability.

NATURE OF SPRAYED COATINGS

SUCCESS IN THE use of thermally sprayed coatings relies on careful adherence to specific process procedures. This is a basic rule of thermal spraying, and deviation from the standards for a particular application, or inattention to detail, especially preparation, will produce an unreliable result.

Sprayed coating systems have four basic components: substrate type, bond coats as necessary, coating structure, and finish.

SUBSTRATES

SUBSTRATES ON WHICH the thermally sprayed coatings are applied include metals, oxides, ceramics, glass, most plastics, and wood. All spray materials cannot be applied to all substrates, since some require special techniques or are temperature sensitive.

Substrate preparation is required for every thermal spraying process, and is virtually the same for each process. Two important steps are: (1) cleaning the surface to eliminate contamination that will inhibit the bonding of the coating to the substrate, and (2) roughening the substrate surface to create minute asperities or irregularities (anchor teeth), which provide a greater effective surface area to enhance coating adhesion and bond strength.

Attention must also be paid to part geometries (no sharp edges where the coating ends), and base material (affected by cleaning agents, grit type, and blasting pressure).

BOND COATS

THE BOND BETWEEN the coating and the substrate may be mechanical or metallurgical. Adhesion is influenced by a combination of: (1) coating material, (2) spray particle size, (3) substrate condition and geometry, (4) degree of surface roughness, (5) surface cleanliness, (6) surface temperature before, during, and after spraying, (7) particle impact velocity, (8) type of base material, and (9) spray angle.

COATING STRUCTURE

THE STRUCTURE AND chemistry of coatings sprayed in ambient air are different from those of the same material in the wrought or presprayed form.

The differences in structure and chemistry are due to the incremental nature of the coating, and its reaction with the process gases and the atmosphere surrounding the coating material while in the molten state. For example, when air or oxygen is used as the process gas, oxides of the spray material are formed while the particles are in transit and become a part of the coating.

Metal coatings tend to be porous and brittle, and to differ in hardness from the original consumable material. The "as-sprayed" structures of coatings will be similar in their lamellar nature, but will exhibit varying characteristics, depending on the particular spraying process used, process variables, techniques employed, and the nature of the spray material applied.

The coating density will vary with the particle velocity, the heat source temperature of the spray process, and the amount of air used. The density also varies with the type of powder, its mesh size, spray rate, standoff distance, and method of injection.

Microscopic examination is the only means of quality evaluation for porosity.

The average particle impact velocities for several thermal spray processes are shown in Figure 28.3.

The nature of the bond in the "as-sprayed" condition can be modified by post spray thermal treatment. Modification is by diffusion, chemical reaction, or both, between the coating and the substrate.

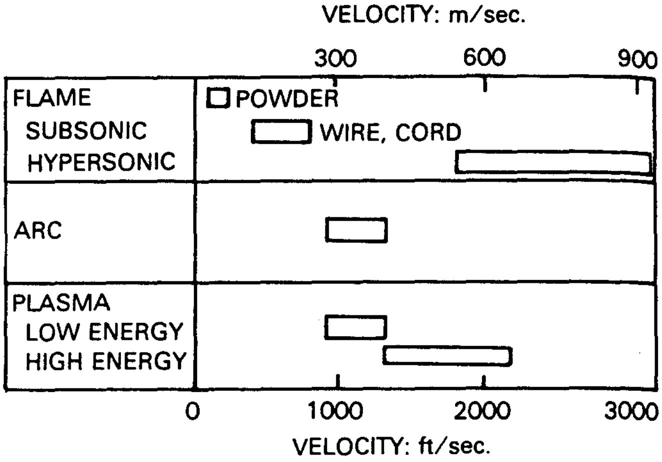

Figure 28.3–Average Particle Impact Velocities for Various Thermal Spray Processes

THERMAL SPRAY EQUIPMENT

FLAME SPRAY EQUIPMENT

A TYPICAL FLAME spraying arrangement consists of the following:

(1) Spray gun
(2) Spray material and the associated feeding equipment
(3) Oxygen and fuel gas supplies, pressure regulators, and flowmeters
(4) A compressed air source and control unit, when required
(5) Workpiece holding device
(6) Gun or workpiece handling device for semi-automatic or automatic processing, as required
(7) Air cooling ring, air jets, or siphon

The gun design depends upon the type of material to be sprayed and its physical form (wire, rod, or powder). When automated, the gun or the workpiece, or both, are driven by mechanisms designed to produce the desired deposit configuration.

The four fuel gases most commonly used for flame spraying are: acetylene, propane, methylacetylene-propadiene (MPS), and propylene.[1] Acetylene in combination with oxygen produces the highest flame temperature. The distinct characteristics of an oxyacetylene flame make it easy to adjust the stoichiometry to produce oxidizing, neutral, or reducing conditions. The significant changes in flame appearance are not so evident with the other three gases. Hydrogen, which is used occasionally, and propane, are suitable for flame spraying metals with low melting points such as aluminum, tin, zinc, and babbitt metal. Table 28.2 lists heat source temperatures for various fuel gases.

Gas Controls

OXYGEN AND FUEL gas flowmeters are used to provide good control of the gas ratio and flame intensity. Their use permits higher spraying rates than with valve control of gas flows. Since the molten particles are exposed to oxygen, an oxide film forms on them, even when a reducing gas mixture is used. The thickness of the oxide film does not vary greatly with changes in the fuel-gas-to-oxygen ratio.

Table 28.2
Heat Source Temperatures

Source	Temperature, °F	Temperature, °C
Acetylene, oxygen	5625	3100
Arcs and plasmas	4000-15000	2200-8300
Hydrogen, oxygen	4875	2690
MPS, oxygen	5200	2870
Natural gas, oxygen	4955	2735
Propane, oxygen	4785	2640

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[1] Properties of these and other fuel gases are discussed in Chapter 14, Oxyfuel Cutting, Welding Handbook, Vol. 2, 8th Ed.

Compressed Air Supply

THE CLEANLINESS AND dryness of the compressed air, when used to atomize and propel the molten surfacing material, is important in producing a quality deposit. Oil or water in the compressed air will cause fluctuations in the flame, produce poor or irregular atomization of the spray material, reduce bond strength, and affect the quality of the deposit. Aftercoolers or a desiccant dryer and chemical filters should be installed between the air source and the spray unit. Accurate regulation of the air pressure is important for uniform atomization.

WIRE FLAME SPRAYING EQUIPMENT

WITH WIRE FLAME spraying, the metal wire to be deposited is normally supplied to the gun continuously from a coil or spool. In some cases, cut lengths of metal rods are used.

A cross section of a typical wire flame spray gun is shown in Figure 28.4. The gun consists essentially of two subassemblies: a drive unit which feeds the wire, and a gas head which controls and mixes the flows of fuel gas, oxygen, and compressed air. The principles of operation of all wire type gas guns are similar. Commercial equipment for wire flame spraying is shown in Figure 28.5.

The wire drive unit consists of a motor and drive rolls. They may be air or electrically powered, with adjustable speed controls. Speed controls may be mechanical, electromechanical, electronic, or pneumatic.

The wire is fed through a central orifice in the nozzle, where it is melted by a coaxial flame. The flame is surrounded by a coaxial stream of compressed gas, usually air, to shear the molten material into droplets and propel it onto the substrate. In special applications, inert gas may be used instead of air. Various sizes of nozzles and air caps are used to accommodate different wire sizes. The arrangement of the oxyfuel gas jets and compressed air orifices differs with the various manufacturers, as do the mechanisms for feeding the wire through the flame.

If the wire feed rate is excessive, the wire tip will extend beyond the hot zone of the flame and not melt or atomize properly. This produces very coarse deposits. If the feed is too slow, the metal will severely oxidize, and the wire may fuse to the nozzle. Such deposits have high oxide content.

Wire spraying units vary in size. Small hand-held units are manipulated in much the same manner as paint spray guns. They are often used to apply protective coatings of aluminum or zinc to large objects such as tanks, ship hulls, and bridges. Larger units are usually designed to be mechanically manipulated for spraying moving parts.

CERAMIC ROD FLAME SPRAYING EQUIPMENT

CERAMIC ROD FLAME spraying is similar to wire flame spraying. Straight lengths of ceramic rod are successively fed into the flame by driven plastic rollers in the gun.

The bond between a ceramic deposit and the substrate is mechanical in nature. The semi-molten particles deform and take the shape of the prepared surface. Proper surface preparation is therefore a prerequisite for a firmly bonded deposit.

The equipment for ceramic rod spraying is similar to wire spraying equipment (Figure 28.1). This equipment requires greater care in adjusting the spraying variables than does wire spraying equipment because of the higher melting points and lower thermal conductivities of ceramics as compared to metals.

Some ceramics applied by this technique are:

(1) Alumina-titania
(2) Alumina
(3) Zirconia

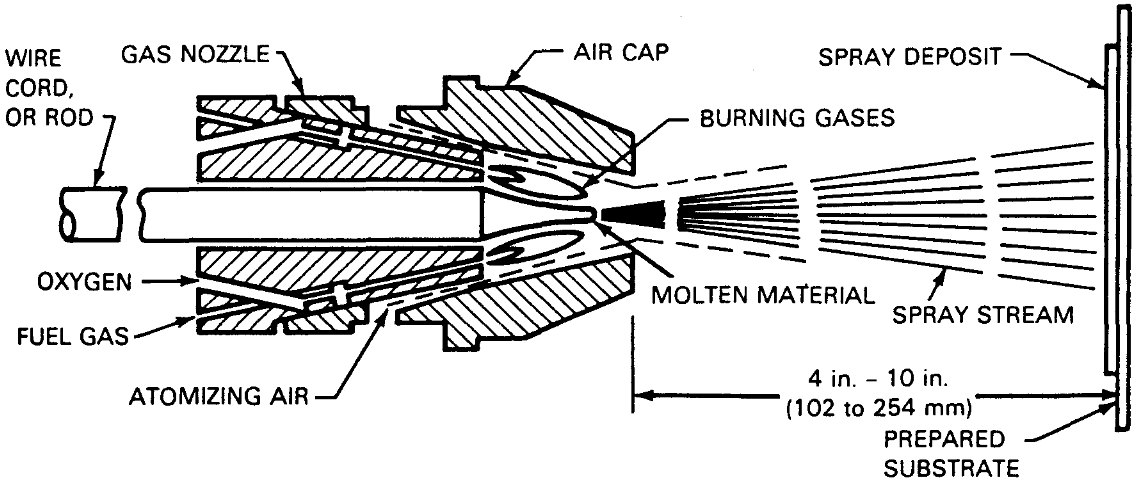

Figure 28.4–Cross Section of Typical Wire, Rod, or Cord Flame Spray Gun

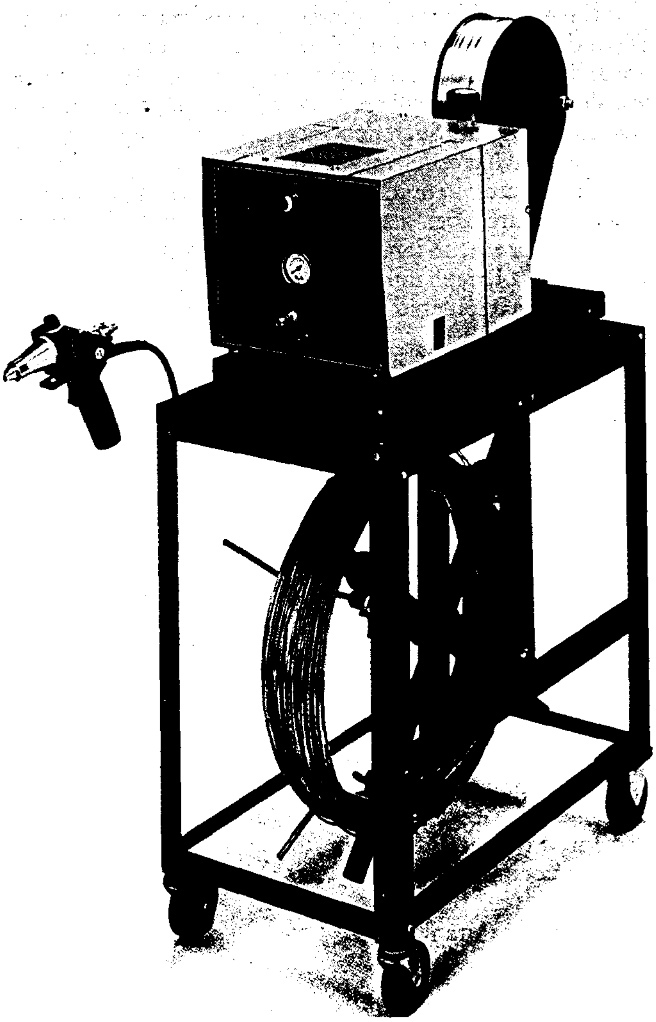

Figure 28.5—Oxyfuel Gas Wire Spray Equipment Capable of Spraying Wires Ranging from Low Melting Alloys (Babbitt) to Higher Melting Point Steels. Aluminum Wire Shown on Top Spool and Carbon Steel Wire on the Bottom Reel.

(4) Rare earth oxides
(5) Zirconium silicate
(6) Magnesium zirconate
(7) Barium titanate
(8) Chromium oxide
(9) Magnesia-alumina
(10) Mullite
(11) Calcium titanate

Each ceramic surfacing material has specific characteristics, economics, advantages, and limitations. The material is selected to provide specific properties for the service conditions, with due consideration of the following factors:

(1) Thermal, electrical, and chemical characteristics
(2) Melting point
(3) Adherence or bond strength
(4) Density
(5) Cost

Some of the important characteristics of ceramic spray deposits are:

(1) Good adherence to a variety of substrate materials
(2) Economically applied in controlled thicknesses
(3) Good physical and chemical properties
(4) Low thermal and electrical conductivities
(5) High wear resistance
(6) Good finishing characteristics.

POWDER FLAME SPRAYING

IN POWDER FLAME spraying, the material to be sprayed is supplied to the gun in powder form from a hopper. The hopper may be remote from the gun or mounted onto it. The powder may be aspirated or carried into the flame by an air feed system, by the oxygen stream, or by gravity. The powder is melted by the flame and propelled onto the substrate by either a compressed air jet or the combustion gases. A hypervelocity powder flame spray torch is shown in operation in Figure 28.6.

In all thermal spraying processes, the powder particle velocity feed rate affects the structure and the deposit efficiency of the coating. If the raw material is not properly heated, deposit efficiency will rapidly decrease, and the coating will contain trapped, unmelted particles. If the particle velocity is too low, some powder will be volatilized, resulting in coating deterioration and higher operating costs.

Powder flame spraying equipment is simpler and less costly than plasma spray equipment. However, the spray rate with flame spraying is lower. The equipment is designed for easy portability.

A special case is a powder flame spray gun which is similar to an oxyacetylene welding torch. Powder to be sprayed is metered into the gas stream before it leaves the tip. Compressed air is not used. The torch can be used for preheating or fusing spray deposits, when powder is not being injected into the gas stream.

Metals, ceramics, and ceramic-metal mixtures can be flame sprayed by the powder method. The metals are usually hard alloys designed for specific wear or corrosion resistant applications. Very hard metallic compounds, such as carbides and borides, can be blended with metal powders to form a composite, wear-resistant coating. The degree of melting of the particles of spray powder depends upon both the melting point of the material and the time

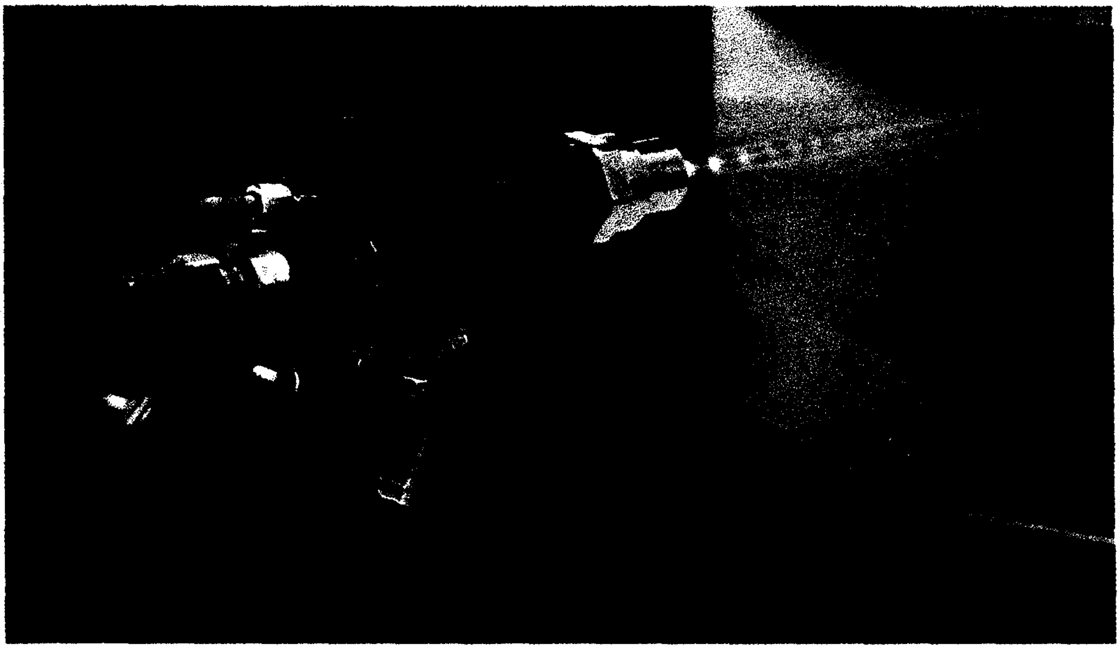

Figure 28.6–Hyper Velocity Oxyfuel Gas Spray Gun (Note Diamond Pattern Resulting from Super Sonic Outlet Velocity. Shown Spraying Tungsten Carbide Powder)

that the particles are exposed to the heat of the flame (called the dwell time). Powders with low melting points will become completely molten, and those with high melting points, such as ceramics, may melt only on the particle surface.

Due to the lower particle velocities and lower temperatures obtained, the coatings produced by powder flame spraying generally have lower adhesion strength, higher porosity content, and lower overall corrosion strength than coatings produced by other spray processes.

The powder feedstock may be pure metal, an alloy, a composite, a carbide, a ceramic, or any combination of these. The process is used to apply "self fluxing" metallic alloy coatings. These materials contain boron and silicon, which serve as fluxing agents, and oxidation is minimized. Fusion or metallurgical bonding to a metal substrate is accomplished by heating the deposit to its melting temperature range. The fusing temperature is usually in excess of 1900°F (1040°C), and is accomplished with any heating source such as a flame, induction coil, or a furnace.

A small amount of gas is diverted to carry the powder from the hopper into the oxyfuel gas stream, where the powder is melted and carried by the flame onto the substrate.

Variations in the powder flame spraying process include compressed gas to feed powder to the flame, additional air jets to accelerate the molten particles, a remote powder feeder with an inert gas to convey powder through a pressurized tube into the gun, and devices for high speed powder acceleration at atmospheric pressure. Such refinements tend to improve flow rate, and sometimes to increase particle velocity, which enhances bond strength and coating density.

DETONATION SPRAYING

DETONATION SPRAYING IS accomplished with a specially designed gun shown in Figure 28.7. The detonation gun is different from other combustion spraying devices. It uses the energy of explosions of oxygen-acetylene mixtures, rather than a steady flame, to blast powdered particles onto the surface of the substrate. The resulting deposit is extremely hard, dense, and tightly bonded.

The detonation gun, schematically shown in Figure 28.8, consists of a long barrel into which a mixture of oxygen, fuel gas, and powdered coating material, suspended in nitrogen, is introduced. The oxygen-acetylene mixture is ignited by an electric spark several times per second, creating a series of controlled detonation waves (flame fronts) which accelerate and heat the powder particles as they move down the barrel. Exit particle velocities of approximately 2,500 ft/sec. (760m/sec.) are produced. After each ejection of powder, nitrogen purges the unit prior to successive detonations. Multiple detonations per second build up the coating to the specified thickness.

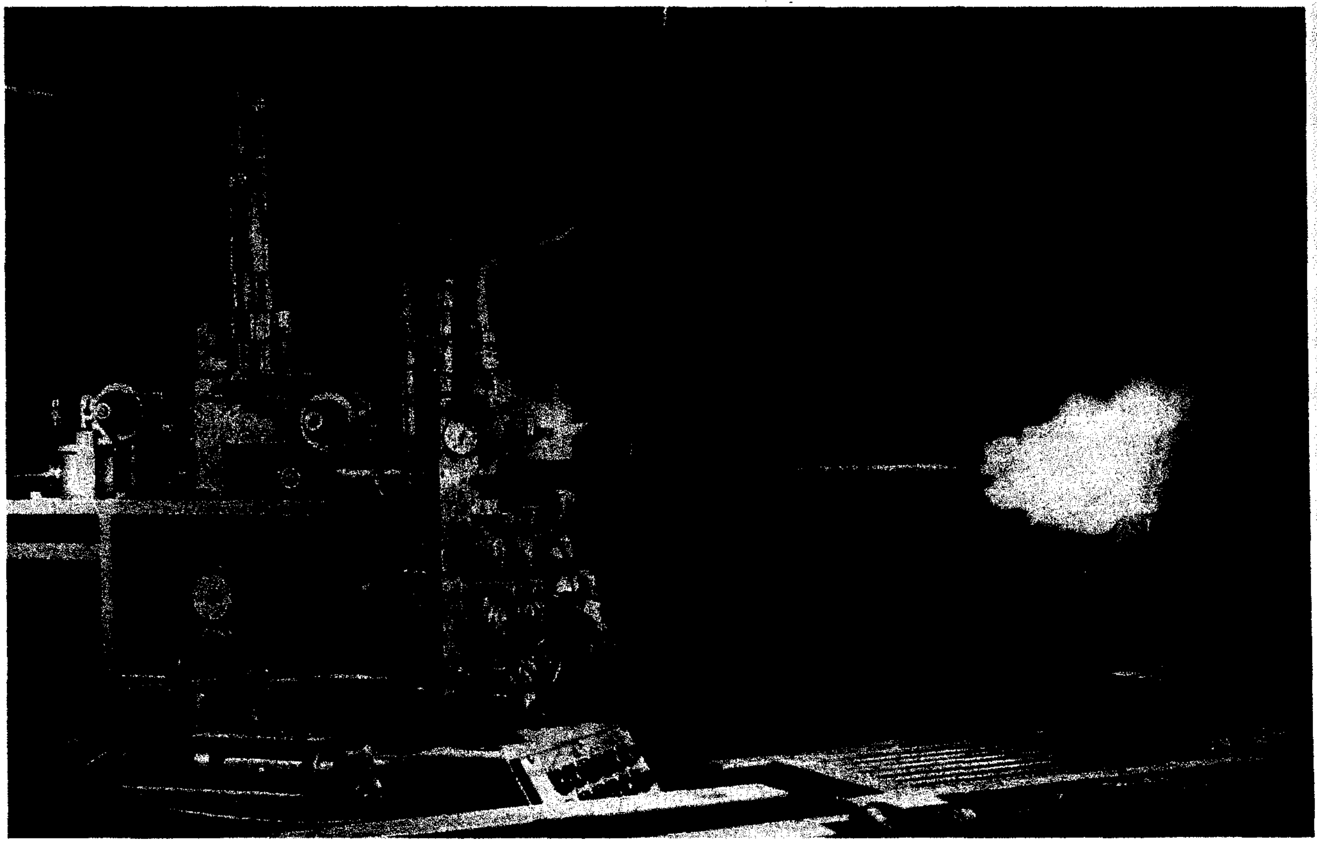

Figure 28.7–Detonation Flame Spraying Equipment

Temperatures above 6000°F (3315°C) are achieved within the detonation gun, while the substrate temperature is maintained below 300°F (150°C) by a carbon dioxide cooling system.

Coating thicknesses range between 0.002 and 0.02 in. (50 and 500 μm). The process produces a sound level in excess of 150 decibels, and is housed in a sound isolating room. The actual coating operation is completely automatic and remotely controlled. The high particle impingement velocity results in a strong bond with the substrate. Excellent finishes are achievable. The porosity content of the coating is low.

CONTINUOUS COMBUSTION SPRAYING

EQUIPMENT FOR THE continuous combustion spraying process is similar to that for the subsonic flame spray process, in that a fuel gas such as propylene is burned with oxygen to provide a heat source. The powder to be sprayed is entrained in a nitrogen carrier gas and injected axially into the torch. The nozzle on the hypersonic gun restricts gas flow and results in exit velocities up to 3,000 ft/s (900 m/s).

Flame sprayed deposits produced by the hypersonic gun are similar to those produced by detonation spraying. Because of the high impingement velocities, the sprayed particles are very tightly bonded to the substrate.

ARC SPRAYING

THE ARC SPRAY process uses an arc between two wires (feedstock). They are kept insulated from each other and automatically advance to meet at a point within an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires initiates an arc as they converge, melting the tips of both wires. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets which form the atomized spray.

The velocity of the gas through the atomizing nozzle can be regulated over a range of 800 to 1100 ft/min. (4.0 to 5.5 m/s) to control deposit characteristics desired. Molten metal particles are ejected from the arc at the rate of several thousand particles per second.

In comparison with wire flame spraying, the quantity of metal oxides is better controlled and spray rates are higher in wire arc spraying. Thus wire arc spraying is often more economical.

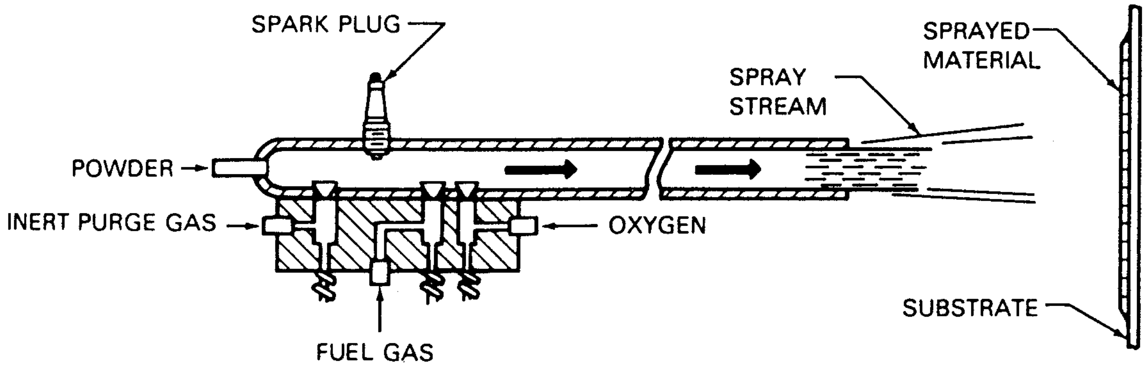

Figure 28.8–Schematic Arrangement of an Oxygen-Fuel Gas Detonation Gun

The wire control unit consists of two reel (or coil) holders, which are insulated from each other, and connected to the spray gun with flexible insulated wire guide tubes. Wire sizes range from 1/16 to 1/8 in. (1.6 to 3.2 mm).

Arc Equipment

A WIRE ARC spray gun is shown schematically in Figure 28.9. A welding type power supply is required to maintain the arc between the two wires.

The arc temperatures exceed the melting point of the spray material. During the melting cycle, the metal is superheated to the point where some volatilization may occur, especially with aluminum and zinc. The high particle temperatures produce metallurgical interactions or diffusion zones, or both, after impact with the substrate. These localized reactions form minute weld spots with good cohesive and adhesive strengths. Thus the coatings develop excellent bond strengths.

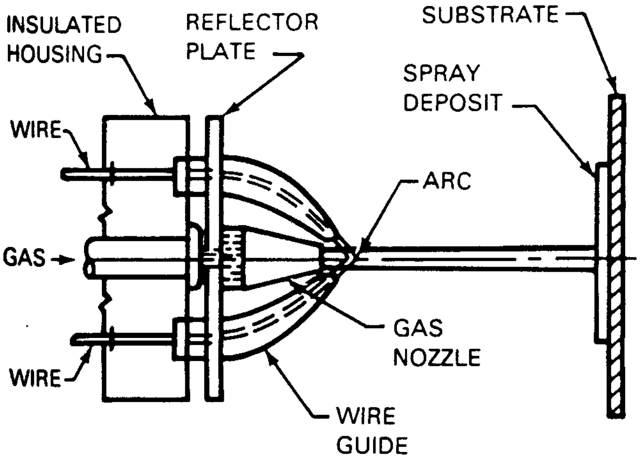

Figure 28.9–Schematic View of a Wire Arc Spray Gun

The wire arc spray process can deposit as little as one lb/hr. Higher deposition rates than those possible with other spray processes are also available with arc spraying. Factors controlling the rate of application are the current rating of the power source and the permissible wire feed rate to carry the available power.

Direct current constant potential power sources are normally used for wire arc spraying; one wire is positive (anode) and the other is negative (cathode). The tip of the cathode wire is heated to a higher temperature than the tip of the anode wire and melts at a faster rate. Consequently, the particles atomized from the cathode are much smaller than those from the anode wire when the two wires are of the same diameter.

The power source, providing a voltage of 18 to 40 volts, permits operation over a wide range of metals and alloys. The arc gap and spray particle size increase with a rise in voltage. The voltage should be kept at the lowest possible level, consistant with good arc stability, to provide the smoothest coatings and maximum coating density.

Systems Operations

WIRE ARC SPRAY systems can be operated from a control console or from the gun. The control console will have the switches and regulators necessary for controlling and monitoring the operating circuits that power the gun and control the spray procedure, namely the following:

(1) A solid-state direct current power source, usually of the constant voltage type
(2) A dual wire feeding system
(3) A compressed gas supply with regulators and flowmeters built into the control assembly
(4) Arc spray gun and pertinent console switching

Controls are provided for the atomizing gas pressure and gas flow rate, wire feed speeds, and arc power requirements. On most equipment, switches are provided at the spray gun to energize the wire feed and the atomizing gas flow.

Energy and labor costs are lower for wire arc spraying because of its higher deposition rate, lower maintenance, low gas costs, and higher deposition efficiencies. One adverse effect of the high energy state of the atomized particles is their tendency to change composition through oxidation or vaporization, or both. The nature of these effects is complex but they can be minimized by judicious wire selection.

The arc spray method is less versatile than flame or plasma methods, because powders and nonconductive materials cannot be used. Particle velocities and temperatures are generally higher than those with wire flame spraying, but lower than those with plasma spraying.

Higher strength bonds can be achieved with some materials by spraying the first pass using high arc voltage, a low gas flow rate, and a short gun-to-work distance. This is called the bond coat mode. These conditions will produce coarse, hot particles that will adhere well to the substrate. To avoid overheating of the substrate, traversing speed across the substrate is rapid, especially in manual spraying, where travel speed is not automatically controlled.

After the first pass has been applied over the entire surface, subsequent spraying is done using standard gas pressure, the lowest possible arc voltage consistant with good arc stability, and the normal spray gun to work distance. These conditions ensure the following:

(1) Fine spray particle size
(2) Minimum loss of alloy constituents
(3) A concentrated spray pattern
(4) High melting rate

PLASMA ARC SPRAYING

THE TERM "PLASMA ARC" is used to describe a family of metal working processes used in spraying, fusion welding and surfacing, and cutting. They all use a constricted arc to provide high density thermal energy. Arc constriction is accomplished by forcing the electric arc through an orifice. During heating, the accompanying gas is partially ionized, producing a plasma. In plasma spraying, a nontransferred arc is established between an electrode and a constricting nozzle. The substrate is not part of the electrical circuit.

Turbine and rocket engine components are exposed to extreme service conditions. Existing engineering materials are not adequate without a protective thermally sprayed coating. In many cases, the spray coating consists of ceramic oxides and carbides which require temperatures higher than those possible with flame and arc processes. The plasma spray process evolved to meet these needs. The plasma spray process also stimulated the evolution of a new family of materials and application techniques for a greatly expanded range of industrial applications. Plasma spraying supplements the older processes of flame and wire arc spraying.

The process uses powdered materials in a plasma (hot ionized or dissociated gas) as the heat source. Plasma generators provide controllable temperatures of from 4000 to 15 000°F (2200 to 8300°C). These temperatures will melt most substances.

In the plasma spray process, a gas or gas mixture is passed through an electric arc between a coaxially aligned tungsten alloy cathode and an orifice within a copper anode. The process is illustrated in Figure 28.10. The gas passing through the orifice is ionized. The temperature of the ionized plasma is much higher than that obtained with a combustion flame.

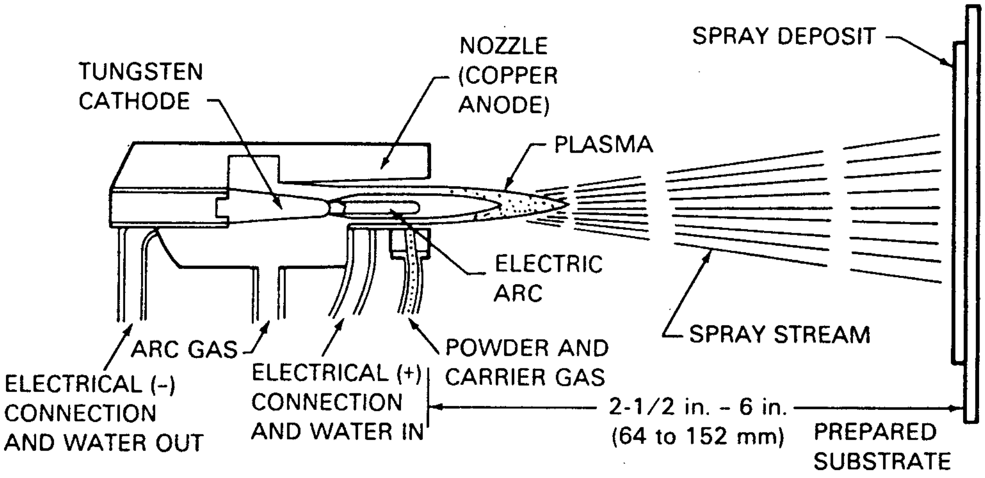

Figure 28.10–Sectional View of Plasma Arc Spraying Torch

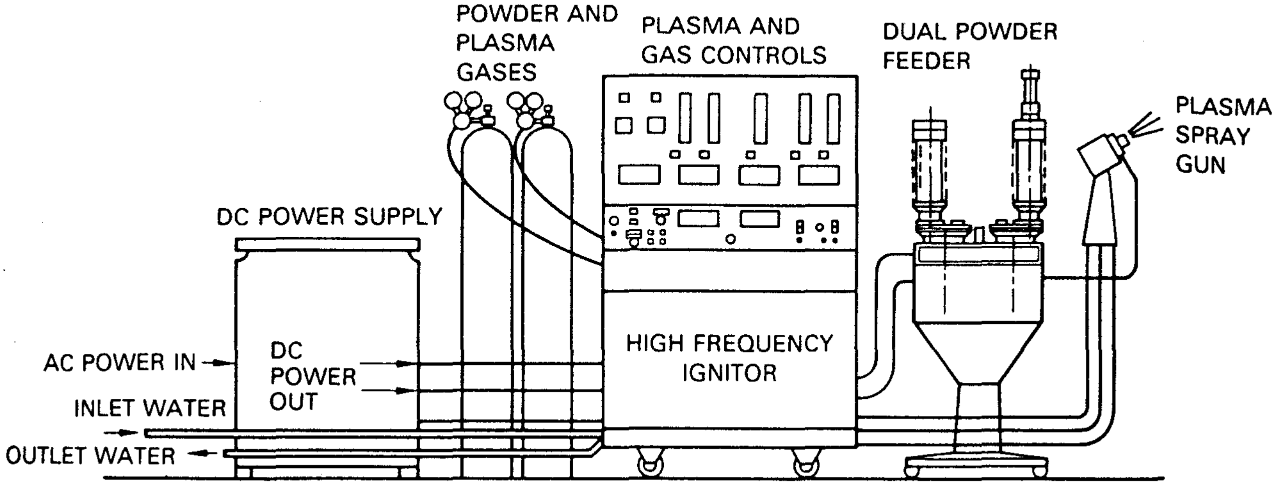

Figure 28.11–Complete Plasma Spray System

EQUIPMENT

A PLASMA SPRAY unit will consist of a plasma gun, power source, powder, powder feed system, and associated fixturing and traversing devices. This is shown schematically in Figure 28.11.

Torch Design

SEVERAL TYPES OF plasma spray guns are available. An 80 kw plasma spray gun is shown in Figure 28.12. In each instance, the arc is generated between an electrode and a water-cooled chamber (nozzle) into which a plasma gas is injected. The gas expands in the heat of the arc, is accelerated, and exits through a nozzle in a cone shaped configuration.

As shown in Figure 28.10, the rear electrode may be fixed or adjustable, but it must be aligned coaxial with the nozzle or front electrode. Flowmeters are used to control the flow of gas through the gun. Several nozzle configurations can be used to accommodate various plasma gases and to spray different types of powders.

Quality deposits require introducing powder at the proper point in the arc plasma and at the correct feed rate. Since the particles are in the plasma for very short times, slight variations in the location of the feed point may significantly change the amount of heat transmitted to the powder.

Current gun designs have power capacities of from 40 to 100 KW. Direct current of 100 to 1100 A is used at 40 to 100 V. High power is necessary when spraying with high particle velocities. Particle velocity is an important variable with respect to bond strength and deposit density and integrity.

Power Supply

POWER SUPPLIES FOR plasma spraying should have the following characteristics:

(1) Constant current dc output
(2) Variable open-circuit and load voltages
(3) Variable current control
(4) Low ripple
(5) Good regulation
(6) Arc starting capability

Rectifier type, solid-state units generally meet the above requirements. Units are easily operated in parallel for high-power operations. In general, they resemble arc welding power sources.

Powder Feed Devices

POWDER FEED MECHANISMS are of three types: aspirator, mechanical, and localized fluid bed. Mechanical feed is the most popular type. It uses the metering action of a screw or wheel to deliver powder at a constant rate to a mixing chamber. The powder is introduced into the carrier gas stream in the mixing chamber.

Units are available to cover a wide range of spray rates. The range of a particular design is determined by the specific gravity of the surfacing material. Modifications are usually available to meet specific spray rate requirements.

System Control

A COMPLETE SYSTEM, including the spray unit, can be operated from a control console. The console provides adjustment of the plasma gas flow rates, plasma current, starting

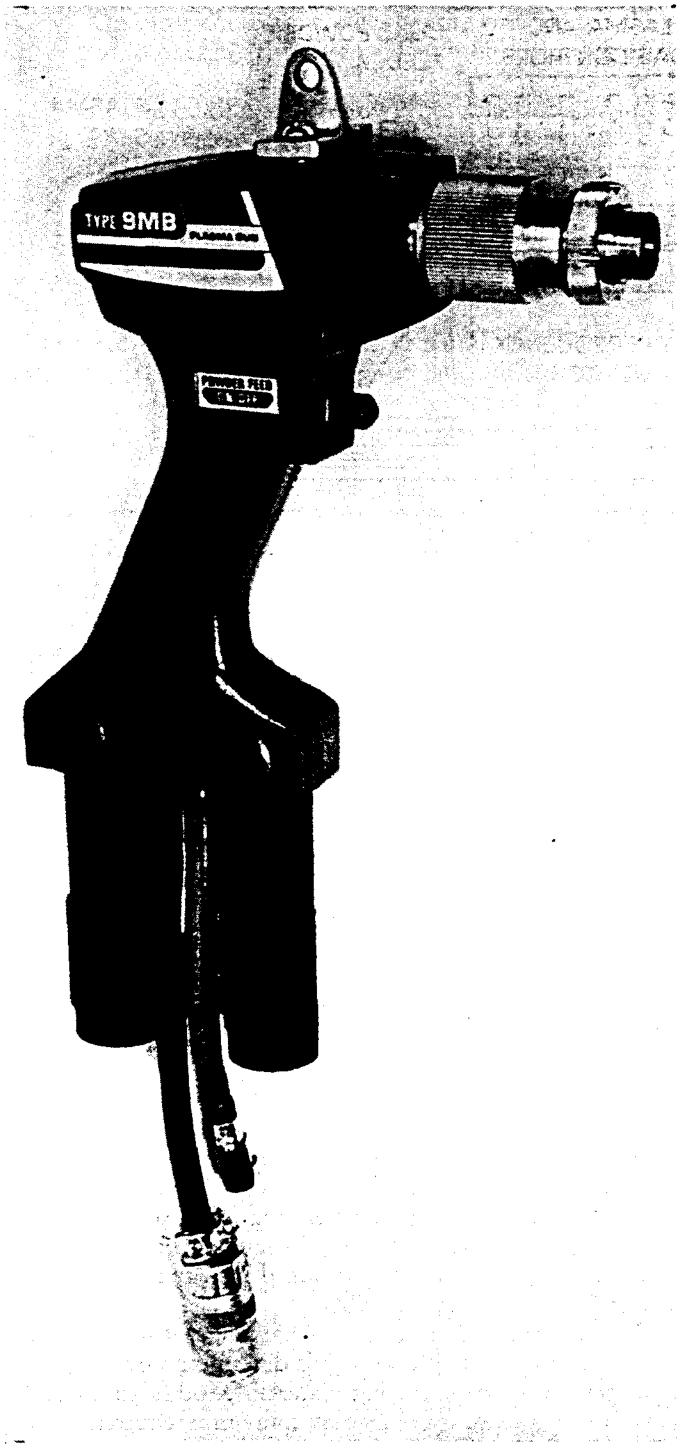

Figure 28.12–Photograph Shows an 80kw Nontransferred Plasma Gun Used to Spray Powders

and stopping functions, and, in some cases, operation of the powder feed unit. These functions are common to all plasma spray systems.

GASES

GASES SERVE THREE purposes in plasma spray systems: as primary plasma gas; as secondary gas mixed in small volumes with the plasma gas; and as the powder carrying gas, usually the same as the primary gas.

Monatomic and diatomic gases can be used for plasma spraying. Argon and helium are the two most frequently used monatomic gases. With monatomic gases, it is possible to attain powder heating rates sufficiently high for most applications. Plasmas generated with polyatomic gases have greater heat contents. They not only release ionization energy but also the energy of molecular recombination. The choice of gas affects the quality of the plasma. The gases should be welding grade with low moisture and oxygen contents.

The four gases commonly used for plasma spraying and their important characteristics are as follows:

(1) Nitrogen is widely used because it is inexpensive, diatomic, and permits high spraying rates and deposit efficiencies. Nozzle life will be shorter than with monatomic gases, but this factor may be offset by the lower cost of this gas.

(2) Argon provides a high velocity plasma. It is used to spray materials that would be adversely affected if hydrogen or nitrogen were used. Carbides and high temperature alloys are most commonly sprayed with argon, especially in aircraft applications.

(3) Hydrogen may be used as a secondary gas in amounts from 5 to 25 percent, with nitrogen or argon. Hydrogen additions raise the arc voltage, and thus the power and heat content of the arc. Hydrogen may have a detrimental affect on certain metals which tend to absorb hydrogen when in a molten condition.

(4) Helium is usually used as a secondary gas mixed with argon, especially when titanium is the substrate. It will also tend to raise the arc voltage.

PLASMA SURFACING

IT IS NECESSARY to use plasma spraying equipment for powders with melting points above 5000°F (2800°C). Because this method is capable of depositing refractory metals and ceramics, it can also deposit powdered materials that are normally applied by flame spraying, but it does so at a higher rate.

A partial list of surfacing materials applied by this method is shown in Table 28.3. Many commercial compositions are proprietary and designed for specific applications.

Plasma sprayed ceramic coatings exhibit higher densities and hardness than flame sprayed deposits. High density

Table 28.3
Materials Commonly Applied by Plasma Spraying

Metals	Carbides[a]	Oxides	Cermets
Aluminum	Chromium carbide	Alumina	Alumina-nickel
Chromium	Titanium carbide	Chromium oxide	Alumina-nickel aluminide
Copper	Tungsten carbide	Magnesia	Magnesia-nickel
Molybdenum		Titania	Zirconia-nickel
Nickel		Zirconia	Zirconia-nickel aluminide
Nickel-chromium alloys			
Tantalum			
Tungsten			

a. Normally combined with a metal powder that serves as a binder.

plasma sprayed deposits can be thinner in some cases, but may be more susceptible to cracking. Deposition procedures can be designed to overcome differences in coefficients of thermal expansion of the ceramic coating and the metal substrate. This can be achieved by spraying mixtures of the ceramics and a suitable metal in various proportions to produce graded (layered) deposits.

CONTROLLED ATMOSPHERE PLASMA SPRAYING

PLASMA ARC SPRAYING lends itself to controlled atmosphere applications. Temperature regulation of both the substrate and atmosphere are more precise in controlled atmospheres. This results in lower oxidation of the sprayed materials and less porosity in the sprayed deposit. It also produces closer control of the composition and morphology of the sprayed coating. This results in greater structural homogeneity, absence of oxide, increased hardness, and a thicker deposit capability. These benefits are produced at a higher deposition rate.

When spraying in an inert gas atmosphere chamber, improvements are achieved only with considerable capital equipment cost. The need for improved coating properties must be weighed against the additional expense of the equipment.

INDUCTION COUPLED PLASMA TORCH

THE INDUCTION COUPLED plasma torch generates a plasma by producing a conductive load (arc) within the inductive field by an ignition system. The inductive field then couples to the conductive gas as it would to an iron bar. See Figure 28.13.

Plasma stability, power conversion efficiency, and maximum heat content are all related to the gas flow pattern, and this pattern varies with different gases. Since there are no electrodes, continuous operation on reactive as well as inert gases is possible without torch deterioration. These gases include air, argon, nitrogen and oxygen.

Control of the plasma effluent is obtained by varying the plasma gas and its flow rate, power input to the induction coil, and the design of the exit nozzle. Gas velocity can be varied from a few feet per second to over 10,000 ft/s (3000 m/s) by changing the exit nozzle size.

This heat source has been used to spray intermetallic powders such as titanium aluminide with excellent results. Lack of an electrode, which might deteriorate during operation, eliminates that potential source of contamination and results in a purer deposit.

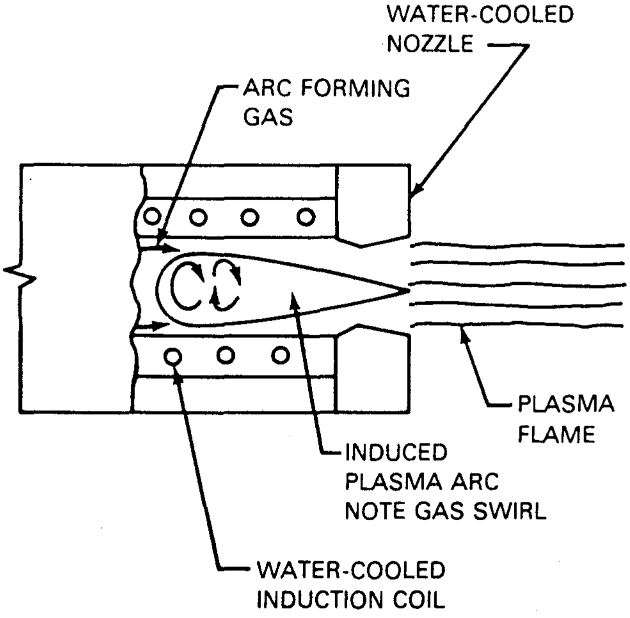

Figure 28.13–Schematic View of Induction Coupled Plasma Torch

FUSED SPRAY DEPOSITS

GENERAL DESCRIPTION

A FUSED SPRAY deposit is a self-fluxing alloy deposited by thermal spraying, which is subsequently heated to coalescence within itself and with the substrate. The materials wet the substrate without the addition of a fluxing agent, provided the substrate is properly cleaned and prepared to receive it. The materials are powdered nickel or cobalt alloys, and they may be applied by powder flame spraying or by plasma spraying.

The application of a fused deposit involves four operations:

(1) Surface preparation
(2) Spraying the self-fluxing alloy
(3) Fusing the coating to the substrate
(4) Finishing the coating to meet surface and dimensional requirements

Fused coatings are dense and nearly porosity free. The alloy compositions can result in hardness levels greater than 50 Rc. Coating thickness is limited to those ranges which can be heated to melting temperature without spalling. Self fluxing coatings are limited to applications where the effects of fusing temperatures and any distortion can be tolerated. Thick coatings of dissimilar metals can be applied in multiple passes. For optimum results, the surface to be coated should be cleaned of all oxide residues after each fusing stage or layer.

A finishing operation is not always required if the as-fused surface is suitable for the application. Centrifuge screw flutes, buffing fixtures, and process piping are examples of components that may be used in the as-fused condition. Pump packing sleeves, pump plungers, piston rods, and process rolls are examples of surfaced machine parts that require a subsequent finishing operation on fused deposits.

A properly sprayed and fused deposit will be nearly homogeneous, metallurgically bonded to the substrate, and have no open or visible porosity. It will have higher hardness than an equivalent mechanically bonded deposit, and will withstand pressures and environments better than nonfused deposits.

SELF-FLUXING ALLOYS

MOST SELF-FLUXING ALLOYS fall into two general groups: Nickel-chromium-boron-silicon alloys and Cobalt-chromium-boron-silicon alloys.

In some cases tungsten carbide or chromium carbide particles are blended with an alloy from one of the above groups.

The boron and silicon additions are crucial elements that act as fluxing agents and as melting point depressants. They permit fusing at temperatures compatible with steels, certain chromium-iron alloys, and some nickel base alloys.

The hardness of fused coatings will range from 20 to 60 Rc, depending upon alloy composition. Hardness is virtually unaffected by the thermal spraying procedures since there is almost no dilution with the base metal.

Selection of an alloy composition for a particular application should be based on certain considerations, including the following:

(1) Fusion temperature of the alloy and thermal effects on the base metal
(2) Relative difference in the coefficients of thermal expansion of the base metal and alloy deposit
(3) Service requirements of the part
(4) Finish requirements of the fused deposit and available finishing equipment

EQUIPMENT

IN ADDITION TO cleaning, blasting, thermal spraying, and work-handling equipment, some device or method is needed to fuse the sprayed deposit. Fusing may be done with an oxyfuel gas torch, in a furnace, or by induction heating.

Fusing Torches

A FUSING TORCH can have a single or multiple jet tip, depending upon the mass of the workpiece. The fusing gas is usually oxy-acetylene, and a neutral or reducing flame is used. Other fuel gases may be used except for cobalt-base alloys, where an oxyacetylene reducing flame is recommended. A combination spraying and fusing torch is available for applying these types of deposits. The coating is alternately deposited and fused. This type of equipment is particularly suited for repair work, but not for large workpieces nor for production work.

Fusing Furnaces

SPRAY DEPOSITS CAN be fused by placing the coated workpiece in an atmosphere furnace operating at the fusing temperature. Argon, dry hydrogen, or vacuum atmospheres may be used. Furnace fusing is advantageous for high production applications, intricate part geometries, or parts with significant variations in section thickness.

BASE METALS

FUSED THERMAL SPRAYED deposits can be applied to a wide variety of metals. However, varying degrees of skill, technique, and procedures are required. Some base metals are easier to surface than are others. Those which can be readily sprayed with one or more self-fluxing alloys and then fused are as follows:

(1) Carbon and low alloy steel with less than 0.25 percent carbon
(2) AISI 300 series stainless steels, except Types 303 and 321
(3) Certain grades of cast iron
(4) Nickel and nickel alloys that are free of titanium and aluminum

Metals that require special procedures to avoid undesirable metallurgical changes are carbon and low alloy steels with more than 0.25 percent carbon, and AISI 400 series stainless steels, except Types 414 and 431. Types 414, 431, and the precipitation hardening stainless steels are not recommended as base metals for self-fluxing alloys.

Cracking of some types of fused sprayed deposits on hardenable steels can be avoided by isothermal annealing of the parts from the fusing temperature. The isothermal anneal prevents the formation of martensite in the substrate material. Fused deposits with a hardenable steel composition and hardnesses above 25 Rc will likely crack when the steel transforms to martensite. Surface cracking results from the rapid expansion that takes place during the transformation. However, there are applications in which cracks in the fused deposit are not detrimental to service requirements.

FUSING

FUSING A SPRAYED deposit is accomplished by heating the workpiece to a temperature range dependent on the particular self-fluxing alloy. The fusing temperatures of nickel-chromium-boron-silicon alloys range from 1875 to 2150°F (1025 to 1175°C). The cobalt-chromium-boron-silicon alloys fuse in the range of 2150 to 2250°F (1175 to 1230°C). The actual fusing temperature depends upon the composition of the alloy.

The most common method of fusing is with one or more oxyfuel gas heating torches, using a reducing flame. A typical torch fusing operation is shown in Figure 28.14. First, the torch is directed on the workpiece, which is heated to a dull red color, about 1400 to 1600°F (760 to 870°C). Then the torch is moved across the spray deposit to gradually increase the surface temperature until the de-

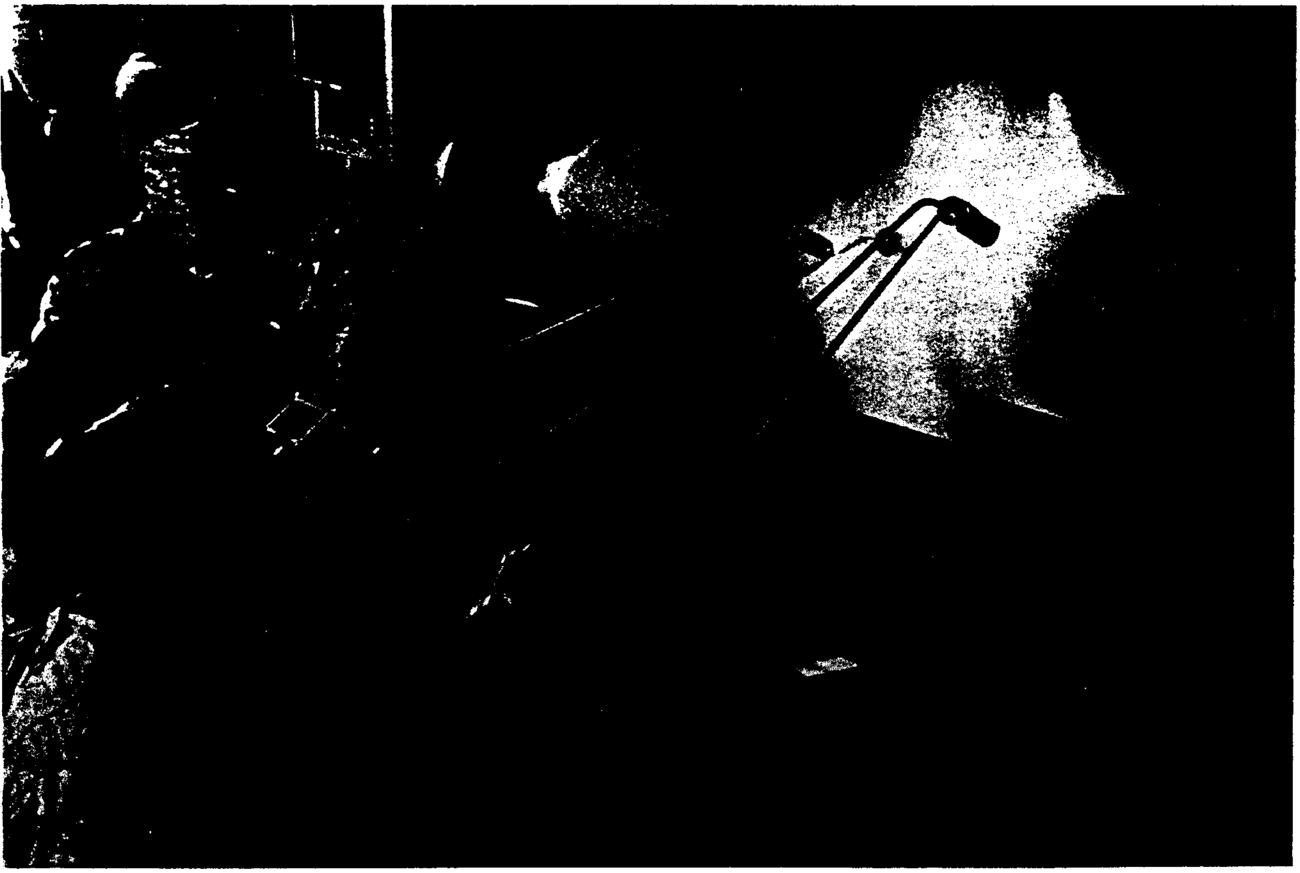

Figure 28.14–Fusing a Deposit on a Large Roll with Oxyacetylene Torches

posit shows a glossy or greasy appearance. This indicates that the deposit has fused. Overheating should be avoided to prevent flow of the molten alloy. The temperature of the workpiece and deposit must be maintained as uniform as possible.

The fusing operation may also be done with other methods of heating, including furnace and induction heating. With these processes, heating is done in a neutral or reducing atmosphere, to avoid oxidation of both the deposit and the base metal.

POST-TREATMENTS

SEALING

SEALING OF SPRAYED deposits is performed to lengthen the service life or prevent corrosion of the substrate, or both. Sprayed deposits of aluminum or zinc may be sealed with vinyl coatings, either clear or aluminum pigmented. The sealer may be applied to fill only subsurface pores in the deposit, or both subsurface pores and surface irregularities. The latter technique will provide a smooth coating to resist industrial atmospheres. The vinyl coatings may be applied with a brush or spray gun.

Sealing is also used on coated machine parts. Where the spray deposit will be exposed to acids, it is recommended that the surface be sealed with either a high melting point wax sealer or a phenolic plastic solution. Spray deposits on high-pressure hydraulic rams, pump shafts, and similar parts should be sealed with air-drying phenolics, to prevent the seepage of liquid through the coating around the packing. Pressure cylinders of all types are reclaimed by thermal spraying. Prior to finish grinding, the cylinder bore is sealed with a phenolic. This prevents grinding wheel particles from embedding in the pores of the sprayed metal and causing premature wear.

Epoxies, silicones, and other similar materials are used as sealants for certain corrosive conditions. Vacuum impregnations with plastic solutions is also possible.

DIFFUSING

A THIN LAYER of aluminum may be diffused into a steel or silicon bronze substrate at 1400°F (760°C). The diffused layer can provide corrosion protection against hot gases up to 1600°F (870°C). After depositing the aluminum, the part can be coated with an aluminum pigmented bitumastic sealer or other suitable material, to prevent oxidation of the aluminum during the diffusion heat treatment. There are similar aircraft applications with diffusion temperatures dependent upon the base material to which the aluminum is applied.

SURFACE FINISHING

TECHNIQUES FOR SURFACE finishing of thermal spray deposits differ somewhat from those commonly used for metals. Most sprayed deposits are primarily mechanically bonded to the substrates, except for fused coatings. Excessive pressure or heat generated in the coating during the finishing operation can cause damage such as cracking, crazing, or separation from the substrate.

Since the composition of an as-sprayed deposit is an aggregation of individual particles, improper finishing techniques can dislodge particles singly or in clusters. This may cause a severely pitted surface. The deposited particles should be cleanly cut and not pulled from the surface. Even so, a totally finished surface will probably not be shiny but may have a matte finish due to porosity of the deposit.

The selection of a finishing method depends on the type of deposit material, its hardness, and the coating thickness. Consideration should be given to the properties of the substrate material as well as dimensional and surface roughness requirements. Spray deposits of soft metals are usually finished by machining, especially those applied to machine components. A good finish is obtained using high cutting speeds and carbide tools for such applications. More often, however, sprayed deposits are finished by grinding, particularly the hardfacing and ceramic coatings.

Various other finishing methods are occasionally used. These include buffing, tumbling, burnishing, belt polishing, lapping, and honing.

Machining

TUNGSTEN CARBIDE TOOLS are commonly used for machining sprayed metal deposits and fused coatings. Proper tool angles play a critical role in the success of machining these coatings. The surface speeds and the depth of cut are of equal importance. Improper tool angle and tool pressure can result in excessive surface roughness and the destruction of the bond between the coating and the substrate.

A cutting tool with a slightly rounded tip and a rake angle of three degrees should be used. On outside circumferences, the tip of the tool should be set three degrees below center; in bores, this should be three degrees above center. This will help to limit the stress on the deposit. Peripheral speed should not exceed 75 ft/min. (400 mm/sec.). The feed should be slow with light cuts for best surface finish.

Special cutting tools, such as oxide-coated carbide, cubic boron-nitride, ceramics, cermets, and diamonds may be used to machine very hard metal, ceramic, and cermet deposits. In many cases, machining with these tools is replacing grinding of intricate shapes and large pieces. Machining of flat deposits requires extreme care at the corners and edges to avoid damage. Depth-of-cut and feed rate should be low.

Grinding

Metal Deposits. Wet grinding is the preferred method. Large, wide wheels are used, and the required amount of stock can be removed with one operation. Wet grinding permits closer tolerances than does dry grinding. Grinding wheel manufacturers can recommend wheel types and grinding procedures for various metal deposits, using a particular type of grinding machine.

If it is necessary to grind metal deposits dry, as is done with portable grinders mounted on a lathe, the major amount of materials should be removed first by machining. Then the deposit is ground to the required finish and dimensions.

Wheels used for dry grinding operations may be either aluminum oxide or silicon carbide, depending upon the metal to be ground. The factors to be considered in selecting a wheel for a spray deposit are similar to those for grinding the same metal in wrought or cast form. The grinding technique should be designed to minimize heat buildup in the deposit. The structure of the wheel should be as open as possible and the grain size as coarse as possible, consistent with the finish requirements. The wheel should be narrow, the infeed light, and the traverse as fast as possible without spiraling.

When grinding equipment is not available, metal deposits can be machined to within 0.002 to 0.006 in. (50 to 150 μm) of final size. Then they can be finished to size with a belt polishing unit. Close tolerances and fine finishes are possible with belt polishing, by proper selection of abrasive type and grit size.

Grinding Fused Deposits. Because most fused deposits are designed for hardfacing purposes, grinding is usually the most economical method for finishing them.

Although most fused deposits can be machined with the proper type of cutting tool, close tolerance work is difficult because of rapid tool wear and the large amount of heat generated. Dry grinding may be suitable for some operations, but, in this case also, heat and fast wheel wear make close tolerance difficult. Wet grinding can produce close tolerance parts, fine finishes, and economical stock removal rates. Nickel-base alloys are best ground with silicon carbide grinding wheels, and cobalt-base alloys with aluminum oxide grinding wheels.

Grinding wheel manufacturers should be consulted for recommendations of the appropriate type for the job. Good practice usually suggests a coarse wheel, consistent with finish requirements; an open structure or soft bond; as large a wheel as possible; and good wheel dressing techniques. Surface finish of fused coatings can often be improved after grinding by polishing with fine grit belts.

Grinding Ceramic Deposits. The as-sprayed surface finish of flame sprayed ceramics is, in general, more coarse than 150 μm. Many applications require a better finish, and this can be accomplished by grinding. Although the individual particles of a ceramic deposit have extreme hardness, the deposit can be finished by conventional grinding techniques on standard equipment. However, it is necessary to use the proper grinding wheel, in some cases a diamond wheel, and to follow correct procedures. General recommendations for grinding ceramic deposits are available from grinding wheel manufacturers.

Flood cooling should be employed during grinding. Water containing a rust inhibitor is best. Water-soluble coolants are likely to stain light-colored ceramic deposits.

Other Finishing

OTHER METHODS OF surface finishing are sometimes used for as-sprayed and fused deposits. These include:

(1) Manual buffing or polishing
(2) Abrasive tumbling
(3) Honing
(4) Lapping

As-sprayed or machined deposits may be buffed or polished manually with abrasive stones, cloth, or paper. Abrasive tumbling of small parts will polish the surface by removing the "high spots." An abrasive medium, cleaners, and usually a liquid are vibrated or rotated in a drum in which the parts are finished.

Honing is done with abrasive stones mounted in a loading device. The part normally moves in one direction or rotates while the stones are oscillated under pressure, transverse to the work motion. Lapping is done with a fine, loose abrasive mixed with a vehicle, such as water or oil. The mixture is spread on lapping shoes or plates that are then rubbed against the spray deposit. The lap rides against the deposit, and their relative movements are continually changed.

QUALITY CONTROL

A PROPERLY DESIGNED quality control program can ensure consistent quality in thermal sprayed deposits. Proper quality control consists of more than just the examination of the workpiece after the spraying is complete. Each step in the operation should be monitored by an inspector. This includes not only the spraying and fusing steps, but also the preparation of the substrate and the various stages of handling and storage of the workpiece between operations. In addition, the quality of the spray materials must be controlled. Since bond strength and spray deposit soundness are difficult to determine by nondestructive techniques, the procedures for accomplishing each step of the thermal spraying operation should be documented. The procedures should be qualified by appropriate destructive tests of sample parts.

In general, sprayed deposits are inspected visually for quality and soundness. With fused deposits, lack of bonding may be detected by localized torch heating of the suspected area. Lack of bonding will be indicated by a hot spot or spalling of the deposit material. Ultrasonic techniques may also be used to detect lack of bonding. Penetrant or magnetic particle inspection can detect surface porosity and cracks. Magnetic particle inspection can be used only on ferromagnetic spray deposits.

PROPERTIES

THE QUALITY AND the properties of thermal sprayed deposits are largely determined by the size, temperature, and velocity of the spray droplets as they impinge on the substrate, and the degree of oxidation of both the droplets and the substrate during spraying. These factors will vary with the method of spraying and the procedures employed.

Metals and alloys deposited by the thermal spray process do not retain their original chemical composition unless special techniques are used. Their properties may change significantly depending upon the spray method used. With plasma and other arc methods, appreciable amounts of low melting point constituents may be lost by vaporization. Oxidation of the droplets may also be significant when air is used as the propellant.

The physical and mechanical properties of a spray deposit normally differ greatly from those of the original material. The deposit structure is lamellar and nonhomogeneous. Its cohesion is generally the result of mechanical interlocking, some point to point fusion, and sometimes oxide to oxide bonding. The tensile strengths of these structures are low compared to those of the same materials in wrought or cast form. Sometimes the compressive strength is quite high but the ductility is low. Deposits from wire or rod are less dense than the original material. In any case, spray deposits should be considered as a separate and distinct form of fabricated material.

Oxide spray deposits tend to retain their physical properties with only modest losses. In many cases, the deposit will have a crystalline structure. Alpha alumina may deposit with a metastable gamma structure. The chemical compositions of reactive type ceramics, such as carbides, silicides, and borides, normally change when the materials are sprayed in air with the flame or plasma methods.

MICROSTRUCTURE

THE MICROSTRUCTURE OF a transverse section through a flame sprayed metal deposit will show a heterogeneous mixture of layered metal particles (white), metal oxide inclusions (gray), and pores (black). A photomicrograph of a transverse section through a flame sprayed deposit of 0.80 percent carbon steel is shown in Figure 28.15. The light layered particles are bonded to one another by chemical and mechanical interactions. A photomicrograph of a transverse section through a copper deposit and its substrate at the bond line is shown in Figure 28.16. The roughness of the prepared substrate surface is apparent.

Figure 28.15–Transverse Section Through a Flame Sprayed AISI 1080 Steel Deposit (x500 Reduced on Reproduction)

Figure 28.16–Transverse Section Through a Thermal Sprayed copper Deposit (Top) and the Substrate (Bottom) (x500 Reduced on Reproduction)

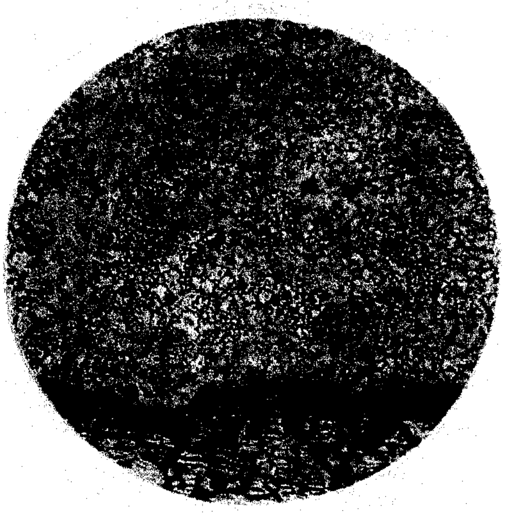

Figure 28.18–Microstructure of a Fused Coating of a Self-Fluxing Nickel-Chromium Alloy (Top) on a Substrate (Bottom) (x250 Reduced on Reproduction)

The microstructure of the polished and etched surface of the 0.80 percent carbon steel deposit is shown in Figure 28.17. It has an emulsified appearance because the flattened steel particles (light) are separated by the oxide (gray).

As-sprayed, self-fluxing alloy deposits are similar in appearance to any typical metal deposit, except that there is significantly less oxide. These materials are oxidation resistant in nature. After fusing, the deposit will have a cast structure with some porosity and inclusions. The microstructure of a fused nickel-chromium self-fluxing alloy deposit is shown in Figure 28.18. The roughness of the prepared substrate is also evident.

Figure 28.17–Section Parallel to the Surface of a Flame Sprayed Deposit of AISI 1080 Steel (x500 Reduced on Reproduction)

HARDNESS

THE HETEROGENEOUS STRUCTURES of spray deposits generally have a lower macrohardness than the original rod or wire supplied to the gun. However, the hardness of individual deposit particles (microhardness) may be much higher than that of the overall deposit. The hardness test should be selected to give the overall deposit hardness or the particle hardness. The thickness of the deposit must also be considered in selecting the type of test. If the deposit is too thin, the indenter may penetrate through it and into the substrate. This would obviously give a false reading.

The Brinell and Rockwell hardness tests can be used to determine the hardness of fairly thick metallic deposits. Superficial Rockwell and Vickers hardness tests are suitable for thin metallic deposits. Requirements for various hardness tests are covered in the appropriate ASTM Standards. Table 28.4 relates the minimum spray deposit thickness to the various Rockwell hardness tests.

Hardness tests with diamond indenters are not entirely satisfactory for determining the true hardness of heterogeneous spray deposits, but they can be used for spot checks and shop guides. Microhardness tests can be used to determine the hardness of individual particles. Since the deposited particles are relatively thin, hardness impressions

Table 28.4
Minimum Deposit Thickness for Rockwell Hardness Tests

Rockwell Scale	Minimum Thickness in.	mm
15N	0.015	0.38
30N	0.025	0.64
45N	0.035	0.89
A	0.040	1.0
B	0.060	1.5
C	0.070	1.8
D	0.050	1.3

should be taken on a transverse section. The Knoop indentation hardness test is best suited for this.

BOND STRENGTH

THE STRENGTH OF the bond between a spray deposit and the substrate depends upon many factors, including the following:

(1) Substrate material and its geometry
(2) Preparation of the substrate surface
(3) Spray angle to substrate
(4) Preheat
(5) Bond layer material and its application method and procedures
(6) Deposit material and its application method and procedures
(7) Thickness of deposit
(8) Post spraying thermal treatment

A standard test for determining the bond or cohesive strength of thermal spray deposits is described in ASTM C633, Standard Test Method for Adhesion or Cohesive Strength of Flame Sprayed Coatings.

In this test, each specimen is an assembly of a coated substrate block and a loading block. The flat end of the substrate block is prepared, and the deposit is applied. Then, the deposit is machined or ground flat and uniform in thickness using procedures appropriate for the deposited material. The loading block is then adhesive bonded to the flat deposit surface to produce a tension specimen. The specimen is loaded in tension at a constant rate using a self-aligning device. The maximum load is recorded. From this, the bond strength or the cohesive strength of the deposit can be calculated, depending upon the fracture location. The bond strengths of several self-bonding spray materials are presented in Table 28.5.

This test method is limited to deposit thicknesses greater than 0.015 in. (0.4 mm), because adhesive bonding agents tend to infiltrate porous deposits. If the bonding agent penetrates to the substrate, it will affect the test results.

Table 28.5
Typical Bond Strength of Self-Bonding Materials*

	Bonding strength, psi (kPa)		
	Plasma	Flame Sprayed	
Material	Sprayed	Powder	Wire
Columbium	2400 (16500)	-	-
Molybdenum	3200 (22100)	3600 (24800)	3300 (22800)
Nickel-aluminide	3000 (20700)	2750 (19000)	3150 (21700)
Tantalum	2750 (19000)	-	-

* Applied to a smooth, unprepared metal surface.

DENSITY

THERMAL SPRAYED DEPOSITS have densities less than 100 percent of the filler metals because they are porous and contain some oxide. The densities of the flame sprayed deposits and the original wire for several metals are given in Table 28.6.

Porosity in spray deposits consists of isolated and sometimes interconnected pores. It is difficult to determine the amount accurately. However, it can be estimated by several methods. The simplest one is to superimpose a grid over the microstructure (photomicrograph) of a prepared surface and then count the number of grid squares occupied by pores. Other methods include water or toluene immersion, and paraffin absorption. Because of lack of total interconnection of the pores, however, no method is perfect.

The porous nature of spray deposits can be used to advantage, especially for bearing surfaces. The porosity permits oil retention and provides an escape for foreign material from actively loaded areas. Where corrosion is a factor, porosity is a disadvantage. It limits the use of deposits to those that are anodic to the base material, unless special overcoatings of paint or sealers are used.

SHRINKAGE

SPRAY DEPOSITS CONTRACT upon cooling. The amount of shrinkage varies widely with different materials and spray-

Table 28.6
Comparison of the Densities of Flame Sprayed Metal Deposits and the Wire

	Density, lb/in.^{3} (kg/m^3)	
Metal	Flame Sprayed Deposit (Wire)	Wire
Type 1100 Aluminum	0.087 (2408)	0.098 (2713)
Copper	0.271 (7501)	0.324 (8968)
Molybdenum	0.326 (9024)	0.369 (10214)
AISI 1025 steel	0.244 (6754)	0.284 (7861)
Type 304 stainless steel	0.249 (6892)	0.290 (8027)
Zinc	0.229 (6839)	0.258 (7141)

ing methods, but it will not be the same as that of the original material in cast or wrought form. Contraction sets up tensile stresses in the deposit as well as shear stresses across the bond between the deposit and substrate. These stresses tend to crack or spall the deposit. Surface preparation, selection of material, and coating thickness are important factors in preventing these problems. Metals having low coefficients of thermal expansion should be used where possible, especially for thick deposits and buildup of internal surfaces.

APPLICATIONS

CORROSION AND OXIDATION PROTECTION

THERMAL SPRAY DEPOSITS can provide protection against many types of corrosive attack on iron and steel. Zinc, aluminum, stainless steel, bronze, hard alloys, and ceramics are used as surfacing materials. Service conditions determine both the material type and its application procedures. Undercoatings for organic materials, such as paints and plastic finishes, can be applied by this process. A thick layer of zinc or aluminum can protect steel against oxidation and provide a strong bond for an organic coating.

Nickel, nickel-copper alloys, stainless steels, and bronzes are some metals that are cathodic to steel. They should be used as a deposit on steel only if they are made impermeable to corrosive agents by sealing. The sealer is likely to entrap air bubbles in pores of the spray deposits. The component should not be heated because expansion of the air bubbles may rupture the sealer.

Hard alloy deposits are often used on machine components such as pump plungers, pump rods, hydraulic rams, packing sections of steam turbine shafts, and valves. When sealed, these materials provide both corrosion and wear resistance.

Several different materials may be used to give oxidation protection, the choice depending on the operating temperature. For applications up to 1600°F (870°C), the part can be aluminized by depositing a thin layer of aluminum. The aluminum is then diffused into the surface by a suitable heat treatment. For temperatures above 1600°F (870°C), a nickel-chromium alloy deposit may be used. This is followed by a coating of aluminum. Often, this combination deposit is then covered with an aluminum pigmented bitumastic sealer. The part is then diffusion heat-treated in a furnace, or it is placed directly in service if the operating temperature is above 1600°F (870°C). Such deposits are sometimes used for cyanide pots, furnace kiln parts, annealing boxes, and furnace conveyors.

Zirconia and alumina ceramics are sometimes used for thermal barrier layers. When the workpiece will be exposed to thermal cycling, a bond layer of nickel aluminide or nickel-chromium alloy may help to minimize thermal stresses in the ceramic deposits.

WEAR RESISTANCE

IN THE MECHANICAL field, thermal spray hardfacing materials can be used to combat many types of wear. The ability of metal spray deposits to absorb and maintain a film of lubricant is a distinct advantage in many applications. Spray deposits often give longer life than the original surfaces, except where severe conditions of shock loading or abrasion are encountered. A low cost base metal can be protected on just the areas of wear with a high quality, wear resistant deposit.

An arc spray gun being used to deposit a nickel aluminide bonding material on the I.D. of a four inch steel cylinder is shown in Figure 28.19. Compressed air shears off molten droplets at a right angle to the axis of the spray gun.

Some metal deposits, such as nickel-copper alloys, nickel, and stainless steel, are virtually impervious to penetration by corrosives when they are applied in sufficient thickness and are exposed only to moderate pressure. These surfaces can be vacuum impregnated with various phenolic or vinyl solutions or with fluorocarbon resins for high-pressure operation. For applications where extreme wear or corrosion resistance, or both, are encountered, fused spray coatings may be used.

ELECTRICAL CHARACTERISTICS

THE ELECTRICAL RESISTANCE of a metal spray deposit may be 50 to 100 percent higher than that of the same metal in cast or wrought form. This should be taken into consideration in the design of spray deposits for electrical conductors. Such applications include spraying of copper on electrical contacts, carbon brushes, and glass in automotive fuses, as well as silver or copper contacts.

In the field of electrical insulation, various ceramic deposits can be used for insulators. Magnetic shielding of electrical components may be provided with deposits of zinc or tin zinc applied to electronic cases and chassis. Condenser plates can be made by spraying aluminum on both sides of a cloth tape.

FOUNDRY

CHANGES IN CONTOUR of expensive patterns and match plates can be readily accomplished by the application of thermal spray deposits followed by appropriate finishing. Patterns and molds can be repaired with wear resistant deposits. Blow holes in castings that appear during machining can be filled to salvage the parts.

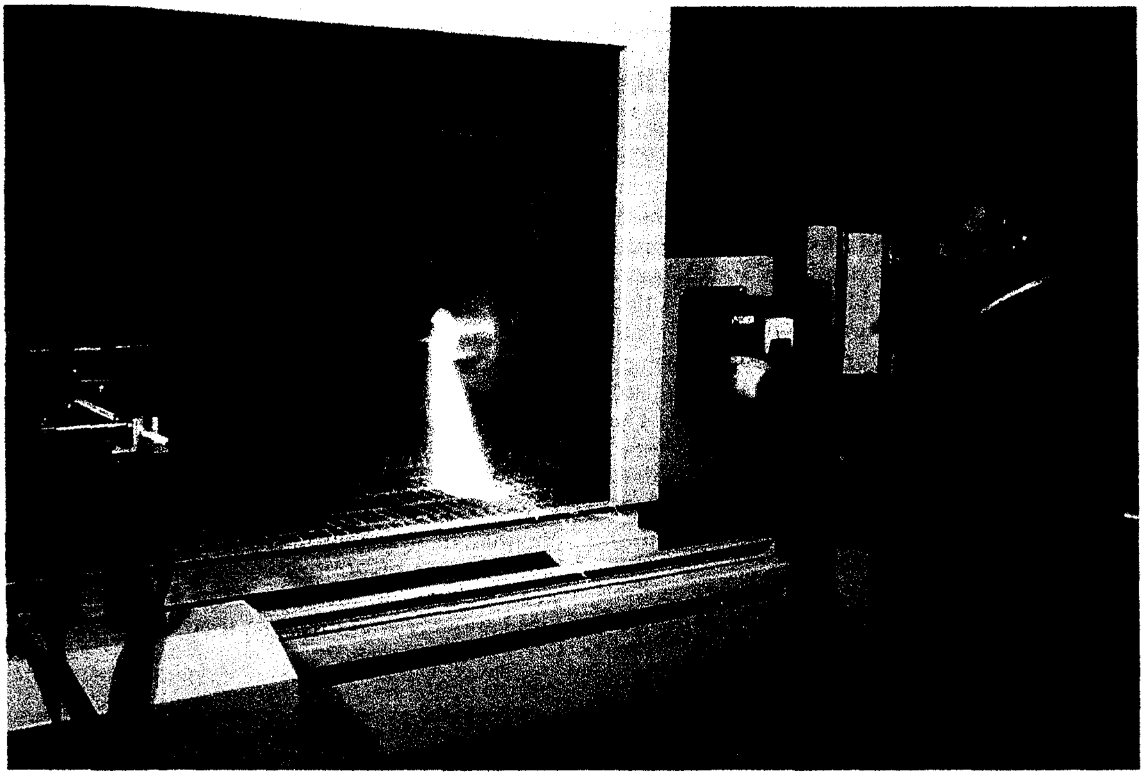

Figure 28.19—Wire Arc Spray Gun Used to Deposit Nickel Aluminum Bonding Material on the I.D. of a 4-in. (100 mm) Diameter Steel Cylinder. Compressed Air Shears Off Droplets at a Right Angle to Axis of Spray Gun.

BRAZING AND SOLDERING

THERMAL SPRAYING IS frequently used for the preplacement of soldering or brazing filler metals. The usual practice is to apply the filler metal using standard thermal spraying techniques.

AIRCRAFT AND MISSILES

THERMAL SPRAYING IS used for air seals and wear resistant surfaces to prevent fretting and galling at elevated temperatures. Deposits of alumina and zirconia are used for thermal insulation.

A robot set up for plasma arc spraying of a bond coat on a part from the hot section of a gas turbine engine is shown in Figure 28.20. The bond coat is part of a thermal barrier coating system.

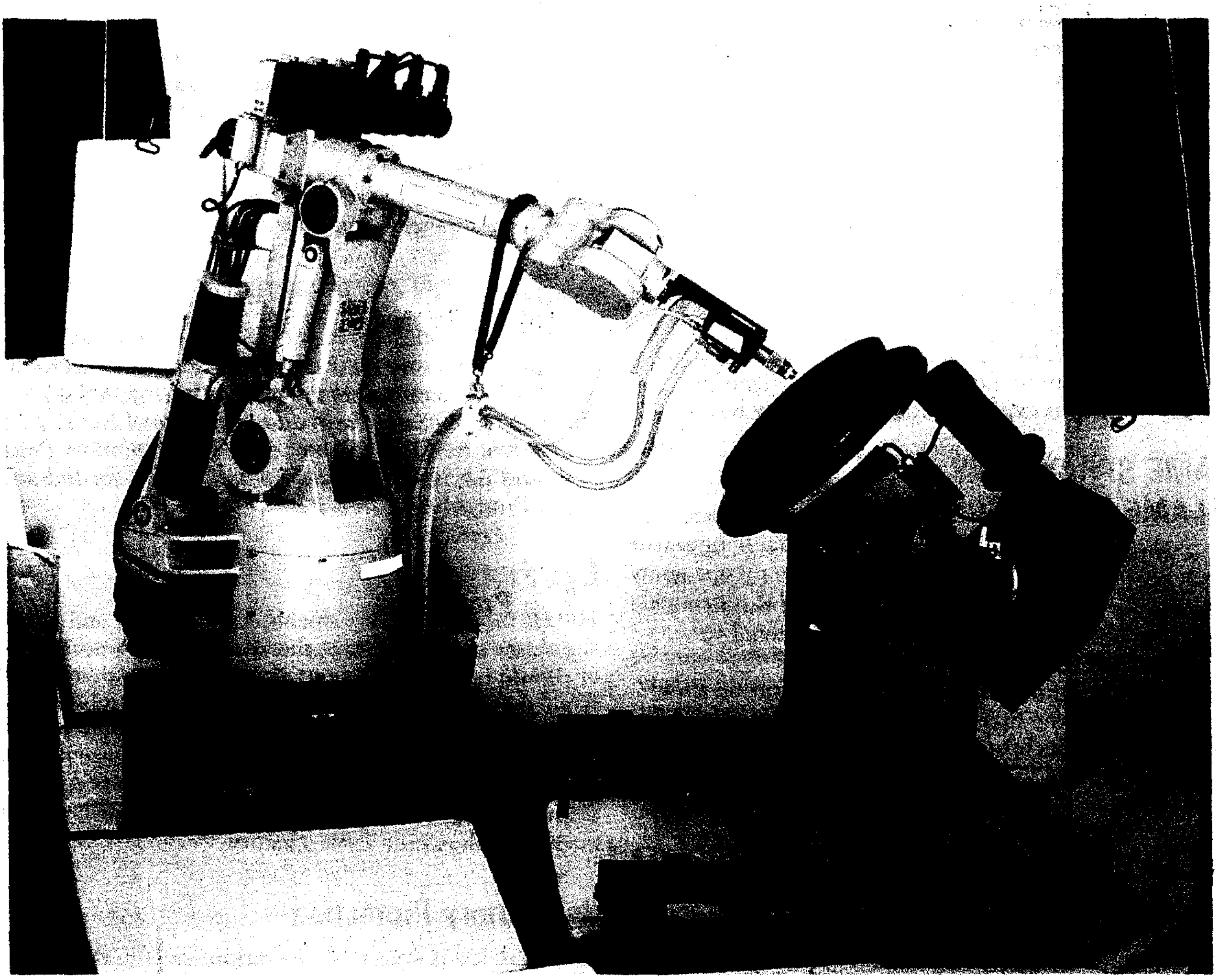

Figure 28.20—Robotic Spraying of Bondcoat on a Part from the Hot Section of a Gas turbine Engine

SAFETY

THE POTENTIAL HAZARDS to the health and safety of personnel involved in thermal spraying operations and to persons in the immediate vicinity can be grouped as follows:

(1) Electrical shock
(2) Fire
(3) Gases
(4) Dust and fumes
(5) Arc radiation
(6) Noise

These hazards are not unique to thermal spraying methods. For example, flame spraying has hazards similar to those associated with the oxyfuel gas welding and cutting processes. Likewise, arc spraying and plasma spraying are similar in many respects to gas metal arc and plasma arc welding, respectively. However, thermal spraying does generate dust and fumes to a greater degree than the welding processes do.

GAS SYSTEMS

LOCAL, STATE, AND federal regulations relative to the storage of gas cylinders should be investigated and complied with. Safe storage, handling, and use of gas cylinders are described in ANSI Z49.1, *Safety in Welding and Cutting*, and CGA P-1, *Safe Handling of Compressed Gases*. Improper storage, handling, and use of these cylinders constitute safety hazards in thermal spraying operations. Oil or grease must not be used on oxygen equipment; only special oxidation resistant lubricants may be used.

Acetylene pressures in excess of 15 psi (103kPa) are dangerous and should not be used. When acetylene pressure of 15 psi is too low for the application, another fuel gas should be used. Alloys containing more than 67 percent copper or silver must not be used in acetylene systems, because dangerous explosive compounds may be formed.

FLAME SPRAY GUNS

FLAME SPRAY GUNS must be maintained in accordance with the manufacturer's recommendations. Each operator should be familiar with the operation of the flame spray gun and should read the instruction manual thoroughly before using it.

A friction lighter, a pilot light, or arc ignition should be used to ignite the fuel gas. Matches are not safe. A flame spray gun and its hoses should not be hung on gas regulators or cylinder valves because of the danger of fire or explosion.

PLASMA AND ARC SPRAYING EQUIPMENT

PLASMA AND ARC spraying use equipment where high voltages and amperages present a hazard. Operators should be thoroughly instructed and trained in the operation of the unit. They should be familiar with the operating and safety recommendations, and at the same time observe proper safety precautions for electrical equipment.

The plasma spraying equipment itself should be kept in a condition safe to operate. Exposed electrodes of plasma guns should be grounded or adequately insulated. Periodic inspections should be made of cables, insulation, hoses, and gas lines. Faulty equipment must be repaired or replaced immediately. The entire system, including the power supply, must be shut down before repairing any part of the power supply, console, or gun.

Arc spray guns should be cleaned frequently according to the manufacturer's operation manual to prevent the accumulation of metal dust. If the arc spray gun is suspended on a cable, the suspension hook must be insulated or grounded. Contact between any ungrounded portion of the plasma or arc spray gun and the spray chamber must be avoided.

FIRE PREVENTION

FINELY DIVIDED AIRBORNE solids, especially metallic dusts, must be treated as explosives. To minimize danger from dust explosions, adequate ventilation should be provided to spray booths. A wet collector of the water-wash type is recommended to collect the spray dust. Bag or filter type collectors are not recommended. Good housekeeping in the work area should be maintained to avoid accumulation of metal dusts, particularly on rafters, tops of booths, and in floor cracks.

Paper, wood, oily rags, and other combustibles in the spraying area can cause a fire and should be removed before the equipment is operated.

PROTECTION OF PERSONNEL

THE GENERAL REQUIREMENTS for the protection of thermal spray operators are the same as for welders, set forth in ANSI Z49.1, *Safety in Welding and Cutting*; ANSI Z87.1, *Practices for Occupational and Educational Eye and Face Protection*; ANSI Z88.2, *Practices for Respiratory Protection*; and ANSI Z89.1, *Safety Requirements for Industrial Head Protection.*

Eye Protection

HELMETS, HAND HELD shields, face shields, and goggles should be used to protect the eyes, face, and neck during all thermal spraying operations. These are described in ANSI Z87.1 and Z89.1. Safety goggles should be worn at all times. Helmets, hand held shields, and goggles must be equipped with suitable filter plates to protect the eyes from excessive ultraviolet, infrared, and intense visible radiation. A guide for the selection of the proper filter shade number is shown in Table 28.7.

Respiratory Protection

MOST THERMAL SPRAYING operations require that respiratory devices be used by the operator. The nature, type, and magnitude of the fume and gas exposure determine which

Table 28.7
Recommended Eye Filter Plates for Thermal Spraying Operations

Operation	Filter Shade Numbers
Wire flame spraying (except molybdenum)	5
Wire flame spraying of molybdenum	5 to 6
Flame spraying of metal powder	5 to 6
Flame spraying of exothermics or ceramics	5 to 8
Plasma and arc spraying	9 to 12
Fusing operations	5 to 6

respiratory protective device should be used. The selection of these devices should be in accordance with ANSI Z88.2, *Practices for Respiratory Protection*. This standard contains descriptions, limitations, operational procedures, and maintenance requirements for standard respiratory devices. All devices selected should be of a type approved by U.S. Bureau of Mines, National Institute for Occupational Safety and Health, or other approving authority for the purpose intended.

Ear Protection

EAR PROTECTORS OR properly fitted soft rubber ear plugs must be worn to protect the operator from the high intensity noise from the thermal spray gun. Such protection should reduce the noise level to below 80 decibels. Cotton wads are not recommended for ear protection, as they are ineffective against high-intensity noise. Federal, State, and local codes should be followed for noise protection requirements.

Protective Clothing

APPROPRIATE PROTECTIVE CLOTHING requirements for a thermal spraying operation will vary with the size, nature, and location of the work to be performed. When working in confined spaces, flame resistant clothing as well as leather or rubber gauntlets should be worn. Clothing should be fastened tightly around the wrists and ankles to keep dusts from contacting the skin.

For work in the open, ordinary clothing such as overalls and jumpers may be used. However, open shirt collars and loose pocket flaps are potential hazards. High-top shoes are recommended and cuffless trousers should cover the shoe tops.

The intense ultraviolet radiation of plasma arc spraying can cause skin burns through normal clothing. When using this process, the clothing should provide protection against such radiation. For exposure to more intense radiation, leather welder capes are necessary. Protection against radiation with arc spraying is essentially the same as that used for electric arc welding.

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CHAPTER 29

OTHER WELDING PROCESSES

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CHAPTER 29

OTHER WELDING PROCESSES

THERMIT WELDING

FUNDAMENTALS OF THE PROCESS

Definition

THERMIT[1] WELDING (TW) is a process that produces coalescence of metals by heating them with superheated molten metal from an aluminothermic reaction between a metal oxide and aluminum. Filler metal is obtained from the liquid metal. The process had its beginning at the end of the 19th century when Hans Goldschmidt of Goldschmidt AG West Germany (Orgotheus Inc. USA) discovered that the exothermic reaction between aluminum powder and a metal oxide can be initiated by an external heat source. The reaction is highly exothermic, and therefore, once started, it is self-sustaining.

Principles of Operation[2]

THE THERMOCHEMICAL REACTION takes place according to the following general equation:

$$\text{Metal oxide} + \text{aluminum (powder)} \rightarrow \text{aluminum oxide} + \text{metal} + \text{heat}$$

The reaction can only be started and completed if the oxygen affinity of the reducing agent (aluminum) is higher than the oxygen affinity of the metal oxide to be reduced. The heat generated by this exothermic reaction results in a liquid product consisting of metal and aluminum oxide. If the density of the slag is lower than that of the metal, as in the case of steel and aluminum oxide, they separate immediately. The slag floats to the surface and the molten steel drops into the cavity to be welded.

Typical thermochemical reactions and the thermal energies produced are as follows:

$$3Fe_3O_4 + 8\ Al \rightarrow 9Fe + 4Al_2O_3\text{: } H = 3350\text{kJ}$$
$$3FeO + 2\ Al \rightarrow 3Fe + Al_2O_3\text{: } H = 880\text{kJ}$$
$$Fe_2O_3 + 2\ Al \rightarrow 2Fe + Al_2O_3\text{: } H = 850\text{kJ}$$
$$3CuO + 2\ Al \rightarrow 3Cu + Al_2O_3\text{: } H = 1210\text{kJ}$$
$$3Cu_2O + 2\ Al \rightarrow 6Cu + Al_2O_3\text{: } H = 1060\text{kJ}$$

In the above reactions, aluminum is the reducing agent. Theoretically, the elements magnesium, silicon, and calcium can be used as well; but, for general applications, magnesium and calcium have found limited use. Silicon is often used in Thermit mixtures for heat treatment, but it is rarely used in welding. In some cases, an aluminum-silicon alloy is used as the reducing agent.

The first of the reactions above is the one most commonly used as a basis of mixtures for Thermit welding. The proportions of such mixtures are usually about three parts by weight of iron oxide to one part of aluminum. The theoretical temperature created by this reaction is about 5600°F (3100°C). Additions of nonreacting constituents, as well as heat loss to the reaction vessel and radiation, reduce this temperature to about 4500°F (2480°C). This is about the maximum temperature that can be tolerated, since aluminum vaporizes at 4530°F (2500°C). On the other hand, the maximum temperature should not be much lower because the aluminum slag (Al_2O_3) solidifies at 3700°F (2040°C).

The heat loss depends very much upon the quantity of Thermit being reacted. With large quantities, the heat loss per pound of Thermit is considerably lower and the reaction more complete when compared with small quantities of Thermit.

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[1] *Thermit* is the term commonly used to identify this welding process even though it is a registered trademark. More detailed metallurgical information is presented in the Thermit welding chapter, ASM International's *Metal Handbook*, Vol. 6, 9th Ed., 1985.

[2] See also Chapter 2, "Physics of welding", Vol. 1, 8th Ed., 38-39.

Alloying elements can be added to the Thermit compound in the form of ferroalloys to match the chemistry of the parts to be welded. Other additions are used to increase the fluidity and lower the solidification temperature of the slag.

The Thermit reaction is nonexplosive and requires less than one minute for completion, regardless of quantity. To start the reaction, a special ignition powder or ignition rod is required; both can be ignited by a regular match. The ignition powder or rod will produce enough heat to raise the Thermit powder in contact with the rod to the powder's ignition temperature, which is about 2200°F (1200°C).

The parts to be welded should be aligned properly; the faces to be joined should be free of rust, loose dirt, moisture, and grease. A proper gap must be provided between the faces, the size depending upon the width of the joint. Wider joints normally require a larger gap. A mold, which may be built up on the parts or premanufactured to conform to the parts, is placed around the joint to be welded.

To fabricate a butt joint, the joint faces should be preheated sufficiently to promote complete fusion between the Thermit deposit and the base metal. Even though it is called a welding process, Thermit welding resembles metal casting where proper gates and risers are needed to:

(1) Compensate for shrinkage during solidification
(2) Eliminate typical defects that appear in castings
(3) Provide proper flow of the molten steel
(4) Avoid turbulence as the metal flows into the joint

APPLICATIONS

Rail Welding

THE MOST COMMON application of the process is the welding of rail sections into continuous lengths. It is an effective means of minimizing the number of bolted joints in the track structure. In coal mines, the main haulage track is often welded to minimize maintenance and to reduce excessive coal spillage caused by uneven track. Crane rails are usually welded to minimize joint maintenance and vibration of the building as heavily loaded wheels pass over the joint.

Thermit mixtures are available for all types of rail steels. The majority of rails are C-Mn steels, but Cr, Cr-Mo, Cr-V, Cr-Mn, and Si alloy rail steels are manufactured abroad. Addition of rare earth metals or alloys may decrease the amount of sulfur and phosphorous in the weld deposit, resulting in an improvement in mechanical properties.

Welding with Preheat. Premanufactured molds of split design are generally used for welding standard rail sizes. The mold should be aligned so that its center coincides with the center of the gap between the rail ends. The rail ends are preheated in the range of 1100 to 1800°F (600 to 1000°C) with a gas torch flame directed into the mold as shown in Figure 29.1. A refractory-lined crucible containing the Thermit charge is positioned above the mold halves after preheating is completed. The charge is then ignited, and the molten steel pours into the joint. In most procedures, the metal is fed into the middle of the joint gap (center-poured); in other procedures, the metal enters the sidecup of the mold at the outer leg of the rail base and rises vertically in the center of the joint.

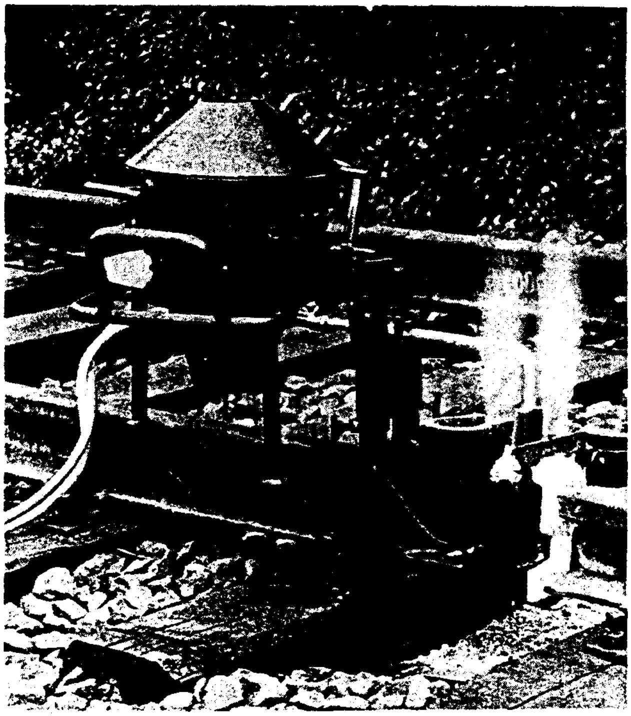

Figure 29.1–Preheating Rail Ends With a Gas Torch Prior to Thermit Welding

A self-tapping seal (thimble) is used in the bottom of the crucible. A few seconds after the Thermit reaction is complete, the molten metal melts the seal and pours out of the bottom of the crucible into the gap between the two rail sections. The lower density liquid slag floats to the top of the Thermit metal in the crucible. It does not reach the mold cavity until all of the molten steel has entered and filled both the cavity between the rail sections and the mold itself. The slag remains on top of the weld and solidifies there. When the metal has solidified, the mold halves are removed and discarded. The excess metal is removed by hand grinding or by hydraulic or manual shearing devices.

Preheating times and temperatures may be reduced by using a larger Thermit charge. The heat dissipated into the work during welding has to be provided by a larger mass of molten steel.

Welding without Preheat. The self-preheating method is designed to eliminate the variables associated with torch preheating and the equipment needed to perform that operation. The rail ends are preheated by a portion of the molten metal produced by the Thermit reaction. The crucible and mold are a one-piece design as shown in Figure 29.2. The molds, commonly known as *shell molds*, are premanufactured of sand, bonded with phenolic resins. They are very light, nonhygroscopic, and moisture-free with a long shelf life. After the Thermit reaction is completed, the molten steel automatically flows from the crucible into the joint rather than passing through the atmosphere, as is the case with a separate crucible.

Figure 29.3, a section through a mold, shows the shape of the cavity in which the molten filler metal flows. There is a hollow chamber in the mold underneath the weld area that receives the first molten metal, allowing it to preheat the rail ends. This metal is called the *preheat metal*. By the time the chamber is filled, sufficient molten metal should have passed over the rail ends to preheat them to the required temperature to assure complete fusion with the base metal. Thermit portions for this process are about twice the size of those used for the external preheat method.

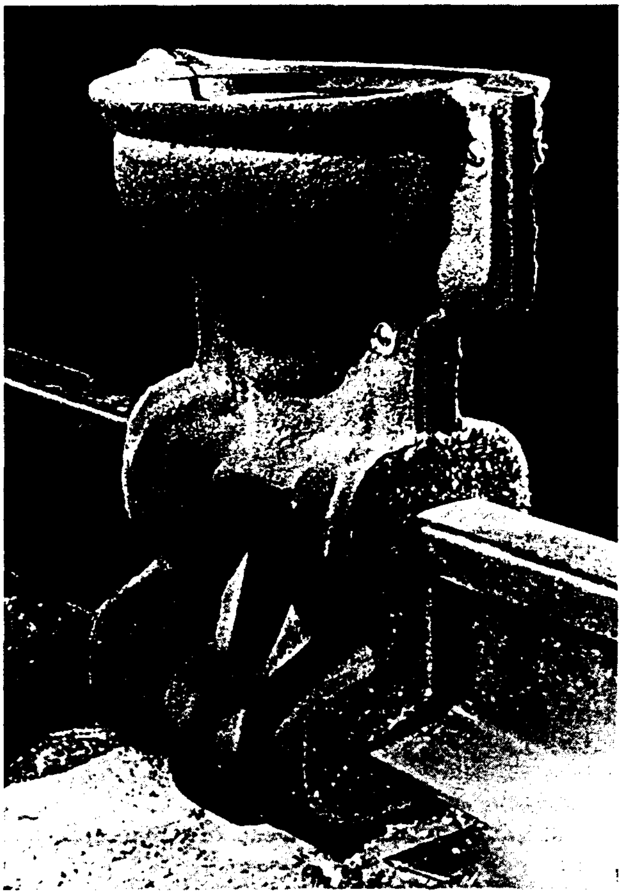

Figure 29.2–Combination Mold-Crucible in Position for Thermit Welding Without Preheat

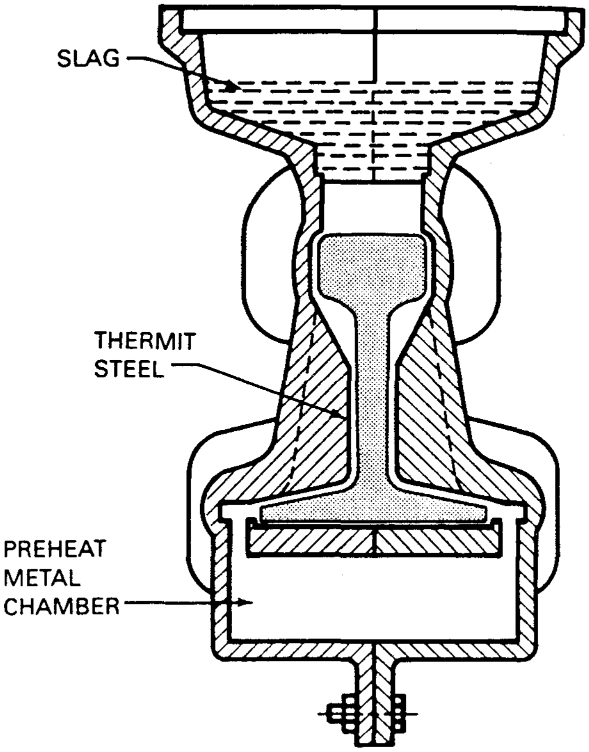

Figure 29.3–Section Through a Mold-Crucible Having a Preheat Metal Chamber

The heat-affected zones in the adjacent rail sections are considerably smaller than when external preheating is used. Figure 29.4 shows a typical section through a Thermit rail weld made with the self-preheating process.

Repair Welding

REPAIR WELDS ARE normally nonrepetitive, and therefore, premanufactured molds are not used. A mold must be made for each weld so that it will conform to the shape of the part.

Preparing the Joint. The pieces to be joined should be properly positioned in contact and aligned for welding. Firm marks should then be made on the pieces outside the area to be covered by the mold box. They will be used to reposition the pieces after the grooved faces are prepared for welding, thus maintaining the original part dimensions. The metal may then be cut with a cutting torch along the line of fracture to provide a parallel-sided gap. The gap

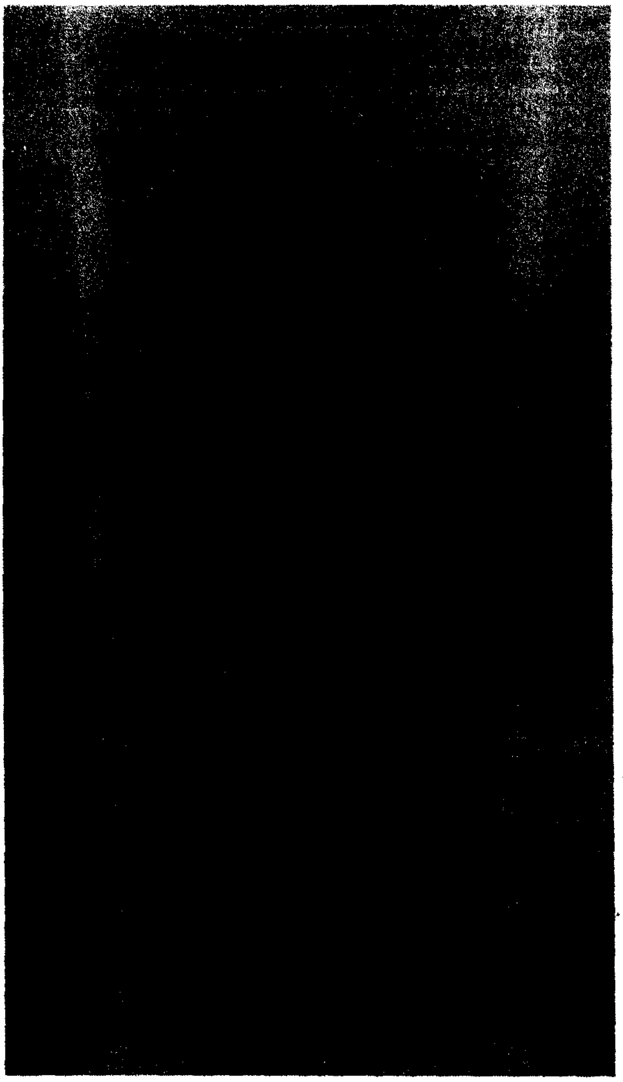

Figure 29.4—Photomacrograph of a Vertical Section Through a Typical Thermit Rail Weld

width depends upon the size of the section to be welded as shown in Table 29.1. All loose oxide and slag from torch cutting, as well as dirt and grease, should be removed from the workpieces where the mold will be located.

To allow for contraction of the weld during cooling, the pieces are initially spaced 1/16 to 1/4 in. (2 to 6 mm) further apart than their original positions, using the markers on the pieces for reference. The exact increase depends upon the size of the weld and the gap length. The amount of contraction allowance required can be judged quite accurately with experience.

Applying the Mold. When a single large weld is to be made, a wax pattern is used to shape the mold cavity at the joint, similar to the investment (lost-wax) casting process. The wax is placed in the gap and on the surfaces of the parts to produce the exact shape desired for the finished weld, including the collar of weld reinforcement. A sand mold is then built up around the pattern using a suitable mold box to contain the mold sand.

Wood patterns of pouring and heating gates and risers are positioned within the mold as it is being rammed. Where two pieces of the same size are to be welded together, the heating gate is centered directly on the wax pattern. If unequal sections are being welded together, the heating gate is directed toward the larger section to provide somewhat uniform heating of the two parts. Where there are one or more high points on a joint of complex cross section, riser gates will be required at all of them. The top of the mold is hollowed out to provide a basin for the slag produced by the thermit reaction. The mold must be adequately vented to facilitate the escape of moisture and other gases during the preheating and welding process. Finally, the wood patterns are removed. Figure 29.5 shows a section through a Thermit weld mold with the crucible in position and ready for welding.

The quality of the molding sand requires special attention. It must have a high melting temperature, high permeability, and adequate shear strength. The sand should be free of clay components with low melting points.

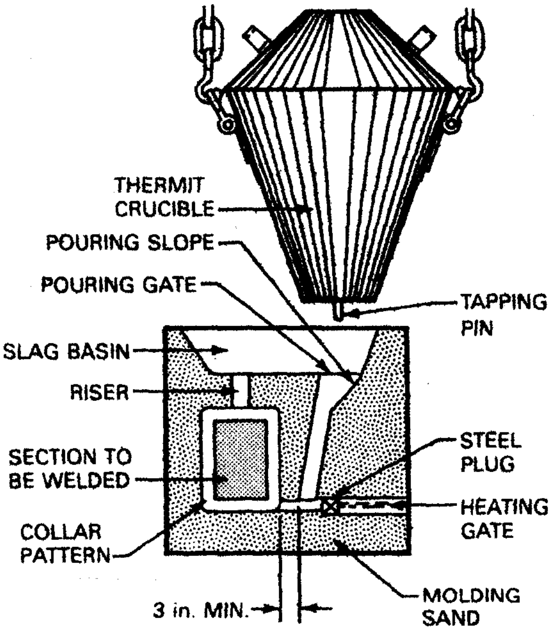

Figure 29.5—Cross Section of a Typical Thermit Mold for Repair Welding With External Preheat

Preheating. Preheating is accomplished by directing a gas flame into the chamber through the heating gate. A torch designed specifically for the purpose may burn propane, natural gas, kerosene, or gasoline.

The initial purpose of preheating is to remove the wax. The heat is applied gradually, and the torch is frequently removed from the heating gate to allow the melted wax to flow out. After the wax has been removed, the heat is gradually increased to preheat the faces of the base metal and thoroughly dry the mold. The mold must be completely dried to avoid weld porosity generated by residual moisture in the molding sand. Preheating is continued until the ends of the parts to be welded are cherry red in color, an indication that their temperature is between 1500°F and 1800°F (800 and 1000°C).

Upon completion of the preheating, the heating gate must be blocked. A short length of steel rod of appropriate diameter is pushed into the gate against a shoulder and then backed with molding sand.

Charging the Crucible. The Thermit reaction, as in the case of rail welding with preheat, takes place in a refractory-lined, cone-shaped crucible as shown in Figure 29.6. A hard refractory (magnesite) stone at the bottom of the crucible holds a replaceable refractory orifice or thimble. The thimble is plugged by inserting a tapping pin through it and then placing a metal disk on top of the pin. The disk is covered with a layer of refractory sand. The Thermit mixture should be placed in the crucible in a manner that will not dislodge the sand layer.

Low carbon steel punchings are sometimes added to the Thermit mixture to augment the metal produced. The quantity of Thermit mixture required for a joint can be calculated by the following equation:

$$X = \frac{E}{0.5 + 0.01S} \tag{29.1}$$

where:

X = quantity of Thermit required
E = quantity of molten steel required to fill the gap, including 10 percent for losses
S = percent of steel punchings to be included in the charge

The quantity X will be in lb when E is in lb and kg when E is in kg.

Approximately 25 lb (11.5 Kg) of Thermit mixture is required for each pound of wax in the pattern.

Making the Weld. The reaction can be initiated by two methods: (1) starting powder that can be ignited by a match or regular gas striker, or (2) an ignition rod.

After the reaction is complete and the action of the molten metal subsides, the crucible is tapped by striking the

Table 29.1
Examples of Thermit Weld Dimensions and Mold Requirements

			Risers		Pouring Gates		Heating Gates		Connecting Gates		
Section Size or Diam., in.	Gap, in.	Collar, in.	No.	Diam., in.	No.	Diam., in.	No.	Diam., in.	No.	Diam., in.	Thermit Req'd[a] lb.
				Rectangular Sections							
2x2	7/16	1-1/2x7/16	1	3/4	1	3/4	1	1-1/4			6
2x4	9/16	1-5/16x9/16	1	3/4	1	1	1	1-1/4			12
4x4	11/16	2-5/8x11/16	1	1	1	1	1	1-1/4			25
4x8	7/8	3-7/16x7/8	1	1	1	1	2[b]	1-1/4			50
8x8	1-1/8	4-5/8x1-1/8	1	1-3/4	1	1-1/4	2[b]	1-1/4	—	—	125
8x12	1-1/4	5-1/2x1-1/4	1	1-3/4	1	1-1/4	1	1-1/4	1	1-1/4	175
12x12	1-7/16	6-1/2x1-7/16	1	2-1/2	1	1-1/2	2[b]	1-1/2	1	1-1/2	300
12x18	1-11/16	7-3/4x1-11/16	1	2-1/2	1	1-1/2	2[b]	1-1/2	1	1-1/2	500
16x16	1-3/4	8-15/16x1-3/4	1	2-3/4	2	2	2	1-1/2	2	1-1/2	700
16x24	2	9-15/16x2	1	2-3/4	2	2	2	1-1/2	2	1-1/2	1150
24x24	2-5/16	11-13/16x2-5/16	2	2-1/2	2	2	2	1-3/4	2	1-3/4	1875
24x36	2-5/8	14-1/8x2-5/8	2	2-1/2	2	2	2	2	4	2	3125
				Round Sections							
2	7/16	1-3/8x7/16	1	3/4	1	3/4	1	1/1/4			5
4	5/8	2-3/8x5/8	1	1	1	1	1	1-1/4			25
8	1	4-3/16x1	1	1-1/2	1	1-1/4	1	1-1/4			75
12	1-5/16	5-7/8x1-5/16	1	1-3/4	1	1-1/2	1	1-1/112	1	1-1/2	200
16	1-5/8	7-1/2x1-5/8	1	2	1	1-1/2	1	1-1/2	1	1-1/2	425

a. Thermit required includes provision for a 10% excess of steel in slag basin for a single pour and a 20% excess for a double pour.

b. Includes one separate back heating gate.

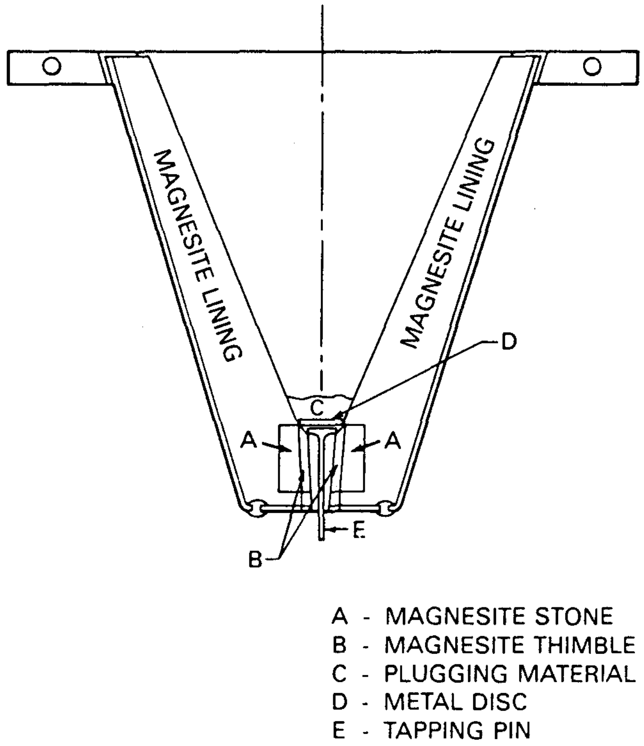

Figure 29.6–Cross Section of a Thermit Crucible

tapping pin with a sharp upward blow. The molten steel flows into the mold and fills the joint.

The mold is stripped away after the weld metal has solidified. Whenever possible, the entire weldment should be annealed to stress relieve it.

If required, the collar around the weld may be removed by machining or grinding. Risers and the gate are removed with an oxyfuel gas cutting torch.

Applications of Repair Welding. Thermit welding is employed in the marine field for repair of heavy sections of ferrous metal such as broken stern frames, rudder parts, shafts, and struts.

Broken necks, pinions, and pinion teeth of sheet and plate rolls are replaced with entirely new pieces, cast or forged slightly oversize to permit machining. They are Thermit welded to the main section.

Badly worn wobblers on the ends of steel mill rolls may similarly be replaced with a sufficiently tough Thermit metal deposit that is machinable. The method is particularly applicable for repairs involving large volumes of metal, where the heat of fusion cannot be raised satisfactorily or efficiently by other means or where fractures or voids in large sections require a large quantity of weld metal.

Thermit welding can be used for the repair of ingot molds at significant savings over replacement: the bottom of the mold can be cut off and completely rebuilt with Thermal metal, or an eroded cavity in the bottom can be filled with Thermit metal. The first method of repair is more sophisticated and requires larger quantities of Thermit, but the life of the ingot mold will be more than doubled. The latter type of repair has to be repeated after every second or third pour.

With large dredge cutters, the blades may be Thermit welded to a center ring. Quantities up to several thousand pounds are poured at one time. In this case, Thermit welding is a production tool rather than a repair method.

Reinforcing Bar Welding

THERMIT WELDING WITHOUT preheat is one way of splicing concrete reinforcing steel bars. Continuous reinforcing bars permit the design of concrete columns or beams smaller in section than when the bars are not welded together.

Two premanufactured mold halves are positioned at the joint in the aligned bars and sealed to them with adhesive compound and sand to avoid loss of molten metal. The arrangements for horizontal and vertical welding are shown in Figure 29.7. A closure disk is located in a well at the base of the Thermit crucible section of the mold. The Thermit powder is placed in the crucible and the reaction initiated. After completion of the reaction, the molten steel melts through the closure disk and fills the gap between the bars. The initial molten steel entering the mold chamber preheats the bar ends as it flows over them into a preheat metal chamber. The molten steel fills the joint gap and completes the weld. Reinforcing bars can be welded by this process in any position with properly designed molds. Thermit welded reinforcing bar specimens tested in tension and bending are shown in Figure 29.8.

As an alternative to welding, reinforcing bars can be joined end-to-end by depositing Thermit metal between a steel sleeve and the enclosed bars. The joint is primarily mechanical. Arrangements for horizontal and vertical connections are shown in Figure 29.9 The sleeve is placed around the abutted bars. Its inside diameter is somewhat larger than the diameter of the bars to provide space for the cast steel. Both the inner surface of the sleeve and the surfaces of the bars are serrated. A graphite or CO_2—cured sand mold is mounted over an orifice in the sleeve through which the molten steel flows into the annular space between the bars and sleeve. The Thermit mix is placed above a metal closure disk within the mold.

Upon ignition of the Thermit powder, molten steel is produced. It melts the metal disk, flows into the annular space between the bars and the sleeve, and then solidifies. About five minutes are required to make a joint with this technique.

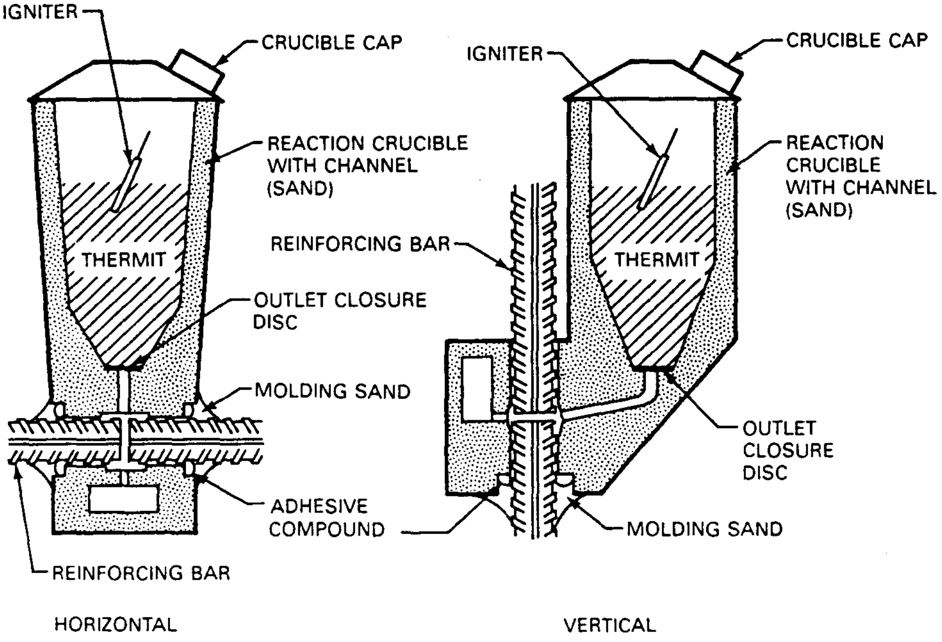

Figure 29.7–Thermit Welding Concrete Reinforcing Steel Bars

Electrical Connections

A THERMIT MIXTURE of copper oxide and aluminum is used for the welding of joints in copper conductors. The reaction between the two materials produces superheated molten copper and slag in one to five seconds. Other metals in the form of slugs or powder can be added to produce alloys for particular applications of the process.

The process is primarily used for welding copper bars, cables, and wires together, as well as copper conductors to steel rails for grounding. For the latter application, a graphite mold is clamped to the rail section at the joint. As soon as the Thermit reaction is complete, the molten copper melts the disk and flows into the joint cavity. It solidifies in a few seconds and creates a weld between the base metal and the copper cable. Then the mold is removed. It can be used again after removing the slag from the reaction chamber.

Heat Treatment of Welds

THE DEVELOPMENT OF high alloy steels and the application of the Thermit process for welding them created a need for special types of Thermit mixtures that produce heat only. Molten metal is not produced. This particular type of Thermit is designed to create sufficient heat for heat-treating purposes.

Using special binders, the Thermit mixture itself is formed to the configuration of the parts to be heat-treated. It keeps its exact shape during and after the

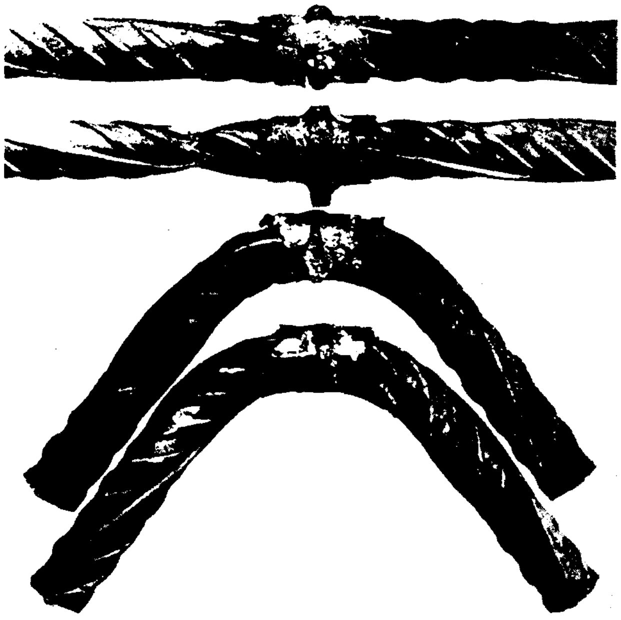

Figure 29.8–Thermit Welded Reinforcing Steel Bars After Tensile and Bend Testing

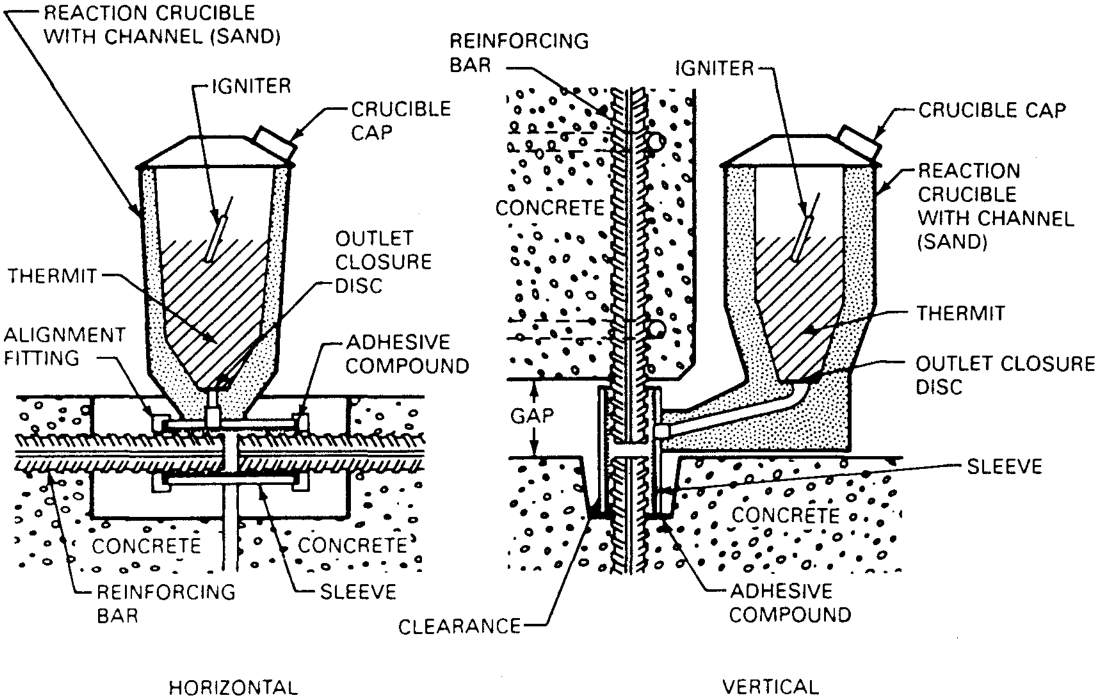

Figure 29.9–Thermit Sleeve Joint for Reinforcing Bars

Thermit reaction. The maximum temperature produced in the part can be adjusted by the design of the Thermit compound. Figure 29.10 shows Thermit blocks in place for heat treating a rail section.

SAFETY

THE PRESENCE OF moisture in the Thermit mix, in the crucible, or on the workpieces can lead to rapid formation of steam when the Thermit reaction takes place. Steam pressure may cause violent ejection of molten metal from the crucible. Therefore, the Thermit mix should be stored in a dry place, the crucible should be dry, and moisture should not be allowed to enter the system before or during welding.

The work area should be free of combustible materials that may be ignited by sparks or small particles of molten metal. The area should be well ventilated to avoid the buildup of fumes and gases from the reaction. Starting powders and rods should be protected against accidental ignition.

Personnel should wear appropriate protection against hot particles or sparks. This includes gloves, full face shields with filter lenses for eye protection, and headgear. Safety boots are recommended to protect the feet from hot sparks. Clothing should not have pockets or cuffs that might catch hot particles.

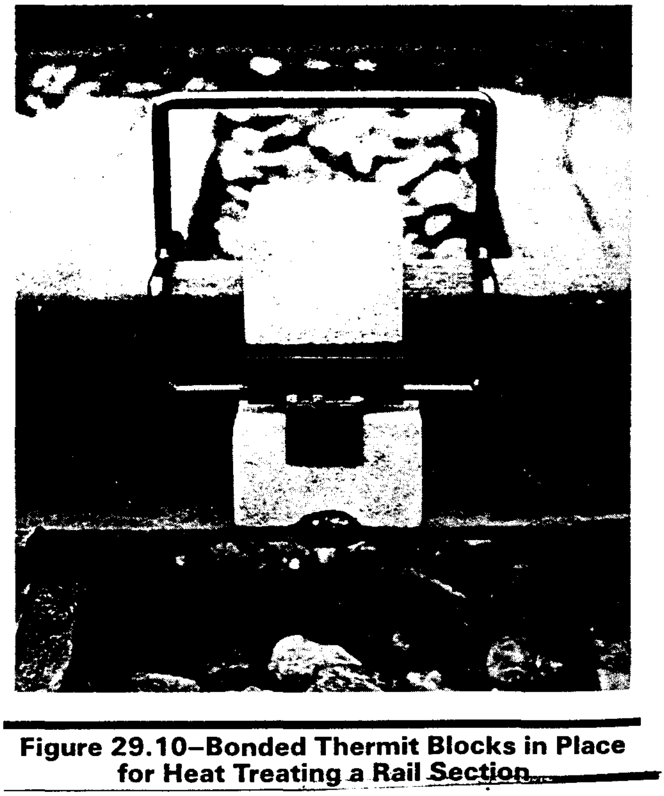

Figure 29.10–Bonded Thermit Blocks in Place for Heat Treating a Rail Section

Preheating should be done taking safety precautions applicable to all oxyfuel gas equipment and operations. For additional information, refer to American National Standard Z49.1, *Safety in Welding and Cutting.*[3]

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[3] Available from the American Welding Society.

COLD WELDING

FUNDAMENTALS OF THE PROCESS

Definition and General Description

COLD WELDING (CW) is a solid-state process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. A characteristic of the process is the absence of heat, either applied externally or generated by the welding process itself. A fundamental requisite for satisfactory cold welding is that at least one of the metals to be joined is highly ductile and does not exhibit extreme work-hardening. Both butt and lap joints can be cold welded. Typical joints are shown in Figure 29.11.

Materials Welded

METALS WITH FACE-CENTERED cubic (FCC) lattice structure are best suited for cold welding, provided they do not work-harden rapidly. Soft tempers of metals such as aluminum and copper are most easily cold welded. It is more difficult to weld cold-worked or heat-treated alloys of these metals. Other FCC metals that may be cold welded readily are gold, silver, palladium and platinum.

The joining of copper to aluminum by cold welding is a good application of the process, especially where aluminum tubing or electrical conductor grade aluminum is joined to short sections of copper to provide transition joints between the two metals. Such cold welds are characterized by substantially greater deformation of the aluminum than the copper because of the difference in the yield strengths and work-hardening behaviors of the two metals.

Dissimilar Metal Welds

NUMEROUS DISSIMILAR METALS may be joined by cold welding whether or not they are soluble in one another. In some cases, the two metals may combine to form intermetallic compounds. Since cold welding is carried out at room temperature, there is no significant diffusion between dissimilar metals during welding. The alloying characteristics of the metals being joined do not affect the manner in which the cold welding operation is carried out. However, interdiffusion at elevated temperatures can affect the choice of postweld thermal treatments and the performance of the weld in service.

Welds made between metals that are essentially insoluble in each other are usually stable. Diffusion can form an intermetallic compound at elevated service temperatures. In some cases, this intermetallic layer can be brittle and cause a marked reduction in the ductility of the weld. Such welds are particularly sensitive to bending or impact loading after an intermetallic layer has formed.

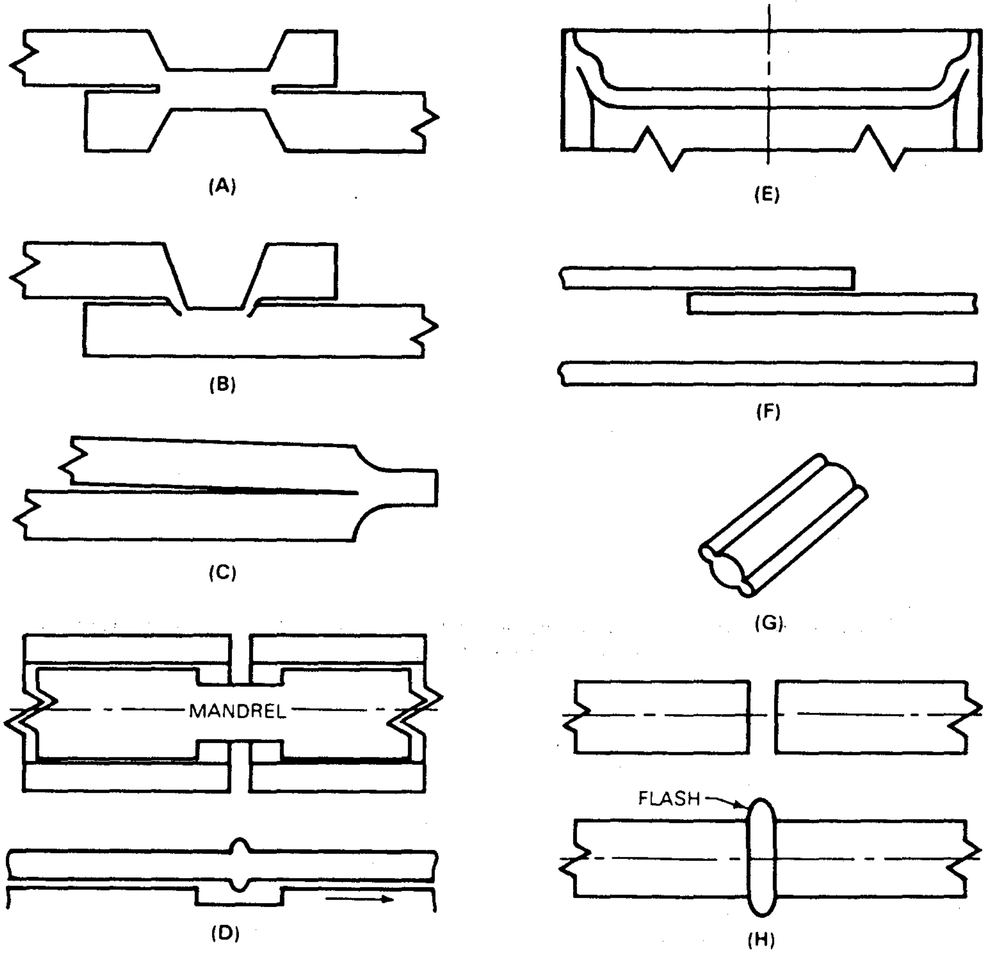
The rate at which intermetallic compounds form depends upon the specific diffusion constants for the particular metals in the weld as well as the time and temperature of exposure. Thus, bimetal cold weldments require careful consideration of the diffusion couple and the service environment. For example, a layered structure forms at the interface in an aluminum-copper weldment at elevated temperatures as shown in Figure 29.12. The layered structure contains a brittle Al-Cu intermetallic compound that weakens the weldment. Figure 29.13 shows how rapidly the thickness of the diffused zone increases at high service temperatures. Mechanical tests have shown that the strength and ductility of the joint decrease when the thickness of the interfacial layer exceeds about 0.002 in. (0.05 mm). Consequently, aluminum-copper cold welds should be used only in applications where service temperatures are low and peak temperatures seldom, if ever, exceed 150°F (65°C).

Metallurgical Structure

IN BUTT JOINTS, the lateral flow of metal between the dies during upset produces a cross-grained structure adjacent to the interface of the weld, as shown in Figure 29.14. This cross-grained material is essentially a narrow transverse section in the weldment. The presence of this section is not important in metals that are essentially isotropic, such as aluminum and some aluminum alloys. In nonisotropic metals, fatigue or corrosion resistance may be substantially lower at the welded joint.

Surface Preparation

COLD WELDING REQUIRES that clean metal faces come into intimate contact for a satisfactory joint. Proper surface preparation is necessary to assure joints of maximum strength. Dirt, absorbed gas, oils, or oxide films on the



(A) LAP WELD, BOTH SIDES INDENTED; (B) LAP WELD, ONE SIDE INDENTED; (C) EDGE WELD, BOTH SIDES INDENTED; (D) BUTT JOINT IN TUBING, BEFORE AND AFTER WELDING; (E) DRAW WELD; (F) LAPPED WIRE, BEFORE AND AFTER WELDING; (G) MASH CAP JOINT; (H) BUTT JOINT IN SOLID STOCK, BEFORE AND AFTER WELDING.

Figure 29.11–Contour of Typical Cold Welded Joints

surface interfere with metal-to-metal contact and must be removed to obtain strong welds.

The best method of surface preparation for lap welds is wire brushing at a surface speed of about 3000 ft/min (15.2 m/s). A motor-driven rotary brush of 0.004 in. (0.1 mm) diameter stainless steel wire is commonly used. Softer wire brushes may burnish the surface; coarser types may remove too much metal and roughen the surface. The surfaces should be degreased prior to brushing to avoid contamination of the wire brushes. It is important that the clean surface not be touched with the hands because grease or oil on the faying surfaces impairs the formation of a strong joint. Welding should take place as soon as practical after cleaning to avoid interference with bonding from oxidation. In the case of aluminum, for example, welding should be done within about 30 minutes.

Chemical and abrasive cleaning methods have not proved satisfactory for cleaning surfaces to be joined by cold welding. The residue from chemical cleaning or abrasive particles embedded in or left on the surface may prevent the formation of a sound weld.

EQUIPMENT

PRESSURE FOR WELDING may be applied to overlapped or butted surfaces with hydraulic or mechanical presses, rolls, or special manual or pneumatically operated tools. A hand tool of the toggle cutter type is suitable for very light work.

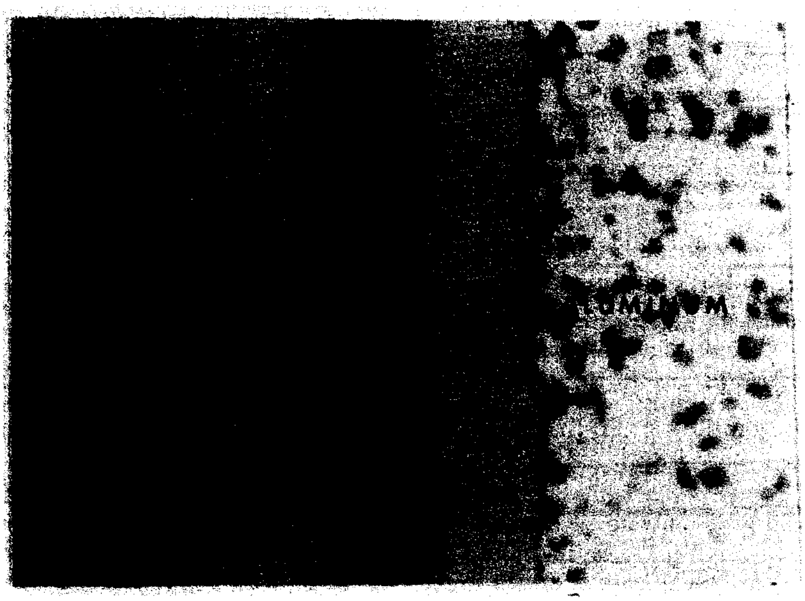


Figure 29.12—Layered Structure in an Aluminum-Copper Cold Weld After Exposure at 500°F (260°C) for 60 Days

A common manually operated press, as shown in Figure 29.15, may be used for medium size work. Heavy work requires power operated machines. The rate of pressure application does not usually affect the strength or quality of the weld.

Regardless of how pressure is applied, the proper indentation for lap welds is important. The indentation may take the form of a narrow strip, a ring, or a continuous seam. Typical weld indentor configurations used for cold welding are presented in Figure 29.16. The selection of indentation configuration is largely determined by the desired appearance and performance characteristics.

The bar type indentation, Figures 29.16(A) and (B), causes metal deformation along both of its sides. Indentation in the form of a ring, Figure 29.16(C), may cause undesirable curvature of the sheet surfaces. A ring weld may

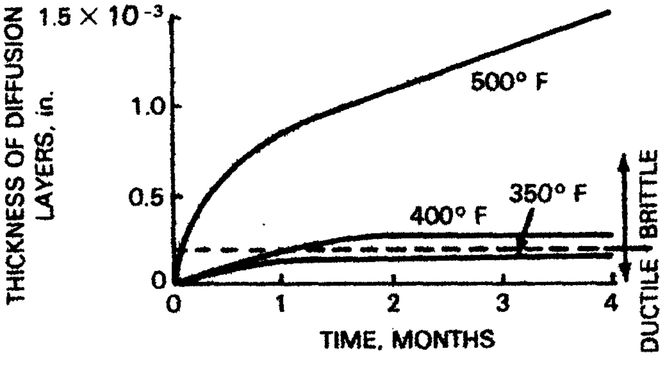


Figure 29.13—Change in Thickness of the Diffusion Layer in Aluminum-Copper Cold Welds With Time at Three Elevated Temperatures

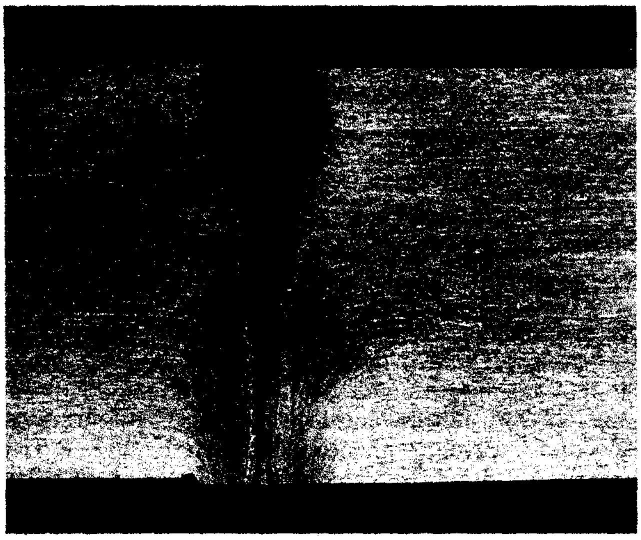


Figure 29.14—Transverse Flow Lines in a Cold Welded Butt Joint

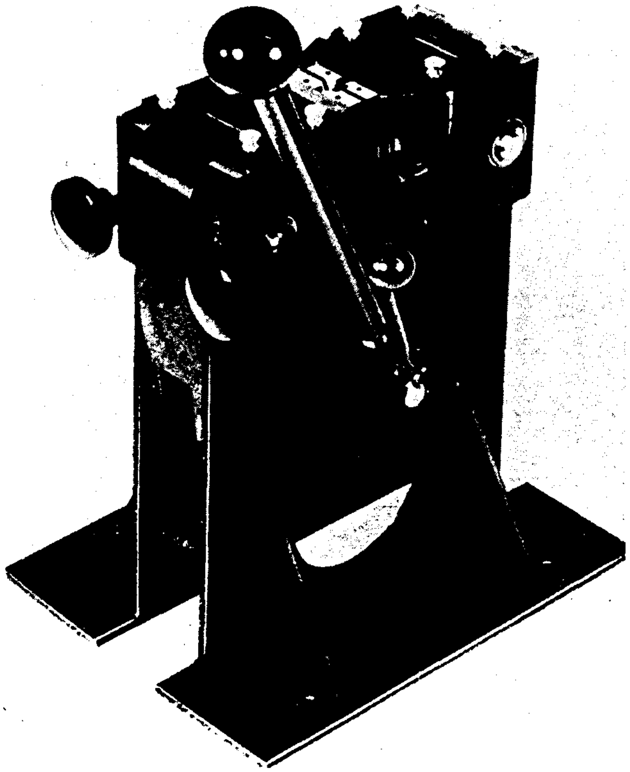


Figure 29.15–A Manually Operated Cold Welding Machine

have a smooth convex dome of metal within the ring. This dome is formed when the metal is forced from between the dies as pressure is applied. Continuous seam welding, Figure 29.16(E), can be employed in the manufacture of thin-wall tubing or lap welds in sheet.

Symmetrical dies that indent both sides of the joint, Figures 29.11(A) and (C), are generally used. If one surface must be free of indentation, a flat plate or anvil may be used on one side to produce the weld shown in Figure 29.11(B). Thinner gages of sheet metal or wire can be cold welded using simple dies mounted in hand-operated tools.

Draw welding is a form of lap welding used to seal containers. Both the lid and the can are flared before welding. The components are placed in a close fitting die. A punch forces the components into the die which cold welds the flared metal as it is drawn down over the punch. Figure 29.11(E) illustrates such a joint.

Dies are usually subjected to high pressures and should be made of tool steel hardened to about 60 Rockwell C. Pressures of from 150 to 500 ksi (1000 to 3400 MPa) are required to weld aluminum depending upon alloy composition and temper. Copper requires pressures that may be two to four times greater than those required for aluminum. Aluminum can be cold welded to copper using specially designed dies to compensate for the difference in yield strengths.

BUTT JOINTS

COLD WELDING IS commonly used to produce butt joints in wire, rod, tubing, and simple extruded shapes of like and unlike metals. Figures 29.11(D) and (H) illustrate butt joints in tubing and solid forms. The weld can be as strong as the base metal when correct procedures are used.

Preparation for Welding

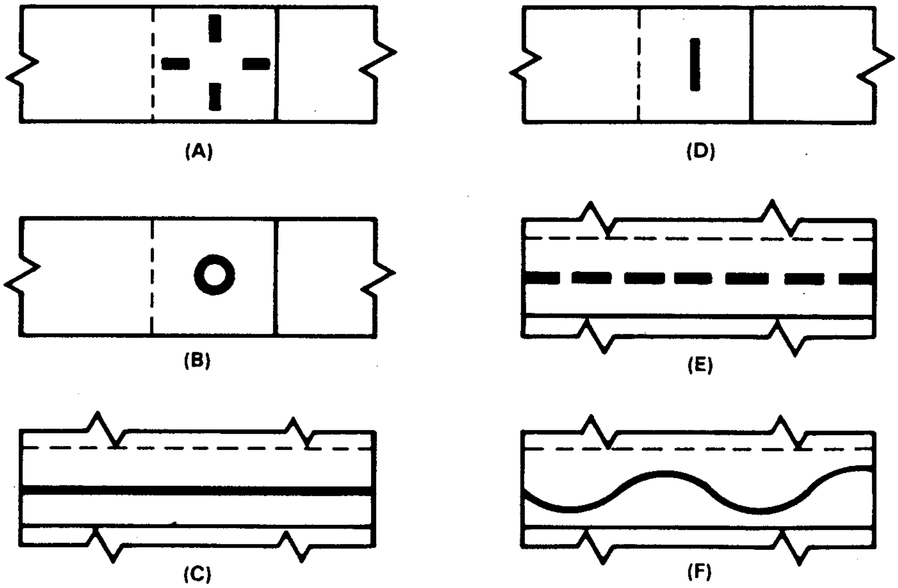
A SHORT SECTION is usually sheared from the ends of the parts to be joined to expose fresh clean surfaces. The shear should be designed to produce square ends so that the parts do not deflect from axial alignment as welding force is applied. During shearing, a thin film of a particular metal being cut can accumulate on the shear blades. If the shear is then used to cut a different metal, accumulated metal on the blade may transfer to the cut surface and inhibit welding. Therefore, the shear blades should be cleaned before shearing parts of another metal for cold welding.

It is not usually necessary to degrease parts to be cold welded before shearing if the residual film of lubricant is very thin. However, degreasing may be necessary if there is a heavy oil film on the metal to avoid contamination of the cut surfaces and to prevent the parts from slipping in the clamping dies. The best practice is to clean before shearing.

Welding Procedure

THE PARTS SHOULD be positioned in the clamping dies with sufficient initial extension of each part between the dies to ensure adequate upset to produce a satisfactory weld. However, extension of the parts should not be excessive or the parts may bend instead of upsetting. The upsetting force will cause the parts to bend or assume an S-shaped curve, as shown in Figure 29.17, if the initial die opening is too large. The ends can deflect and slide past one another when force is applied if the projecting length of each part exceeds about twice the thickness or diameter of the parts. In other words, the initial opening between the dies should be no greater than four times the diameter or thickness of the parts. This distance is the maximum total upset that can be used to effect welding. The minimum upset distance varies with the alloy being joined.

The welding dies should firmly grip the parts to prevent slippage when the upset force is applied. Any slippage will reduce the amount of upset. For a firm grip, the dimensions of the parts are critical so that the dies can nearly close to hold each part securely. The allowable tolerance depends on (1) the design of the die and die holder, and (2) the gripping surface finish. Deep knurling on the gripping



(A) AND (B), BAR TYPE; (C) RING TYPE; (D), (E), AND (F), INTERMITTENT AND CONTINUOUS SEAM TYPES

Figure 29.16–Typical Lap Weld Indentor Configurations Used in Cold Welding

surfaces will indent into the part. The allowable tolerance for round parts is about 3 percent of the part diameter.

Somewhat wider tolerances are permissible for rectangular-shaped parts because the dies usually bear on only two sides. The gap between the closed grips must, however, be small to obtain uniform upsetting of metal. It should be no more than about 10 percent of the part thickness.

The application of upset force causes the metal between the dies to upset laterally as illustrated in Figure 29.18. This lateral flow of metal:

(1) Breaks up the oxide film present on the abutting surfaces and carries most of it away from the joint surface
(2) Enables oxide-free metal on one side of the interface to achieve intimate contact with oxide-free metal on the other side
(3) Provides the energy that enables the contacting surfaces to achieve a metallurgical bond with one another

Thus, all requirements needed to form a metal bond are fulfilled, and a metallurgical union forms. The flash formed by the lateral flow of metal can be pinched off by the dies as they close together.

Cold welds are usually insensitive to the rate of upsetting of the metal, within limits. Regardless of upset speed, welding will take place if there is sufficient upset.

Multiple Upset

THE AMOUNT OF upset required to produce a full-strength weld in some alloys sometimes exceeds that which can be provided in one step because of a limitation on part extension. If an initial upset will produce a bond of sufficient strength to hold the parts together, additional upset can be applied to produce a full-strength weld by repositioning the weldment in the dies. Surface preparation prior to welding is relatively unimportant when a multiple upset-

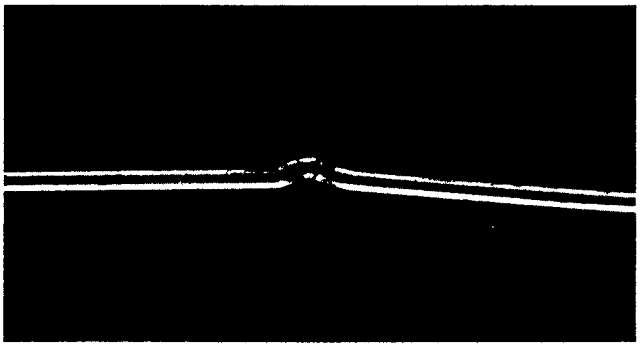


Figure 29.17–Bending Produced During Upset From Excessive Projecting Lengths

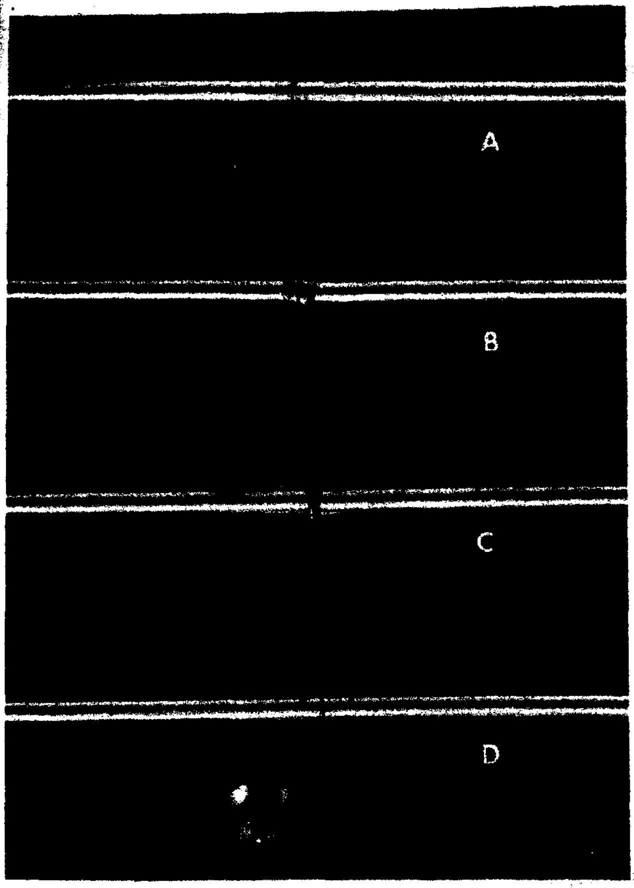


Figure 29.18—States of Upset During Butt Cold Welding

ting technique is used. This technique will completely displace contaminants from the interface.

Single upset welding is not normally used for welding butt joints in wires smaller than 3/16 in. (4.8 mm) in diameter. A cross section of a single upset butt joint in type 1100 aluminum wire is shown in Figure 29.19. Compare this weld with the multiple upset weld in Type 1100 aluminum alloy illustrated in Figure 29.20. The multiple upset, offset-flash technique is commonly used in wire drawing to splice 0.025 to 0.128 in. (0.64 to 3.25 mm) diameter wires as well as those aluminum alloy wires that cannot be welded effectively with single upset. Figure 29.21 illustrates the various stages involved in making a multiple upset butt weld between strips.

Offset Welds

FIGURE 29.22 ILLUSTRATES a cold weld being made in a die designed to produce an offset flash. This technique will produce a discontinuous flash that is easy to remove as well as a weld joint that is at an angle to the wire axis. The weld joint being at an angle to the axis will be less influenced by discontinuities in the weld.

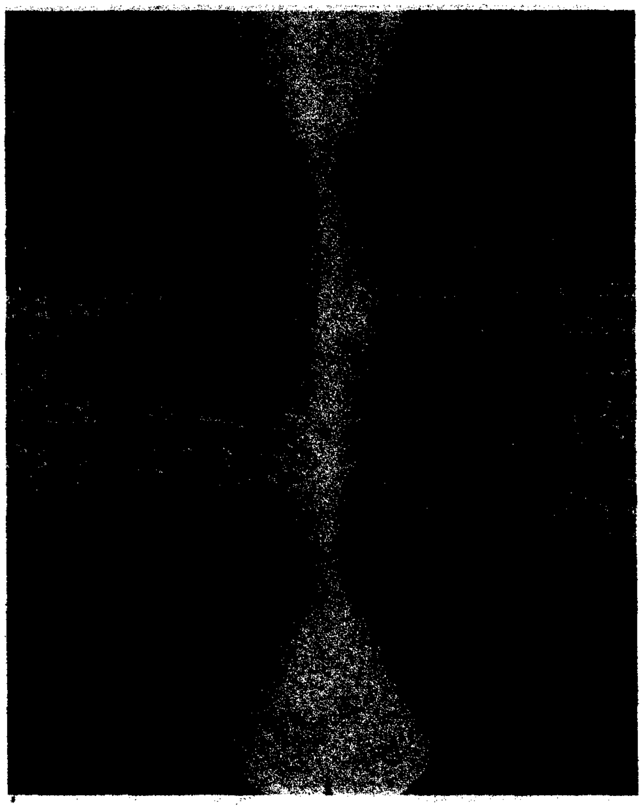


Figure 29.19—Single Upset Cold Weld in Type 1100 Aluminum Wire

Application

COLD WELDED BUTT joints are used in the manufacture of aluminum, copper, gold, silver, and platinum wire. The most common use is to join successive reels of wire for continuous drawing to smaller diameters. Butt joints are also used to repair breaks in the wire that occur during the drawing operation. Diameters ranging from 0.0025 to 0.50 in. (0.06 to 12.7 mm) have been welded successfully. The aluminum alloys that have been welded with good results include Types EC, 1100, 2319, 3003, 4043, all of the 5000 series, 6061, and 6201. With most of these alloys, the as-welded wire can be drawn successfully to smaller diameters after removal of the flash. Cold welded joints in wire of very high-strength alloys, such as Types 2014 and 7178, usually must be annealed to prevent breaks during subsequent drawing operations. Aluminum alloys that contain lead and bismuth (Types 2011 and 6262) are difficult to cold weld.

Figure 29.20—Multiple Upset Cold Weld in Type 1100 Aluminum Wire Using an Offset Flash Technique

Where welding is permitted by ASTM Specifications, cold welding is used to join successive lengths of wire to permit stranding of long lengths of multiple-strand electrical conductors. The weld flash is removed, and the weld is dressed with a file or suitable abrasive to obtain a smooth, uniform appearance.

Welds in annealed wire of any of the weldable aluminum alloys exhibit tensile strengths exceeding 95 percent of the base metal. In cold-worked Type EC or 5005 aluminum wire and heat-treated Type 6201 wire, weld efficiencies of 92 to 100 percent are attained. In bend testing, the welded joint can be bent or twisted about half as many times before failure as unwelded wire of the same alloy.

Seven-strand No. 4 AWG aluminum alloy conductors with a cold weld in one strand have shown the same breaking strength as similar conductors without welded strands. Types EC, 5005, and 6201 aluminum alloys were used in making these tests.

For copper wire, work hardening at the cold weld increases the metal strength to that of the drawn wire.

LAP WELDING

Procedures

LAP WELDS CAN be used for joining aluminum sheet or foil to itself and also to copper sheet or foil. Pressure is applied to the lapped parts by dies that indent the metal and cause it to flow at the interface. This pressure ranges between 150 and 500 ksi for aluminum, depending upon the compressive yield strength of the alloy being welded. Excellent lap welds can be produced in nonheat-treatable aluminum alloys, such as Types EC, 1100, and 3003. However, aluminum alloys containing more than three percent magnesium, the 2000 and 7000 series of wrought alloys, and castings are not readily lap welded.

Table 29.2 gives recommended deformations and typical joint efficiencies for lap welds in several common aluminum alloys. For most alloys, joint strength is maximum when deformations between 60 and 70 percent are used. It is apparent that the intrinsic strength of the weld may increase at deformations exceeding 70 percent, but the overall strength of the assembly is decreased. Lap welds exhibit good shear and tensile strengths but have poor resistance to bending or peel loading.

Equal deformations can be achieved when lap welding aluminum to copper or welding dissimilar aluminum alloys together by using dies with the bearing areas approximately in inverse proportion to the compressive yield strength of each metal.

Applications

COMMERCIAL APPLICATIONS OF lap welding are shown in Figures 29.23 and 29.24. They include packaging as well as electrical applications. The latter is probably the field in which lap welding finds the greatest application. It is especially useful in the fabrication of electrical devices in which

Table 29.2
Lap Type Cold Welds in Selected Aluminum Alloys

Alloy	Temper	Recommended Deformation, %	Joint Efficiency, %
3003	0	50	85
3003	H14	70	70
3003	H16	70	60
3003	H18	60	55
3004	0	60	60
3004	H34	55	40
5052	0	60	65
5052	H34	60	45
6061	T6	60	50
7075 Alclad	T6	40	10

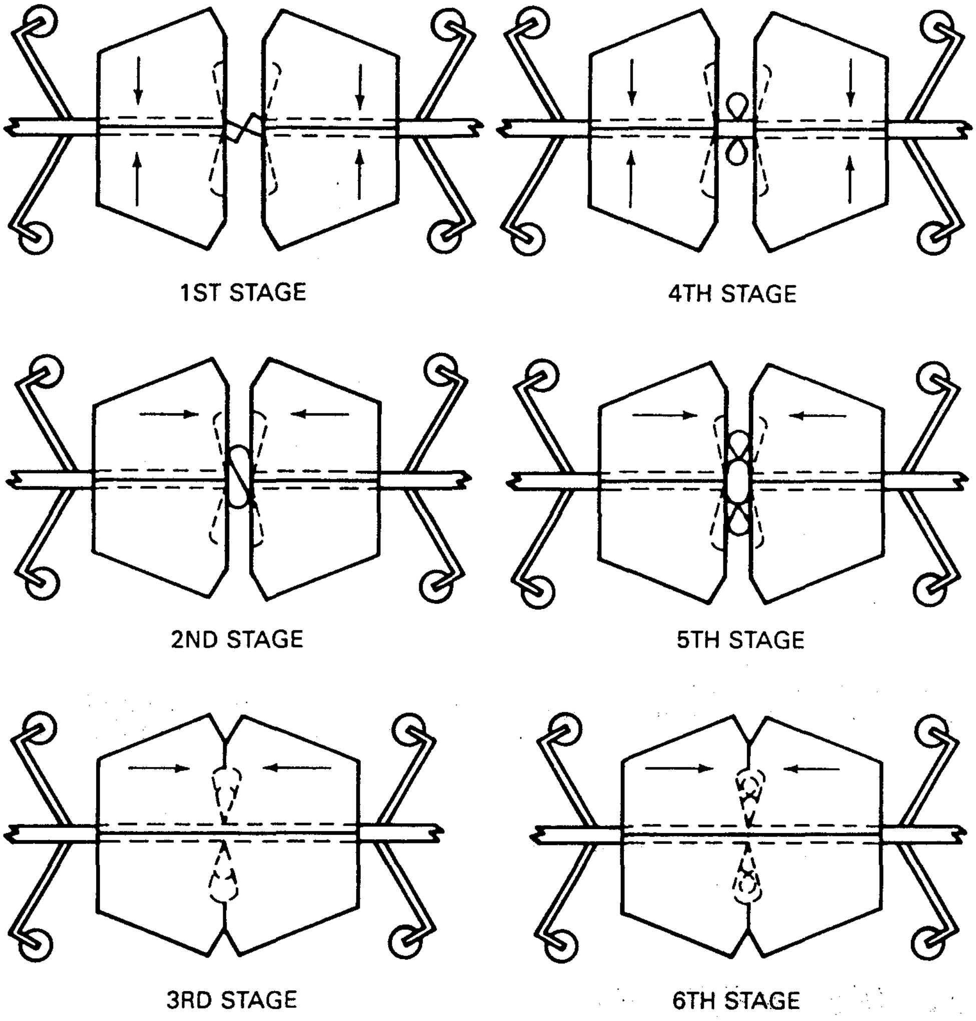


Figure 29.21–Stages in Multiple Upset Welding of Butt Joints Between Strips

a transition from aluminum windings to copper terminations is required. The range of electrical applications covers large distribution transformers to small electronic devices.

A variation of cold lap welding is the sealing of commercially pure aluminum, copper, or nickel tubing by pinching it in two between two dies. The tubing is placed transversely between two radius-faced linear dies. As the dies are forced together, the tubing is pinched flat against itself. As the force on the dies is increased, the metal between the dies is upset and extruded from between them as in lap welding. The force is increased until the tube walls are cold welded together and then finally parted in two across the midpoint of the weld. As with sheet, the interior of the tubing must be clean to accomplish a leak-free weld across the flattened tube.

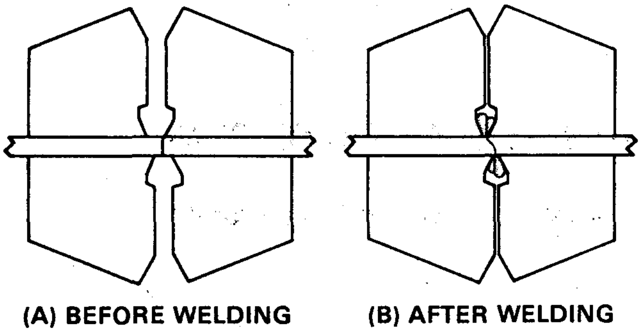


Figure 29.22–Cold Welding of Wire With an Offset Flash Technique

Figure 29.23–Application of Cold Welding in the Manufacture of an Electrical Component

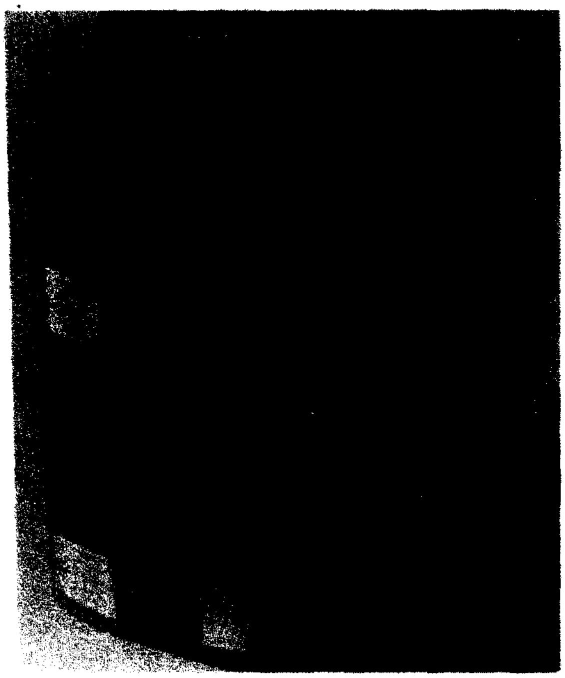


Figure 29.24–Application of Cold Welding in the Manufacture of Industrial Packaging

The die face radius and width must be designed to accomplish cold welding and ultimately cut the tubing in two. The opposing dies must be carefully aligned for welding. The face radius is the key to successful cold welding and must be determined experimentally for the metal and tube wall thickness.

HOT PRESSURE WELDING

DEFINITION

HOT PRESSURE WELDING (HPW) is a solid-state welding process that produces coalescence of metals with heat and application of pressure sufficient to produce macro deformation of the work pieces. Vacuum or other shielding media may be used.

PRESSURE GAS WELDING (PGW)

Definition and General Description

PRESSURE GAS WELDING[4] is an oxyfuel gas welding process which produces a weld simultaneously over the entire faying surfaces. The process is used with the application of pressure. No filler metal is used. The two variations of the process are the closed joint and open joint methods. In the closed joint method, the clean faces of the parts to be joined are abutted together under moderate pressure and heated by gas flames until a predetermined upsetting of the joint occurs. In the open joint method, the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. Both methods are easily adapted to mechanized operation. Pressure gas welding can be used for welding low and high carbon steels, low and high alloy steels, and several nonferrous metals and alloys.

In the closed joint method, since the metal along the interface does not reach the melting point, the mode of welding is different from that of fusion welding. Generally speaking, welding takes place by the action of grain growth, diffusion, and grain coalescence across the interface under the impetus of high temperature [about 2200°F

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[4] More detailed information is presented in Chapter 22, *Welding Handbook*, Section 2, 5th Ed., 1963.

Figure 29.25–Typical Pressure Gas Welds in 1 in. (25 mm) and 1-1/4 in. (32 mm) Diameter Steel Bars

(1200°C) for low carbon steel] and upsetting pressure. The welds are characterized by a smooth-surfaced bulge or upset, as shown in Figure 29.25, and by the general absence of cast metal at the weld line.

In the open joint method, the joint faces are melted, but the molten metal is squeezed from the interface to form a flash when the joint is upset. These welds resemble flash welds in general appearance.

Principles of Operation

Closed Joint Method. The faces to be welded are butted together under initial pressure to assure intimate contact. The metal at the joint is then heated to welding temperature with a gas flame. Finally, the metal is upset sufficiently to produce a weld.

Heating is generally done with water-cooled, multiflame oxyacetylene torches. These torches are designed to generate sufficient heat and distribute it uniformly throughout the entire section to be welded. For sections over 1 in. (25 mm) thick, it is advisable to heat the joint uniformly from all sides as shown in Figure 29.26.

Solid or hollow round sections, such as shafts or piping, are usually welded with circular ring torches. The torch head may be a split type for easy loading and removal of work from the welding machine. A typical head of this type for welding 2.5 in. (63.5 mm) diameter tubing with a 0.25 in. (6.4 mm) wall thickness is shown in Figure 29.27. More elaborate heating heads are required for more complicated shapes. They should conform to the shape of the part to provide uniform heating.

Figure 29.26–Torch Arrangement for Pressure Gas Welding a Type 321 Stainless Steel Ring With 1-7/8 by 2-5/8 in. (50 X 70 mm) Cross Section

Figure 29.27–Split Annular Torch for Pressure Welding Piping, Tubing or Solid Rounds

The apparatus for pressure gas welding must be designed to apply the desired pressure and maintain alignment during welding. Provision for maintaining uniform pressure is essential.

The quality and type of end preparation of the parts to be welded depend upon the type of steel. In general, the abutting ends should be machined or ground to a smooth, clean surface. Freedom from oil, rust, grinding dust, and other foreign material is of great importance.

The geometry of the abutting faces depends upon the application and the alloy. Some control of the shape of the upset metal can be obtained by beveling one or both of the parts. Figure 29.28 illustrates typical joint preparations for pressure gas welding and the effect of beveling on the shapes of the completed welds.

For illustration, assume that two 5 in. (125 mm) diameter by 1/4 in. (6.4 mm) wall steel pipes are to be pressure gas welded end-to-end using a butt joint. The general procedures are as follows: A split torch head that will provide small oxyacetylene flames for the full circumference of the joint is selected. The head is mounted in the same plane as the interface with provision for axial oscillation. The abutting ends of the pipe are beveled to an included angle of 6 to 10 degrees with a smooth, clean finish. The pipes are placed in the machine and aligned. Then a force of 5850 lbs (2650 Kg) is applied to produce a low compressive pressure of 1500 psi (10 MPa).

While this force is maintained, the torch flames are oscillated axially a short distance across the weld joint. As the joint heats up, the metal will upset. The joint faces will close together preventing oxidation at higher temperatures. As the metal temperature increases, the compressive strength of the steel decreases and the joint begins to upset uniformly. At this time, the metal is at welding temperature throughout its full thickness and an upsetting pressure of 4000 psi (28 MPa) is applied until the weld zone is upset for a distance of 0.188 in. (4.8 mm). The torches may then be extinguished and the assembly removed from the machine.

There are a few variations of this basic procedure, the principal one being the sequence of pressure application. These variations are introduced to meet special require-

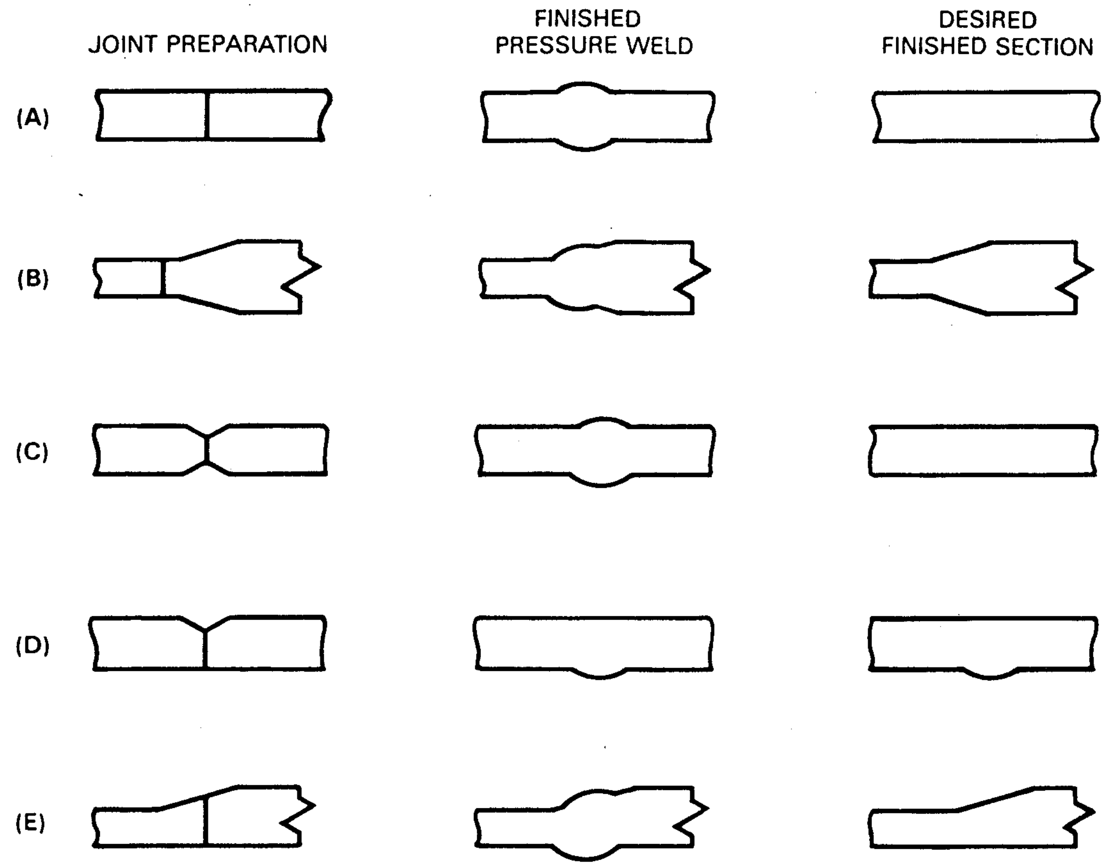


Figure 29.28–Joint Designs for Pressure Gas Welding

ments of certain metals such as high carbon steels, high chromium steels, and nonferrous metals. For example, the constant pressure method is recommended for welding high carbon steel parts.

Another variation of the basic method is applicable to high chromium steels and some nonferrous metals. A high initial pressure in the range of 6000 to 10 000 psi (40 to 70 MPa) is applied before heating is started and is maintained until the metal in the weld zone starts to upset. This high pressure forces the joint faces together to prevent oxidation. Pressure is then decreased until welding temperature is reached when the high pressure is again applied to upset the joint.

Examples of typical pressure cycles used for pressure gas welding several metals are given in Table 29.3. Table 29.4 gives the average dimensions of closed joint pressure welds in parts of various thicknesses.

The quality of a weld depends to an important degree upon proper upsetting during the welding operation. The upset distance or shortening of the weld zone increases with metal thickness. Recommended amounts of upset are given in Table 29.4. These values are usually measured from fixed points on the parts or the welding machine.

Open Joint Method. Machines for open joint pressure gas welding must provide more accurate alignment and be of rugged construction to withstand rapidly applied upset forces. Machines similar to those used for flash welding are suitable.

The most satisfactory heating head is a flat, multiflame type burner, such as the one shown in Figure 29.29, that produces a uniform flame pattern conforming to the cross section of the members to be welded. Good alignment of the heating head with the faces of the joint is important to minimize oxidation and to obtain uniform heating and subsequent upsetting. A removable spacer block can be used during alignment.

Saw cut surfaces are satisfactory for welding since the ends are thoroughly melted before the weld is consummated. A thin layer of oxide on the joint faces has little effect on weld quality, but major amounts of foreign substances, such as rust or oil, should be removed before welding.

Table 29.3
Typical Upset Pressure Cycles for Pressure Gas Welds

		End pressure, psi (MPa)		
Type of metal	Method	Initital	Intermediate	Final
Low carbon steel	Closed joint	500-1,500 (3-10)	. . .	4,000 (28)
High carbon steel	Closed joint	2,700 (19)	. . .	2,700 (19)
Stainless steel	Closed joint	10,000 (69)	5,000 (34)	10,000 (69)
Monel alloy	Closed joint	6,500 (45)	. . .	6,500 (45)
Steel (carbon and alloy)	Open joint	. . .	. . .	4,000-5,000 (28-34)

The general procedure for open joint pressure gas welding is to align the parts with a suitable torch tip properly spaced between the joint faces (Figure 29.29). When thin sections are welded, the torch tip is placed just outside the joint with the flames directed at the joint faces. The tip is designed to heat the full cross section of the faces. The flames are maintained in this position until a molten film entirely covers both faces. The torch is then withdrawn, and the parts are rapidly brought together with a force that will produce a constant pressure of 4000 to 5000 psi (28 to 35 MPa) at the interface. This step is shown in Figure 29.30. Pressure is maintained until upsetting of the metal ceases. The total upset is controlled by both the applied pressure and the temperature of the hot metal. It is not preset on the equipment.

Equipment

Machines. The apparatus for pressure gas welding comprises:

(1) Equipment for applying upsetting force

(2) Suitable heating torches and tips designed to provide uniform and controlled heating of the weld zone

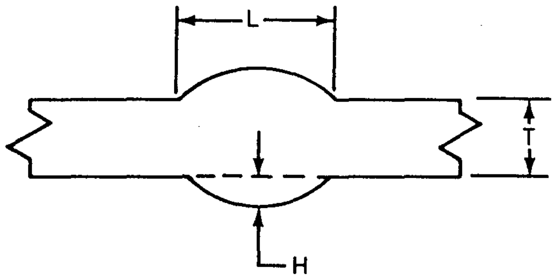
(3) Necessary indicating and measuring devices for regulating the process during welding

The complexity of the machine depends upon the configuration and size of the parts to be welded and the degree to which the process is mechanized. In most cases, it is advisable to use special heating torches and tips as well as special apparatus for gripping and applying force to the parts.

Figure 29.31 illustrates a simple, manually operated gas pressure welding machine capable of welding bars and tubes up to 3 in. (76 cm) in diameter.

Auxiliary Equipment. Some auxiliary equipment is necessary. The gas supply must be adequate for the maximum flow requirement, and the gas regulators must be capable of maintaining a uniform flame adjustment. Quick-acting gas shut-off valves are very desirable. In many instances, needle valves are advantageous for fine adjust-

Table 29.4A
Joint Dimensions of Pressure Gas Welds, Squared End Preparation, Closed Joint Method



Metal Thickness (T), in.	Length of Upset (L), in.	Approx. Upset Hgt (H), in.	Total Upset, in.
1/8	3/16 - 1/4	1/16	1/8
1/4	5/16 - 1/2	3/32	1/4
3/8	9/16 - 5/8	1/8	5/16
1/2	3/4 - 7/8	3/16	3/8
3/4	1-1/16 - 1-3/16	1/4	1/2
1	1-1/4 - 1-1/2	3/8	5/8

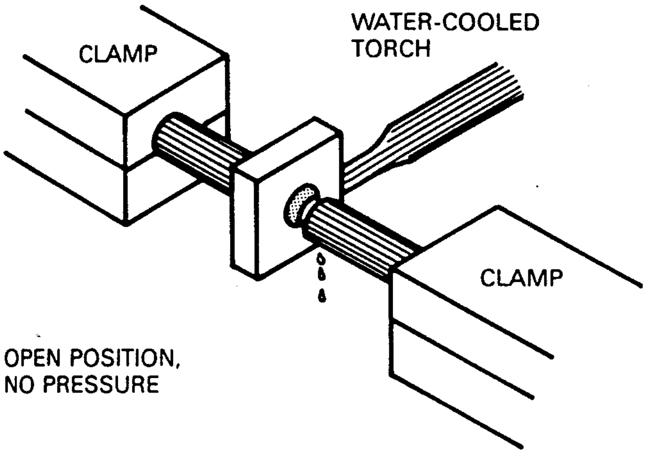


Figure 29.29–Torch and General Setup for Open Joint Pressure Gas Welding

ment of the flame. The best control of gas flow and heat input is obtained when the pressure gages are located close to the torch. This permits the operator to check gas pressures readily. Flowmeters may be used to assure uniform gas flow.

An ample supply of water is needed for cooling the torches and, in some cases, the clamps and parts of the press. Adequate jigs for aligning and supporting the parts are needed. Automatic control units for regulating the upset force and heating cycles and then terminating the operation can be incorporated in a machine.

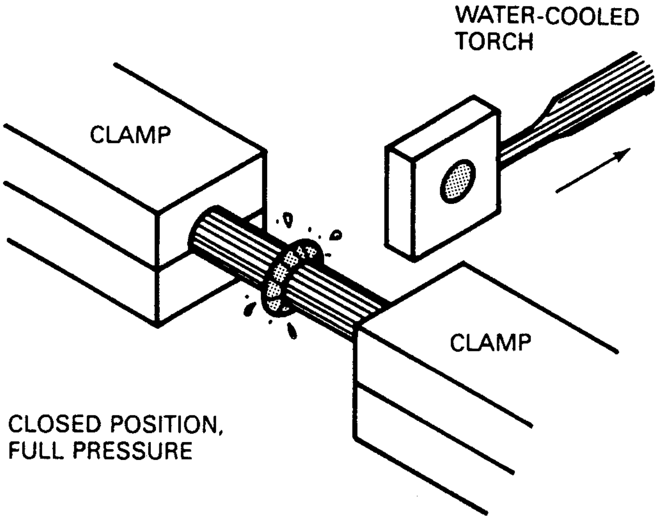
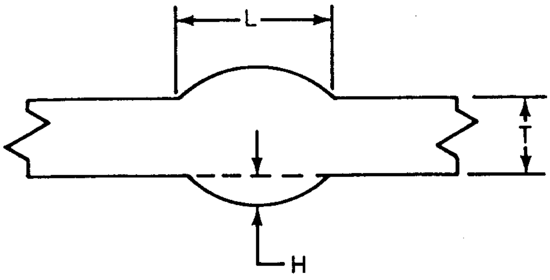


Figure 29.30–An Open Joint Pressure Gas Weld as Upsetting Starts

Applications

Metals Welded. Pressure gas welding has been successfully applied to plain carbon, low alloy, and high alloy steels, and to several nonferrous metals, including nickel-copper, nickel-chromium, and copper-silicon alloys. It has been very useful for joining dissimilar metals.

Table 29.4B
Joint Dimensions of Pressure Gas Welds, Squared End Preparation, Closed Joint Method



Metal Thickness (T), mm	Length of Upset (L), mm	Approx. Upset Hgt (H), mm	Total Upset, mm
3	5-6	2	3
6	8-13	2	6
10	14-16	3	8
13	19-22	5	10
19	27-30	6	13
25	32-38	10	16

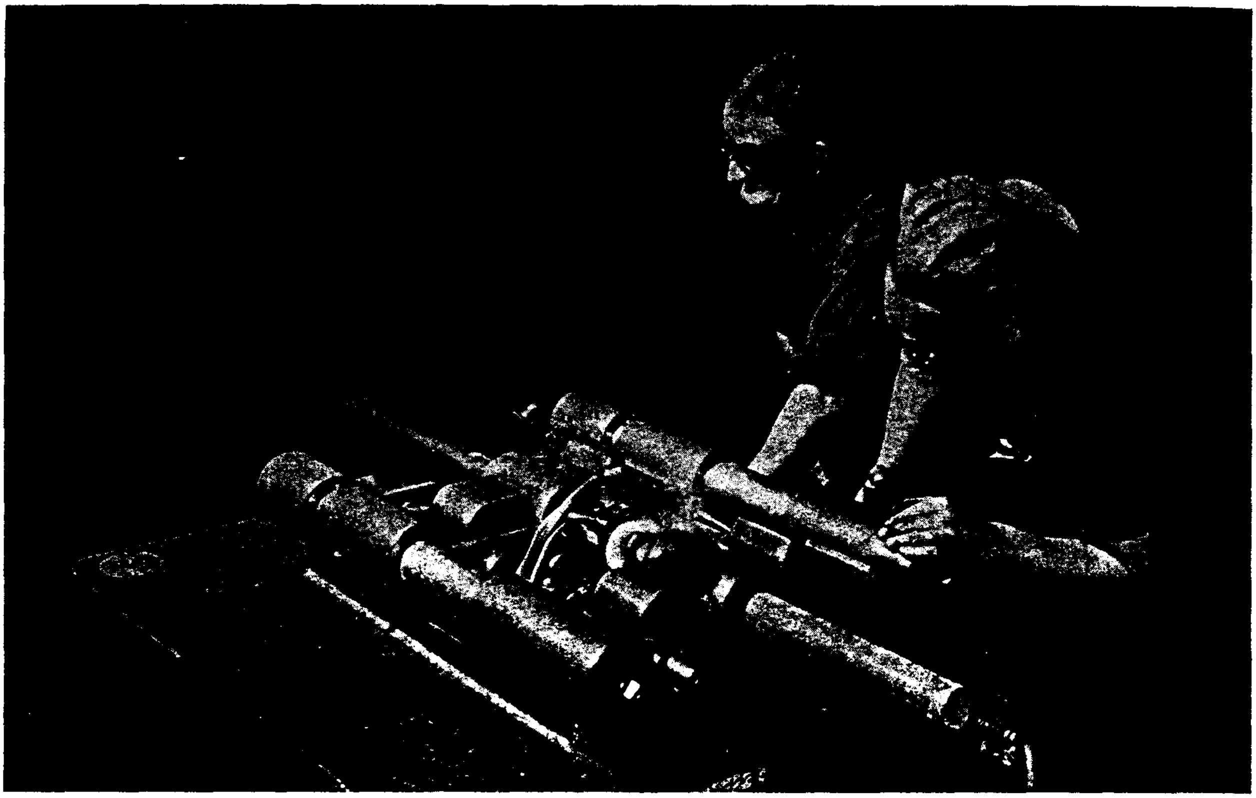


Figure 29.31–A Small Pressure Gas Welding Machine for Rods and Tubes Up to 3 in. Diameter

Rails. The first commercial application of this process was the welding of railroad rails, and thousands of joints were made. However, this process has largely been replaced by the flash welding process. When pressure gas welding is used, the closed butt method is usually employed with equipment specifically designed for this application.

The rail ends are carefully prepared by power sawing and then are cleaned. The rails are gripped by special clamps and a force applied to produce about 2800 psi (20 MPa) on the joint. The joint is then heated with specially shaped heating tips or heads that are oscillated automatically across the joint until the metal reaches welding temperature. Adequate pressure is then applied to produce the required upset. Typical rail welding equipment is shown in Figure 29.32. Most of the upset metal on the ball and edges of the base is removed by oxygen cutting. The welded joint is then indexed or moved to the next position, where the weld zone is normalized to refine the grain size and restore normal hardness. Finally, the weld is ground to rail contour, examined by magnetic particle inspection, and oiled for protection against rusting. Rails that have been welded, normalized, and inspected in this manner have given satisfactory service under both heavy and fast traffic for extended time periods.

Other Applications. Pressure gas welding has been largely superseded by other welding processes. The basic elements of the process assisted in the development of similar processes, such as flash and friction welding, that use other sources of energy. Automatic welding of pipe, a former application, is now accomplished using automatic gas metal arc welding.

Properties and Heat Treatment

IN GENERAL, PRESSURE gas welding has a minimum effect on the mechanical and physical properties of the base metals. Because of the relatively large mass of hot metal in the weld zone, its cooling rate is usually quite low.

In the closed-joint method, the maximum temperature of the metal is below the temperature at which overheating and rapid grain growth occur. In the open-joint method, the melted metal film is squeezed out of the joint during upset. These characteristics are advantageous for welding high carbon steels and some nonferrous alloys that are hot-short or affected by overheating.

Another important factor is the absence of deposited metal. The entire weld zone is base metal, and, hence, it responds to heat treatment in the same manner. This, of course, includes the effect of the heat of welding on the

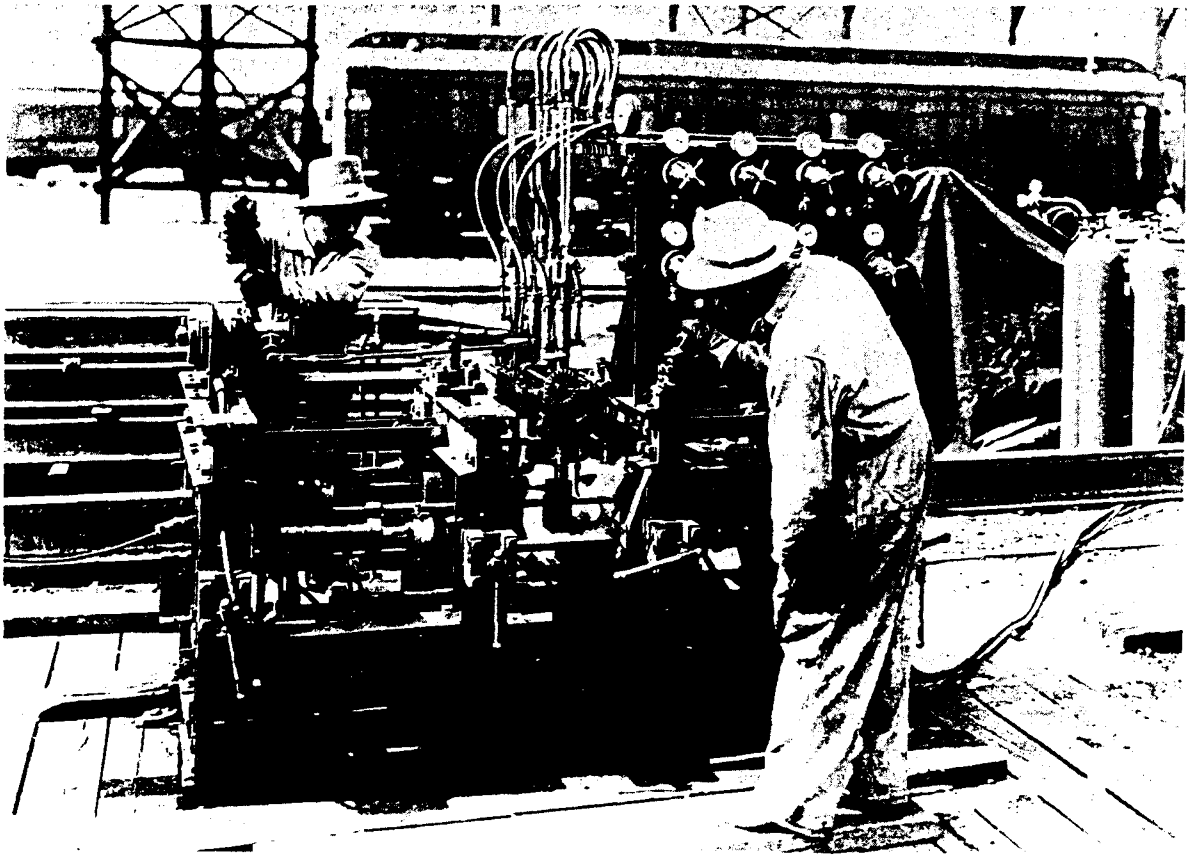


Figure 29.32–Pressure Gas Welding Railroad Rails

corrosion resistance of welded stainless steels. If unimpaired corrosion resistance is desired, stabilized stainless steel must be used or the welded assembly must be given a stabilization heat treatment after welding.

Pressure gas welds in low carbon steels seldom require heat treatment or stress relief since the heat-affected zone in such steels is usually normalized and relatively stress free. Pressure gas welding has been used with low alloy and high carbon steels for fabricating assemblies subject to high service stresses, and postweld heat treatment was necessary. Heat treatment may frequently be done with the same heating heads used for welding.

In rails, for example, the annealed zone on each side of the weld may be too soft. To overcome this problem, the weld zone can be heated to normalizing temperature using heating heads and then air cooled to restore the desired hardness. Similarly, heat treatment with the welding flame may be suitable for developing desired mechanical properties in welded joints in some low alloy steels such as those used for oil well drilling tools. Such heat treatment, which is essentially a normalizing operation, will refine the grain size in the weld zone and improve ductility and toughness. For highly hardenable steels, annealing or slow cooling after the welding operation may be necessary to prevent hardening or surface cracking in the weld zone. To develop optimum properties in welds in heat-treatable steels, furnace heat treatment is commonly used.

Weld Quality

Mechanical Properties.[5] Since there is no deposited metal in pressure welds, the mechanical properties of welds will depend upon the composition of base metals, the cooling rate, and the quality of the weld. When dissimilar steels are joined, the properties of the welded joint will be more nearly those of the weaker member.

Metallurgical Structure. The location of the original interface in pressure gas welds in plain carbon steels and many alloy steels is very difficult to detect in a metallo-

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[5] Mechanical properties of typical pressure gas welds are given in Chapter 22, "Pressure gas welding," *Welding Handbook*, Section 2, 5th ed., 1963.

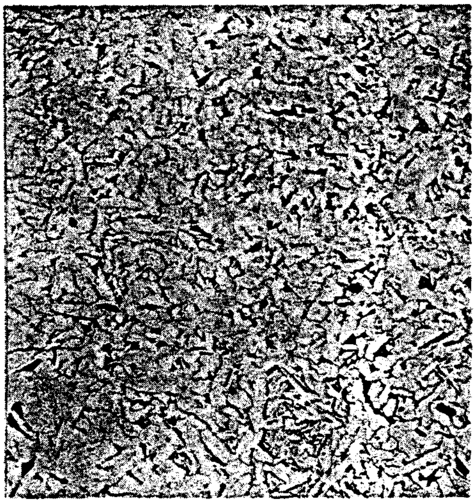

Figure 29.33–Photomicrograph of a Pressure Gas Weld in 1020 Steel, As-Welded

graphic cross section using normal etchants. It is possible to locate the weld line with special polishing and etching techniques. A typical photomicrograph of a pressure gas weld in steel is shown in Figure 29.33. Although not apparent, the interface extends vertically through the center of the photomicrograph.

Quality Control

Process Control. Successful pressure gas welding by the closed joint method requires positive and continuous control of the variables that influence the quality of a weld. The variables include the following:

(1) Degree of roughness and cleanliness of end preparation
(2) Pressure cycle
(3) Alignment of the parts
(4) Welding cycle time
(5) Performance of the heating torches
(6) Desired upset or shortening
(7) Cooling time in the machine after upset

Examination of the pressure-upsetting cycle can indicate if the welding conditions are conforming to the prescribed procedure. With constant heat input into the weld zone, constant width of heated zone, and uniform pressure sequence, the entire cycle of heating and upsetting should be completed with a variation in welding time of not more than 10 percent. On this basis, if a weld requires an unduly long or short time, the conditions that prevailed during welding should be evaluated. A large time variation from nominal would indicate that (1) some factor other than time was controlled improperly, and (2) the weld might be of questionable quality. Malfunctioning of the pressure system or the heating heads and slipping of the parts in the clamps are examples of the conditions that might cause poor quality welds.

Autographic or other records of the following variables have proved of value in maintaining good control:

(1) Pressure cycle
(2) Total time or times for certain stages of the procedure
(3) Gas flow rates
(4) Total upset distance

Some conditions of importance in the closed joint method are not so important with the open joint method. With the open joint method, the cleanliness of the joint faces is not critical except for excessive amounts of foreign matter. Melting of the faces offsets a need for thorough surface preparation. The amount of upset or shortening is not necessarily constant, and, therefore, it is not an index of weld quality. However, due attention must be given to the pressure cycle and the performance of the heating torches.

Inspection. The first inspection is usually a visual one to evaluate the following general characteristic:

(1) Presence or absence of excessive melting
(2) Contour and uniformity of upset
(3) Position of the weld line with respect to the midpoint of the upset zone

If there is no appreciable variation from an accepted standard and the controls were adequate, it may usually be concluded that the pressure weld is of normal quality.

In many highly stressed assemblies, added assurance of weld consistency and quality may be needed. Sample welds selected either at random or at fixed intervals should be destructively tested. This procedure will serve as a positive and continuous check on the welding cycle and process controls as well as the properties of the welded assemblies.

Magnetic particle inspection can be used for nondestructive inspection of pressure welded rails. The nick-break test can be used as a convenient quality check for soundness.[6] Fracture of a sample weld along the weld line will show the extent of metallic bonding, grain size, and evidence of overheating of the faces. Changes in the welding cycle can be checked quickly by this test. Experience has proved that when the nick-break tests show satisfactory crystalline fracture throughout the weld cross section, all other tests will usually prove satisfactory.

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[6] For a description of this test, refer to *Welding Inspection*, 113–114. Miami: American Welding Society, 1980 or API Standard 1104, Para 2.63, 15th ed., 1980, Supplement 1, 1982.

Proof testing may be used as an alternative to destructive testing. The test is designed to disclose defective welds and pass acceptable welds. A welded joint is subjected to either a tensile or a bending load, or both, to produce a maximum tensile stress just below the yield strength of the metal. A poor quality weld will fail in this test.

FORGE WELDING (FOW)

Fundamentals of the Process

FORGE WELDING[7] IS a solid-state welding process that produces a weld by heating the work pieces to welding temperature and applying blows sufficient to cause permanent deformation at the faying surfaces. Forge welding was the earliest welding process and the only one in common use until well into the nineteenth century. Blacksmiths used this process. Pressure vessels and steel pipe were among the industrial items once fabricated by forge welding.

The process finds some application with modern methods of applying the heat and pressure necessary to achieve a weld. The chief present day applications are in the production of tubing and clad metals.

Principles of Operation

THE SECTIONS TO be joined by forge welding may be heated in a forge, furnace, or by other appropriate means until they are very malleable. A weld is accomplished by removing the parts from the heat source, superimposing them, and then applying pressure or hammer blows to the joint.

Heating time is the major variable that affects joint quality. Insufficient heat will fail to bring the surfaces to the proper degree of plasticity, and welding will not take place. If the metal is overheated, a brittle joint of very low strength may result. The overheated joint is likely to have a rough, spongy appearance where the metal is severely oxidized. The temperature must be uniform throughout the joint interfaces to yield a satisfactory weld.

Process Modes

Hammer Welding. In hammer welding, coalescence is produced by heating the parts to be welded in a forge or other furnace and then applying pressure by means of hammer blows. Manual hammer welding is the oldest technique. Pressure is applied to the heated members by repeated high velocity blows with a comparatively light sledge hammer. Modern automatic and semiautomatic hammer welding is accomplished by blows of a heavy power-driven hammer operating at low velocity. The hammer may be powered by steam, hydraulic, or pneumatic equipment.

The size and quantity of parts to be fabricated will determine the choice of either manual or power-driven hammer welding. This process may still be used in some maintenance shops, but it largely has been replaced by other welding processes.

Die Welding. This is a forge welding process where coalescence is produced by heating the parts in a furnace and then applying pressure by means of dies. The dies also shape the work while it is hot.

Metals Welded

LOW CARBON STEELS are the metals most commonly joined by forge welding. Sheets, bars, tubing, pipe and plates of these materials are readily available.

The major influences on the grain structure of the weld and heat-affected zone are the amount of forging applied and the temperature at which the forge welding takes place. A high temperature is generally necessary for the production of a sound forge weld. Annealing can refine the grain size in a forge welded steel joint and improve joint ductility.

Thin, extruded sections of aluminum alloy are joined edge-to-edge by a forge welding process with automatic equipment to form integrally stiffened panels. The panels are used for lightweight truck and trailer bodies. Success of the operation depends upon the use of correct temperature and pressure, effective positioning and clamping devices, edge preparation, and other factors. Although the welding of aluminum for this application is called forge welding, it could be classified as hot pressure welding because the edges to be joined are heated to welding temperature and then upset by the application of pressure.

Joint Design

THE FIVE JOINT designs applicable to manual forge welding are the lap, butt, cleft, jump, and scarf types shown in Figure 29.34. The joint surfaces for these welds are slightly rounded or crowned. This shape ensures that the center of the pieces will weld first so that any slag, dirt, or oxide on the surfaces will be forced out of the joint as pressure is applied. Lap, pin, and butt joints used for automatic forge welding are shown in Figure 29.35.

Scarfing is the term applied to the preparation of the workpieces of forge welding. Similarly, the prepared surface is referred to as a scarfed surface. Each workpiece to be welded must be upset sufficiently for an adequate distance from the scarfed surface to provide metal for mechanical working during welding.

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[7] More detailed information is presented in Chapter 61, *Welding Handbook*, Section 3B, 6th Ed., 1971.

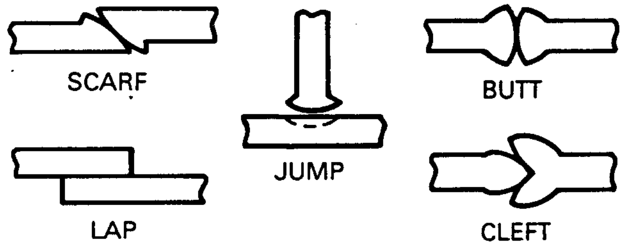

Figure 29.34–Typical Joint Designs Employed for Manual Forge Welding

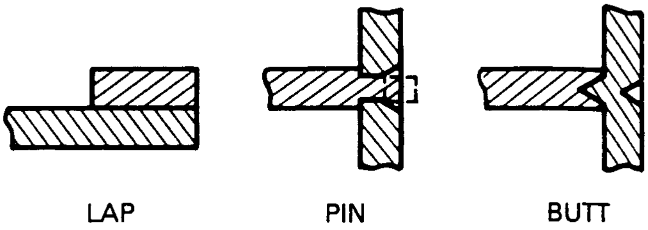

Figure 29.35–Typical Joint Designs Used for Automatic Forge Welding

Fluxes

IN THE FORGE welding of certain metals, a flux must be used to prevent the formation of oxide scale. The flux and the oxides present combine to form a protective coating on the heated surfaces of the metal. This coating prevents the formation of additional oxide and lowers the melting point of the existing oxide.

Two commonly used fluxes for steels are silica sand and borax (sodium tetraborate). Flux is not required for very low carbon steels (ingot iron) and wrought iron because their oxides have low melting points. The flux most commonly used in the forge welding of high carbon steels is borax. Because it has a relatively low fusion point, borax may be sprinkled on the metal while it is in the process of heating. Silica sand is suitable as a flux in the forge welding of low carbon steel.

CARBON ARC WELDING

DEFINITION AND GENERAL DESCRIPTION

CARBON ARC WELDING (CAW) is a process in which an arc is established between a nonconsumable carbon (graphite) electrode and the work, or between two carbon electrodes. The latter is a variation known as twin carbon arc welding. Two other variations known as shielded and gas carbon arc welding no longer have commercial significance.

Although carbon arc welding has been superseded to a great extent by other welding processes, there are many applications for which it can be used to good advantage. In operation, the carbon arc is used only as a source of heat. In this respect, it resembles the gas tungsten arc welding process.

Figure 29.36 shows the carbon arc welding process. The arc stream usually develops a temperature of from 7000 to 9000°F (3870 to 4980°C), depending upon the amount of current used. Because the electrode burns off very slowly, it does not have an appreciable effect on the composition of the deposited metal, provided filler metal is added.

PRINCIPLES OF OPERATION

THE APPLICATION OF heat and the filler metal feed are controlled separately in carbon arc welding. With some welds, the carbon arc is used to fuse the edges together without the addition of filler metal. A carbon arc can produce the high heat needed for welding metals that have high thermal conductivity, such as copper.

In carbon arc welding, direct current electrode negative (straight polarity) should be used. The arc is formed between the tip of the carbon electrode and the base metal. Welding current is adjusted to provide sufficient heat to melt the base metal and welding rod uniformly as welding progresses. Recommended current ranges for carbon and graphite electrodes are given in Table 29.5. Amperages are recommended on the basis of maximum electrode life. Higher amperages can be used, but the electrode will be consumed faster.

The properties of welds made with the carbon arc in mild steel may be adequate for noncritical applications. The process does not provide as much shielding from the atmosphere as the shielded metal arc or gas metal arc welding processes.

EQUIPMENT

CARBON ELECTRODES RANGE in size from 1/8 to 7/8 in. (3.2 to 22 mm) diameter. Baked carbon electrodes last longer than graphite electrodes. Figure 29.37 shows typical air-cooled carbon electrode holders. Water-cooled holders are available for use with the larger sizes of electrodes, or adapters can be fitted to regular holders to permit ac-

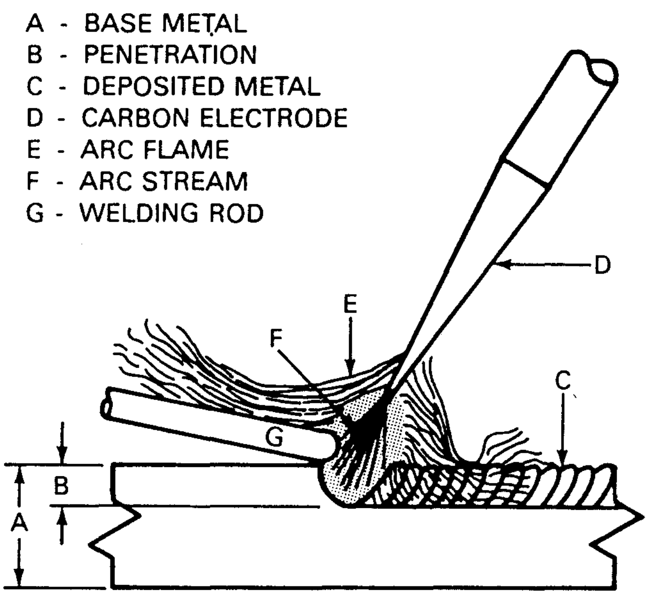

Figure 29.36–Carbon Arc Welding

commodation of the larger electrodes. Direct current welding machines of either the rotating or rectifier type are excellent power sources for the carbon arc welding process.

WELDING TECHNIQUE

THE WORKPIECES MUST be free from grease, oil, scale, paint, and other foreign matter. The two pieces should be clamped tightly together with no root opening. They may be tack welded together.

Table 29.5
Recommended Current Ranges for Carbon and Graphite Electrodes[a]

Electrode Diameter		Current, A[b]	
in.	mm	Carbon Electrodes	Graphite Electrodes
1/8	3.2	15-30	15-35
3/16	4.8	25-55	25-60
1/4	6.4	50-85	50-90
5/16	7.9	75-115	80-125
3/8	9.5	100-150	110-165
7/16	11.1	125-185	140-210
1/2	12.7	150-225	170-260
5/8	15.9	200-310	230-370
3/4	19.0	250-400	290-490
7/8	22.2	300-500	400-750

a. Recommended with regard to maximum electrode life. Where electrode cost is not a factor, higher amperages may be used.

b. Direct current electrode negative (straight polarity)

Carbon electrodes, 1/8 to 5/16 in. (3.2 to 8 mm) diameter may be used depending upon the current required for welding. The end of the electrode should be prepared with a long taper to a point. The diameter of the point should be about half that of the electrode. For steel, the electrode should protrude about 4 to 5 in. (100 to 125 mm) from the electrode holder.

A carbon arc may be struck by bringing the tip of the electrode into contact with the work and immediately withdrawing it to the correct length for welding. In general, an arc length between 1/4 and 3/8 in. (6 and 10 mm) will be best. If the arc length is too short, there is likely to be excessive carburization of the molten metal resulting in a brittle weld.

When the arc is broken for any reason, it should not be restarted directly upon the hot weld metal as this is likely to cause a hard spot in the weld at the point of contact. The arc should be started on cold metal to one side of the joint and then quickly returned to the point where welding is to be resumed.

When the joint requires filler metal, the welding rod is fed into the molten weld pool with one hand while the arc is manipulated with the other. The arc is directed on the surface of the work and gradually moved along the joint, constantly maintaining a molten pool into which the welding rod is added in the same manner as in gas tungsten arc welding. Progress along the weld joint and the addition of welding rod must be timed to provide the size and shape of weld bead desired. Welding vertically or overhead with the carbon arc is difficult because carbon arc welding is essentially a puddling process. The weld joint should be backed up, especially in the case of thin sheets, to support the molten weld pool and prevent excessive melt-through.

For outside corner welds in 14 to 18 gage steel sheet, the carbon arc can be used to weld the two sheets together without a filler metal. Such welds are usually smoother and more economical to make than shielded metal arc welds made under similar conditions.

METALS WELDED

THE CARBON ARC can be used for welding steels and nonferrous metals. It can also be used for surfacing.

Steels

THE PRINCIPLE USE of carbon arc welding of steel is making edge welds without the addition of filler metal. This is done chiefly in thin gage sheet metal work, such as tanks, where the edges of the work are fitted closely and fused together using appropriate flux.

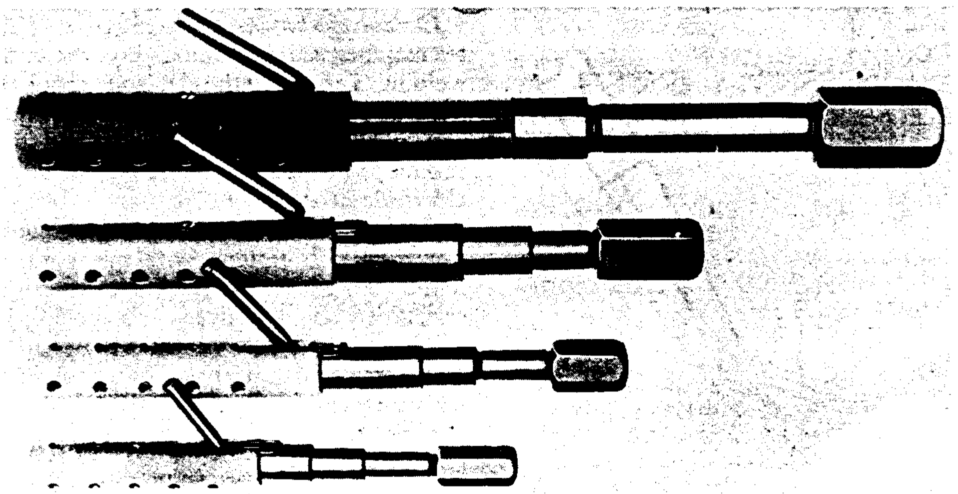

Figure 29.37–Typical Air-Cooled Carbon Electrode Holders

Galvanized sheet steel can be braze welded with the carbon arc.[8] A bronze welding rod is used. The rod is placed in the arc so that the zinc is not burned off the steel sheet. The arc should be started on the welding rod or a starting block. Low current, a short arc length, and rapid travel speed should be used. The welding rod should melt and wet the galvanized steel.

Cast Iron

IRON CASTINGS MAY be welded with the carbon arc and a cast iron welding rod. The casting should preheated to about 1200°F (650°C) and slowly cooled if a machinable weld is desired.

Copper

STRAIGHT POLARITY SHOULD always be used for carbon arc welding of copper. Reverse polarity will produce carbon deposits on the work that inhibit fusion.

The work should be preheated in the range of 300 to 1200°F (150 to 650°C) depending upon the thickness of the parts. If this is impractical, the arc should be used to locally preheat the weld area. The high thermal conductivity of copper causes heat to be conducted away from the point of welding so rapidly that it is difficult to maintain welding heat without preheating.

A root opening of 1/8 in. (3.2 mm) is recommended. Best results are obtained at high travel speeds with the welding rod held within the arc. A long arc length should be used to permit carbon from the electrode to combine with oxygen to form CO. This will provide some shielding of the weld metal.

TWIN CARBON ARC WELDING

WITH A TWIN carbon torch, the arc heat can be used for welding, brazing, surfacing, or soldering operations as well as for preheating or postheating the work. The heat is produced by an arc between two carbon electrodes; the work is not part of the electrical circuit. Twin carbon arc welding is used principally for maintenance operations. A twin carbon arc torch, shown in Figure 29.38, has two adjustable arms in which the carbon electrodes are clamped. To maintain a constant distance between the electrodes (arc length) as they are consumed, adjustment of electrode position can usually be made while operating the torch.

Small ac arc welding machines are normally used with the twin carbon arc. Copper coated carbon electrodes are generally used in 0.250 to 0.375 in. (6.4 to 9.5 mm) diameter. The current should never be set so high that the copper coating is burned away over 0.5 in. (12.7 mm) ahead of the arc. Only enough current should be used to cause the filler material to flow freely on the work. This will avoid consuming carbons too rapidly.

SAFETY

SAFETY PROCEDURES AND equipment normally used with other arc welding processes should also be used with this one. This includes welding helmets with appropriate filter lenses, protective clothing, and gloves. Adequate ventilation should be provided. The requirements of ANSI Z49.1, Safety in Welding and Cutting, latest edition, and appropriate federal, state, and local regulations should be followed when carbon arc welding.

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[8] Refer to Chapter 12 of this volume for a discussion of braze welding.

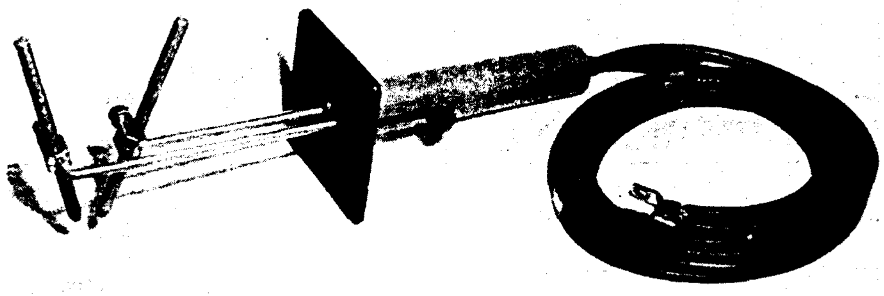

Figure 29.38–A Twin Carbon Arc Welding Torch

BARE METAL ARC WELDING

BARE METAL ARC welding[9] (BMAW) is an arc welding process that uses an arc between a bare or lightly coated electrode and the weld pool. Neither shielding nor pressure is used, and filler metal is obtained from the electrode.

The chief disadvantage of welding with a bare electrode is that the molten filler and weld metal are exposed to the atmosphere. The molten metal transferring across the arc and the molten weld metal are both subjected to oxidation and nitrification. As a result, the molten metal oxidizes rapidly, and the weld metal is likely to have unsatisfactory fusion with the base metal. Formation of porosity in the weld will have a detrimental effect upon the strength and ductility of the welded joint. Nitrogen in the form of nitrides tends to cause high hardness and poor ductility. Water vapor dissociates in the arc to produce hydrogen, which may cause hydrogen embrittlement of some metals and underbead cracking in some steels.

Extruded covered electrodes have largely replaced bare and lightly covered electrodes on the market today. There is still, however, a considerable tonnage of bare electrodes manufactured and used. Most of the bare wires manufactured today are either coiled or spooled for use with the gas shielded welding processes.

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[9] More information is presented in Chapter 61, *Welding Handbook*, Section 3B, 6th Ed., 1971.

ATOMIC HYDROGEN WELDING

ATOMIC HYDROGEN WELDING (AHW) is an arc welding process that uses an arc between two metal tungsten electrodes in a shielding atmosphere of hydrogen and without the applicaton of pressure. Shielding is obtained from the hydrogen. Filler metal may or may not be added.

In this process, the arc is maintained entirely independent of the work or parts being welded. The work is a part of the electrical circuit only to the extent that a portion of the arc comes in contact with the work, at which time a voltage exists between the work and each electrode.

Historically, atomic hydrogen welding was the forerunner of the gas shielded arc welding processes. At that time, it was the best process for welding of metals other than carbon and low alloy steels. With the advent of low-cost inert gases, the gas shielded arc welding processes have largely replaced atomic hydrogen welding.

Hydrogen in its normal state is diatomic. Each molecule consists of two atoms. When an arc is established in hydrogen between two electrodes, the temperature in the arc stream reaches approximately 11 000°F (6090°C) and the molecular hydrogen dissociates into its atomic form. In the process of dissociation, a large amount of heat is absorbed from the arc by the hydrogen. The heat is subsequently liberated on recombination of the hydrogen atoms at the surface of the work. A sudden decrease in the temperature of the hydrogen as it strikes a relatively cold surface (weld area) is accompanied by a rapid release of heat as the hydrogen atoms recombine to the molecular form. By varying the distance between the arc stream and the surface, the available energy can be varied over a wide range. The hydrogen also cools the electrodes and protects both the electrodes and the metal from oxidation.

Atomic hydrogen welding had one unique advantage: the ability to control heat input over a very wide range by manipulating the arc. It was widely used for tool and die repair and similar operations where very precise metal buildup with accurate alloy control was necessary.

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