# Tempering Processes/Technology

## Conventional Processes

Tempering is a process in which previously hardened or normalized steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate, primarily to increase ductility and toughness, but also to increase the grain size of the matrix. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and also to relieve quenching stresses and to ensure dimensional stability. Tempering usually follows quenching from above the upper critical temperature; however, tempering is also used to relieve the stresses and reduce the hardness developed during welding and to relieve stresses induced by forming and machining.

### Principal Variables

Variables that affect the microstructure and the mechanical properties of a tempered steel include:

* Tempering temperature
* Time at temperature
* Cooling rate from the tempering temperature

* Composition of the steel, including carbon content, alloy content, and residual elements

In a steel quenched to a microstructure consisting essentially of martensite, the iron lattice is strained by the carbon atoms, producing the high hardness of quenched steels.

Under certain conditions, hardness may remain unaffected by tempering or may even be increased as a result of it. For example, tempering a hardened steel at very low tempering temperatures may cause no change in hardness but may achieve a desired increase in yield strength. Also, those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium, and tungsten) are capable of secondary hardening; that is, they may become somewhat harder as a result of tempering.

The tempered hardness values for several quenched steels are presented in an adjoining Table. Temperature and time are interdependent variables in the tempering process. Within limits, lowering temperature and increasing time can usually produce the same result as raising temperature and decreasing time. However, minor temperature changes have a far greater

## Typical Hardnesses of Various Carbon and Alloy Steels after Tempering

| Grade | Carbon content, % | 205 °C (400 °F) | 260 °C (500 °F) | 315 °C (600 °F) | 370 °C (700 °F) | 425 °C (800 °F) | 480 °C (900 °F) | 540 °C (1000 °F) | 595 °C (1100 °F) | 650 °C (1200 °F) | Heat treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Carbon steels, water hardening* | | | | | | | | | | | |
| 1030 | 0.30 | 50 | 45 | 43 | 39 | 31 | 28 | 25 | 22 | 95(a) | Normalized at 900 °C (1650 °F), water quenched from |
| 1040 | 0.40 | 51 | 48 | 46 | 42 | 37 | 30 | 27 | 22 | 94(a) | 830-845 °C (1525-1550 °F); average dew point, |
| 1050 | 0.50 | 52 | 50 | 46 | 44 | 40 | 37 | 31 | 29 | 22 | 16 °C (60 °F) |
| 1060 | 0.60 | 56 | 55 | 50 | 42 | 38 | 37 | 35 | 33 | 26 | Normalized at 885 °C (1625 °F), water quenched from |
| 1080 | 0.80 | 57 | 55 | 50 | 43 | 41 | 40 | 39 | 38 | 32 | 800-815 °C (1475-1500 °F); average dew point, |
| 1095 | 0.95 | 58 | 57 | 52 | 47 | 43 | 42 | 41 | 40 | 33 | 7 °C (45 °F) |
| 1137 | 0.40 | 44 | 42 | 40 | 37 | 33 | 30 | 27 | 21 | 91(a) | Normalized at 900 °C (1650 °F), water quenched from |
| 1141 | 0.40 | 49 | 46 | 43 | 41 | 38 | 34 | 28 | 23 | 94(a) | 830-855 °C (1525-1575 °F); average dew point, |
| 1144 | 0.40 | 55 | 50 | 47 | 45 | 39 | 32 | 29 | 25 | 97(a) | 13 °C (55 °F) |
| *Alloy steels, water hardening* | | | | | | | | | | | |
| 1330 | 0.30 | 47 | 44 | 42 | 38 | 35 | 32 | 26 | 22 | 16 | Normalized at 900 °C (1650 °F), water quenched from |
| 2330 | 0.30 | 47 | 44 | 42 | 38 | 35 | 32 | 26 | 22 | 16 | 800-815 °C (1475-1500 °F); average dew point, |
| 3130 | 0.30 | 47 | 44 | 42 | 38 | 35 | 32 | 26 | 22 | 16 | 16 °C (60 °F) |
| 4130 | 0.30 | 47 | 45 | 43 | 42 | 38 | 34 | 32 | 26 | 22 | Normalized at 885 °C (1625 °F), water quenched from |
| 5130 | 0.30 | 47 | 45 | 43 | 42 | 38 | 34 | 32 | 26 | 22 | 800-855 °C (1475-1575 °F); average dew point, |
| 8630 | 0.30 | 47 | 45 | 43 | 42 | 38 | 34 | 32 | 26 | 22 | 16 °C (60 °F) |
| *Alloy steels, oil hardening* | | | | | | | | | | | |
| 1340 | 0.40 | 57 | 53 | 50 | 46 | 44 | 41 | 38 | 35 | 31 | Normalized at 870 °C (1600 °F), oil quenched from |
| 3140 | 0.40 | 55 | 52 | 49 | 47 | 41 | 37 | 33 | 30 | 26 | 830-845 °C (1525-1550 °F); average dew point, |
| 4140 | 0.40 | 57 | 53 | 50 | 47 | 45 | 41 | 36 | 33 | 29 | 16 °C (60 °F) |
| 4340 | 0.40 | 55 | 52 | 50 | 48 | 45 | 42 | 39 | 34 | 31 | Normalized at 870 °C (1600 °F), oil quenched from |
| 4640 | 0.40 | 52 | 51 | 50 | 47 | 42 | 40 | 37 | 31 | 27 | 830-845 °C (1525-1575 °F); average dew point, |
| 8740 | 0.40 | 57 | 53 | 50 | 47 | 44 | 41 | 38 | 35 | 22 | 13 °C (55 °F) |
| 4150 | 0.50 | 56 | 55 | 53 | 51 | 47 | 46 | 43 | 39 | 35 | Normalized at 870 °C (1600 °F), oil quenched from |
| 5150 | 0.50 | 57 | 55 | 52 | 49 | 45 | 39 | 34 | 31 | 28 | 830-870 °C (1525-1600 °F); average dew point, |
| 6150 | 0.50 | 58 | 57 | 53 | 50 | 46 | 42 | 40 | 36 | 31 | 13 °C (55 °F) |
| 8650 | 0.50 | 55 | 54 | 52 | 49 | 45 | 41 | 37 | 32 | 28 | Normalized at 870 °C (1600 °F), oil quenched from |
| 8750 | 0.50 | 56 | 55 | 52 | 51 | 46 | 44 | 39 | 34 | 32 | 815-845 °C (1500-1550 °F); average dew point, |
| 9850 | 0.50 | 54 | 53 | 51 | 48 | 45 | 41 | 36 | 33 | 30 | 13 °C (55 °F) |

Data were obtained on 25 mm (1 in.) bars adequately quenched to develop full hardness. (a) Hardness, HRB

effect than minor time changes in typical tempering operations. With few exceptions, tempering is done at temperatures between 175 and 705 °C (345 and 1300 °F) and for times from 30 min to 4 h.

**Structural Changes.** Based on x-ray, dilatometric, and microstructural studies, there are three distinct stages of tempering, even though the temperature ranges overlap (Ref 1-4):

- Stage I: The formation of transition carbides and lowering of the carbon content of the martensite to 0.25% (100 to 250 °C, or 210 to 480 °F)
- Stage II: The transformation of retained austenite to ferrite and cementite (200 to 300 °C, or 390 to 570 °F)
- Stage III: The replacement of transition carbides and low-temperature martensite by cementite and ferrite (250 to 350 °C, or 480 to 660 °F)

An additional stage of tempering (stage IV), precipitation of finely dispersed alloy carbides, exists for high-alloy steels. It has been found that stage I of tempering is often preceded by the redistribution of carbon atoms, called autotempering or quench tempering, during quenching and/or holding at room temperature (Ref 5). Other structural changes take place because of carbon atom rearrangement preceding the classical stage I of tempering (Ref 6, 7).

**Dimensional Changes.** Martensite transformation is associated with an increase in volume. During tempering, martensite decomposes into a mixture of ferrite and cementite with a resultant decrease in volume as tempering temperature increases. Because a 100% martensitic structure after quenching cannot always be assumed, volume may not continuously decrease with increasing tempering temperature.

The retained austenite in plain carbon steels and low-alloy steels transforms to bainite with an increase in volume, in stage II of tempering. When certain alloy steels are tempered, a precipitation of finely distributed alloy carbides occurs, along with an increase in hardness, called secondary hardness, and an increase in volume. With the precipitation of alloy carbides, the $M_s$ temperature (temperature at which martensite starts to form from austenite upon cooling) of the retained austenite will increase and transform to martensite during cooling from the tempering temperature.

**Tempering Temperature.** Several empirical relationships have been made between the tensile strength and hardness of tempered steels. The measurement of hardness commonly is used to evaluate the response of a steel to tempering. An adjoining Figure shows the effect of tempering

temperature on hardness, tensile and yield strengths, elongation, and reduction in area of a plain carbon steel (AISI 1050) held at temperature for 1 h. It can be seen that both room-temperature hardness and strength decrease as the tempering temperature is increased. Ductility at ambient temperatures, measured by either elongation or reduction in area, increases with tempering temperature.

Most medium-alloy steels exhibit a response to tempering similar to that of carbon steels. The change in mechanical properties with tempering temperature for 4340 steel is shown in an adjoining Figure.

There is no decrease in ductility in the temperature range of tempered martensite embrittlement, or TME (also known as 260 °C [500 °F] embrittlement or one-step temper embrittlement) because the tensile tests are performed on smooth, round specimens at relatively low strain rates. However, in impact loading, catastrophic failure may result when alloy steel is tempered in the tempered martensite embrittlement range (260 to 370 °C, or 500 to 700 °F).

Whereas elongation and reduction in area increase continuously with tempering temperature, toughness, as measured by a notched-bar impact test, varies with tempering temperature for most steels, as shown in an adjoining Figure. Tempering at temperatures from 260 to 320 °C (500 to 610 °F) decreases impact energy to a value below that obtained at about 150 °C (300 °F). Above 320 °C (610 °F), impact energy again increases with increasing tempering temperature. Both plain carbon and alloy steels respond to tempering in this manner. The phenomenon of impact energy centered around 300 °C (570 °F) is called tempered martensite embrittlement (TME) or 260 °C (500 °F) embrittlement.
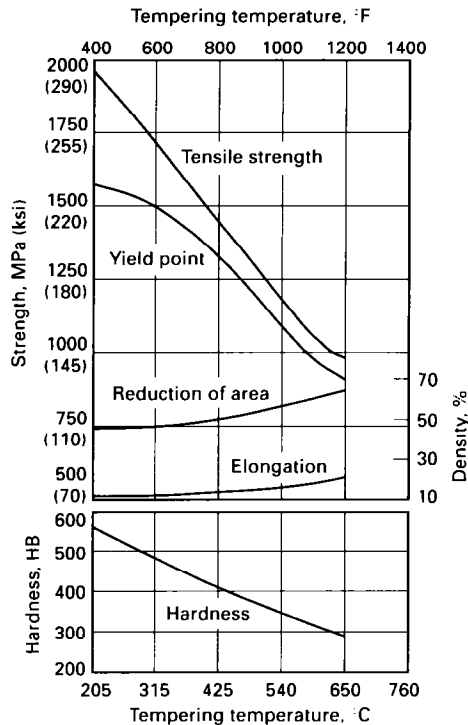
**Tempering Time.** The diffusion of carbon and alloying elements necessary for the formation of carbides is temperature and time dependent. The effect of tempering time on the hardness of a 0.82% C steel tempered at various temperatures is shown in an adjoining Figure. Changes in hardness are approximately linear over a large portion of the time range when the time is presented on a logarithmic scale. Rapid changes in room temperature hardness occur at the start of tempering in times less than 10 s. Less rapid, but still large, changes in hardness occur in times from 1 to 10 min, and smaller changes occur in times from 1 to 2 h. For consistency and less dependency on variations in time, components generally are tempered for 1 to 2 h. The levels of hardness produced by very short tempering cycles,

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**Effect of tempering temperature on room-temperature mechanical properties of 1050 steel.** Properties summarized are for one heat of 1050 steel that was forged to 38 mm (1.50 in.) in diameter, then water quenched and tempered at various temperatures. Composition of heat: 0.52% C, 0.93% Mn
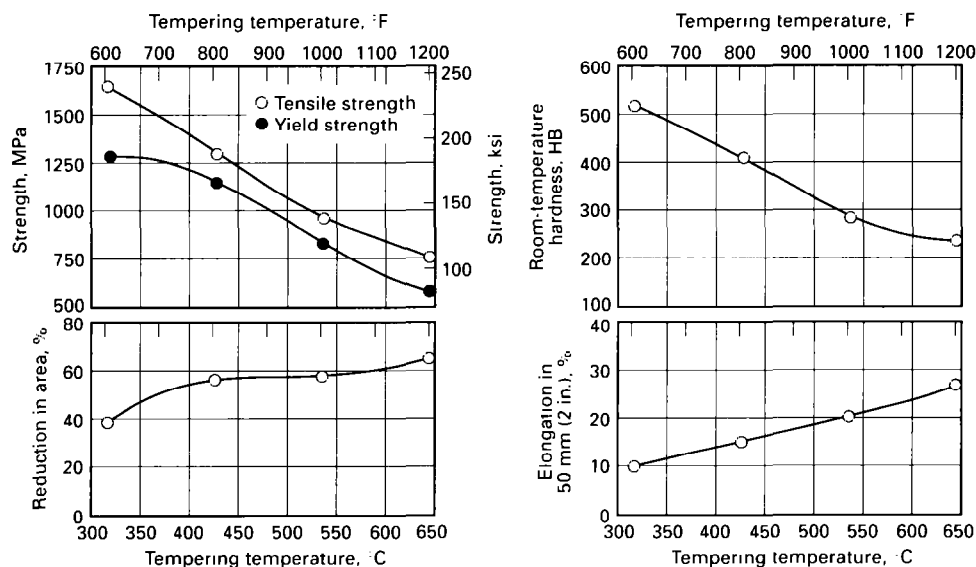
**Effect of tempering temperature on the mechanical properties of oil-quenched 4340 steel bar.** Single-heat results: ladle composition, 0.41% C, 0.67% Mn, 0.023% P, 0.018% S, 0.26% Si, 1.77% Ni, 0.78% Cr, 0.26% Mo; grain size, ASTM 6 to 8; critical points, $Ac_3$, 770 °C (1420 °F); $Ar_3$, 475 °C (890 °F); $Ar_1$, 380 °C (720 °F); treatment, normalized at 870 °C (1600 °F), reheated to 800 °C (1475 °F), quenched in agitated oil; cross section, 13.46 mm (0.530 in.) diam; round treated, 12.83 mm (0.505 in.) diam; round tested; as-quenched hardness, 601 HB. Source: Ref 8



**Notch toughness as a function of tempering temperature for 4140 (UNS G41400) ultrahigh-strength steel tempered 1 h**



## Alloy Content

The main purpose of adding alloying elements to steel is to increase hardenability (capability to form martensite upon quenching from above its critical temperature). The general effect of alloying elements on tempering is a retardation of the rate of softening, especially at the higher tempering temperatures. Thus, to reach a given hardness in a given period of time, alloy steels require higher tempering temperatures than do carbon steels.

Alloying elements can be characterized as carbide forming or non-carbide forming. Elements such as nickel, silicon, aluminum, and manganese, which have little or no tendency to occur in the carbide phase, remain essentially in solution in the ferrite and have only a minor effect on tempered hardness. The carbide forming elements (chromium, molybdenum, tungsten, vanadium, tantalum, niobium, and titanium) retard the softening process by the formation of alloy carbides.

Strong carbide-forming elements such as chromium, molybdenum, and vanadium are most effective in increasing hardness at higher temperatures above 205 °C (400 °F). Silicon was found to be most effective in increasing hardness at 315 °C (600 °F). The increase in hardness caused by phosphorus, nickel, and silicon can be attributed to solid-solution strengthening. Manganese is more effective in increasing hardness at higher tempering temperatures. The carbide-forming elements retard coalescence of cementite during tempering and form numerous small carbide particles. Under certain conditions, such as with highly alloyed steels, hardness may actually increase. This effect, mentioned previously, is known as secondary hardening.

**Other Alloying Effects.** In addition to ease of hardening and secondary hardening, alloying elements produce a number of other effects. The higher tempering temperatures used for alloy steels presumably permit greater relaxation of residual stresses and improve properties. Furthermore, the hardenability of alloy steels requires use of a less drastic quench so that quench cracking is minimized. However, higher hardenability steels are prone to quench cracking if the quenching rate is too severe. The higher hardenability of alloy steels may also permit the use of lower carbon content to achieve a given strength level but with improved ductility and toughness.

**Residual Elements.** The elements that are known to cause embrittlement are tin, phosphorus, antimony, and arsenic.

**Tempering Procedures**

**Bulk processing** may be done in convection furnaces or in molten salt, hot oil, or molten metal baths. The selection of furnace type depends primarily on number and size of parts and on desired temperature. Temperature ranges, most likely reasons for use, and fundamental problems associated with four types of equipment are given in an adjoining Table.

**Selective tempering techniques** are used to soften specific areas of fully hardened parts or to temper areas that were selectively hardened previously. The purpose of this treatment is to improve machinability, toughness, or resistance to quench cracking in the selected zone.

such as in induction tempering, would be quite sensitive to both the temperature achieved and the time at temperature.
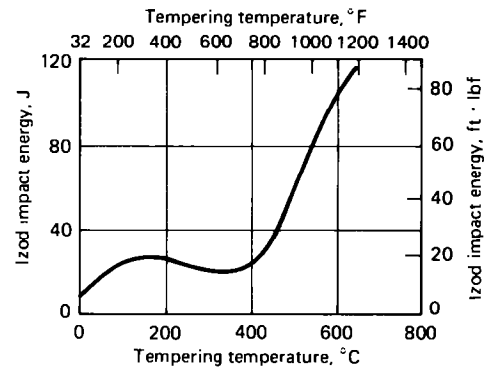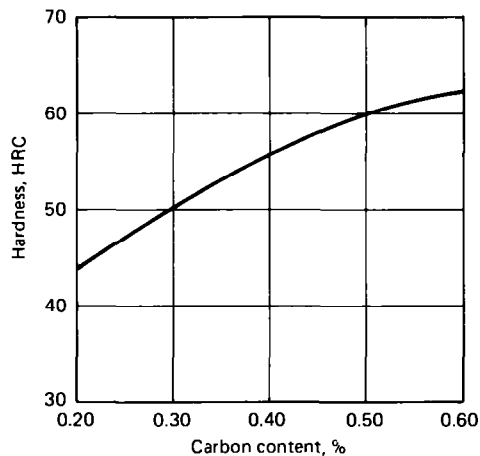
By the use of an empirical tempering parameter developed by Holloman and Jaffe (Ref 10), the approximate hardnesses of quenched and tempered low- and medium-alloy steels can be predicted. Reasonably good correlations are obtained except when significant amounts of retained austenite are present.

**Cooling Rate.** Another factor that can affect the properties of a steel is the cooling rate from the tempering temperature. Although tensile properties are not affected by cooling rate, toughness (as measured by notched-bar impact testing) can be decreased if the steel is cooled slowly through the temperature range from 375 to 575 °C (705 to 1065 °F), especially in steels that contain carbide-forming elements. Elongation and reduction in area may be affected also. This phenomenon is called temper embrittlement.

## Carbon Content

The principal effect of carbon content is on as-quenched hardness. An adjoining Figure shows the relationship between carbon content and the maximum hardness that can be obtained upon quenching. The relative difference in hardness compared with as-quenched hardness is retained after tempering. An adjoining Figure shows the combined effect of time, temperature, and carbon content on the hardness of three carbon-molybdenum steels of different carbon contents. Another Figure shows the hardness of these steels after tempering for 1 h, as a function of tempering temperature. The effect of carbon content is evident.

**Effect of time at four tempering temperatures on room-temperature hardness of quenched 0.82% C steel.** Note nearly straight lines on logarithmic time scale. Source: Ref 9
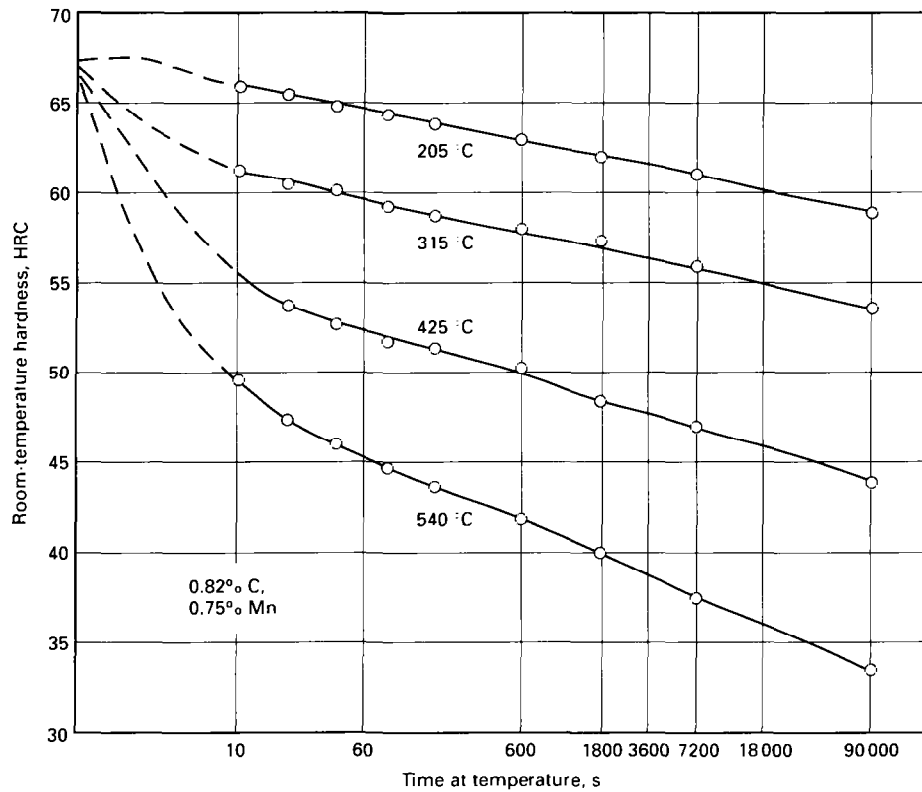


## Relationship between carbon content and room-temperature hardness for steels comprising 99.9% untempered martensite



## Temperature Ranges and General Conditions of Use for Four Types of Tempering

| Type of equipment | Temperature range | | Service conditions |
|---|---|---|---|
| | °C | °F | |
| Convection furnace | 50-750 | 120-1380 | For large volumes of nearly common parts; variable loads make control of temperature more difficult |
| Salt bath | 160-750 | 320-1380 | Rapid, uniform heating; low to medium volume; should not be used for parts whose configurations make them hard to clean |
| Oil bath | ≤250 | ≤480 | Good if long exposure is desired; special ventilation and fire control are required |
| Molten metal bath | >390 | >735 | Very rapid heating; special fixturing is required (high density) |

For certain steels, the tempering mechanism is enhanced by cyclic heating and cooling. A particularly important procedure employs cycles between subzero temperatures and the tempering temperature to increase the transformation of retained austenite. The term used for this procedure, multiple tempering, is also applied to procedures that use intermediate thermal cycles to soften parts for straightening prior to tempering.

## Cracking in Processing

Because of their carbon or alloy contents, some steels are likely to crack if they are permitted to cool to room temperature during or immediately following the quenching operation. Causes include high tensile residual stresses generated during quenching due to thermal gradients, abrupt changes in section thickness, decarburization, or other hardenability gradients. Another potential source is cracking due to quenchant contamination and the subsequent change in quenching severity.

Induction and flame tempering are the most commonly used selective techniques because of their controllable local heating capabilities. Immersion of selected areas in molten salt or molten metal is an alternative, but some control is sacrificed.

**Special processes** that provide specific properties, such as those obtained in steam treating or the use of protective atmospheres, are available.

Accordingly, for carbon steels containing more than 0.4% C and alloy steels containing more than 0.35% C, transfer of parts to tempering furnaces before they cool to below 100 to 150 °C (210 to 300 °F) is recommended. Alternately, quenching oil may be used in tempering operation (martempering), or to avoid cooling below 125 °C (255 °F). Steels that are known to be sensitive to this type of cracking include 1060, 1090, 1340, 4063, 4150, 4340, 52100, 6150, 8650, and 9850.

Other carbon and alloy steels generally are less sensitive to this type of delayed quench cracking but may crack as a result of part configuration or surface defects. These steels include 1040, 1050, 1141, 1144, 4047, 4132, 4140, 4640, 8632, 8740, and 9840. Some steels, such as 1020, 1038, 1132, 4130, 5130, and 8630, are not sensitive.

Before being tempered, parts should be quenched to room temperature to ensure the transformation of most of the austenite to martensite and to

achieve maximum as-quenched hardness. Austenite retained in low-alloy steels will, upon heating for tempering, transform to an intermediate structure, reducing overall hardness. However, in medium- to high-alloy steels containing austenite-stabilizing elements (nickel, for example), retained austenite may transform to martensite upon cooling from tempering, and such steels may require additional tempering (double tempering) for the relief of transformation stresses.

## Temper Embrittlement

When carbon or low-alloy steels are cooled slowly from tempering above 575 °C (1065 °F) or are tempered for extended times between 375 and 575 °C (705 and 1065 °F), a loss in toughness occurs that manifests itself in reduced notched-bar impact strength compared to that resulting from normal tempering cycles and relatively fast cooling rates.

The cause of temper embrittlement is believed to be the precipitation of compounds containing trace elements such as tin, arsenic, antimony, and phosphorus, along with chromium and/or manganese. Although manganese and chromium cannot be restricted, a reduction of the other elements and quenching from above 575 °C (1065 °F) are the most effective remedies for this type of embrittlement.

Steels that have been embrittled because of temper embrittlement can be de-embrittled by heating to about 575 °C (1065 °F), holding a few minutes, then cooling or quenching rapidly. The time for de-embrittlement depends on the alloying elements present and the temperature of reheating (Ref 11).

## Blue Brittleness

The heating of plain carbon steels or some alloy steels to the temperature range of 230 to 370 °C (445 to 700 °F) may result in increased tensile and yield strength, as well as decreased ductility and impact strength. This embrittling phenomenon is caused by precipitation hardening and is called blue brittleness because it occurs within the blue heat range.

If susceptible steels are heated within the 230 to 370 °C (445 to 700 °F) range, they may be embrittled and thus should not be used in parts subjected to impact loads.

## Tempered Martensite Embrittlement

Both intergranular (Ref 13-15) and transgranular fracture modes may be observed in tempered martensite embrittlement (Ref 13, 16). The combination of the segregation of impurities such as phosphorus to the austenitic grain boundaries during austenitizing and the formation of cementite at prior austenitic grain boundaries during tempering are responsible.



**Effect of tempering time at six temperatures on room-temperature hardness of carbon-molybdenum steels with different carbon contents but with prior martensitic structures**
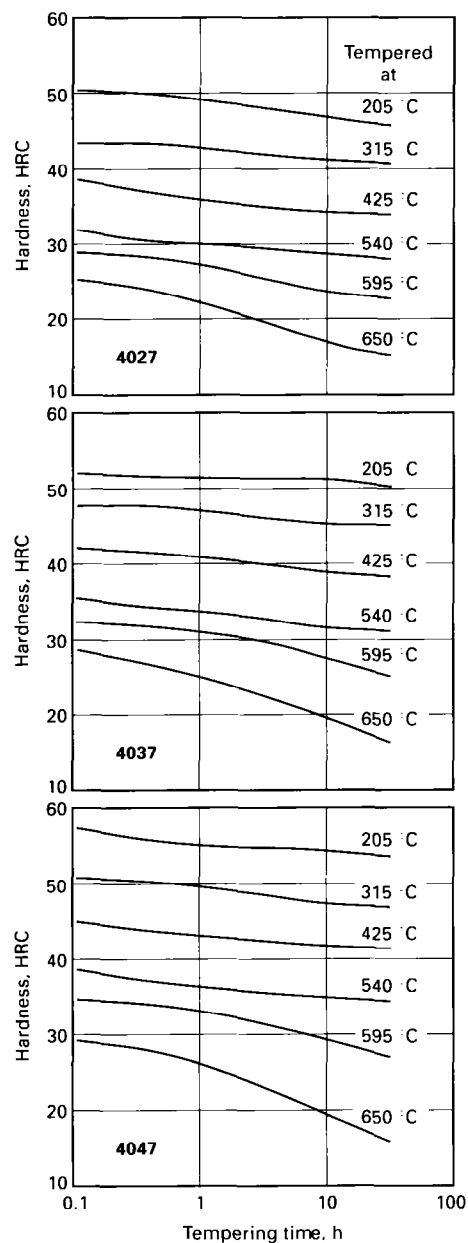


**Effect of carbon content and tempering temperature on room-temperature hardness of three molybdenum steels. Tempering time: 1 h at temperature**
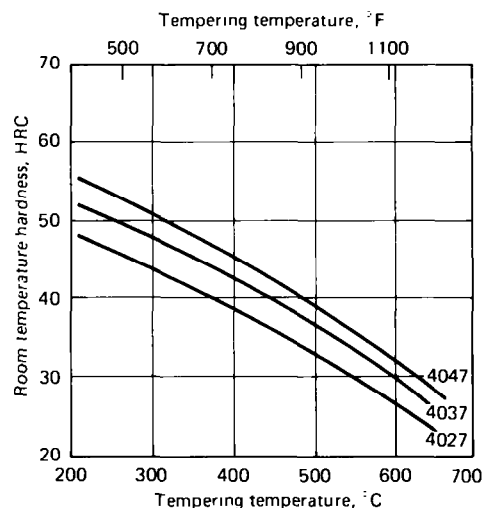
There is a loss in impact toughness for steels tempered in the temperature range of 250 to 300 °C (480 to 570 °F). Steels with lower phosphorus content have superior impact properties than steels with a higher phosphorus level. Also, impact toughness decreases with increasing carbon content (Ref 17). Generally, with steels containing either potent carbide forms such as chromium or other impurities that make them susceptible to tempered martensite embrittlement, tempering between 200 to 370 °C (390 to 700 °F) should be avoided.

## Hydrogen Embrittlement

The selection of tempering temperature and the resultant hardness or plasticity must include the consideration of the potential problem of hydrogen embrittlement under these conditions: the part will be exposed to hydrogen through electroplating, phosphating, or other means, or where environmental conditions will cause the cathodic absorption of hydrogen during service.

Generally, the restricted notch ductility of steels with hardnesses above 40 HRC presents ideal conditions for the development of stress concentrations in parts containing notches or defects that would, in the presence of relatively low hydrogen concentrations, lead to failure at stresses far below the nominal tensile strength of the material. Such parts should be tempered to hardness below 40 HRC if they are to be subjected to relatively high stresses and probable exposure to hydrogen.

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# Martempering of Steel

The process entails an interrupted quench from the austenitizing temperature of certain alloy, cast, tool, and stainless steels. Cooling is delayed just above martensitic transformation for the time needed to equalize temperature throughout a part, for the purpose of minimizing distortion, cracking, and residual stress. The resulting microstructure is primarily martensitic, and is untempered and brittle.

Differences between conventional quenching and martempering (aka marquenching) are shown in an adjoining Figure (see a and b).



**Time-temperature transformation diagrams with superimposed cooling curves showing quenching and tempering.** (a) Conventional process. (b) Martempering. (c) Modified martempering
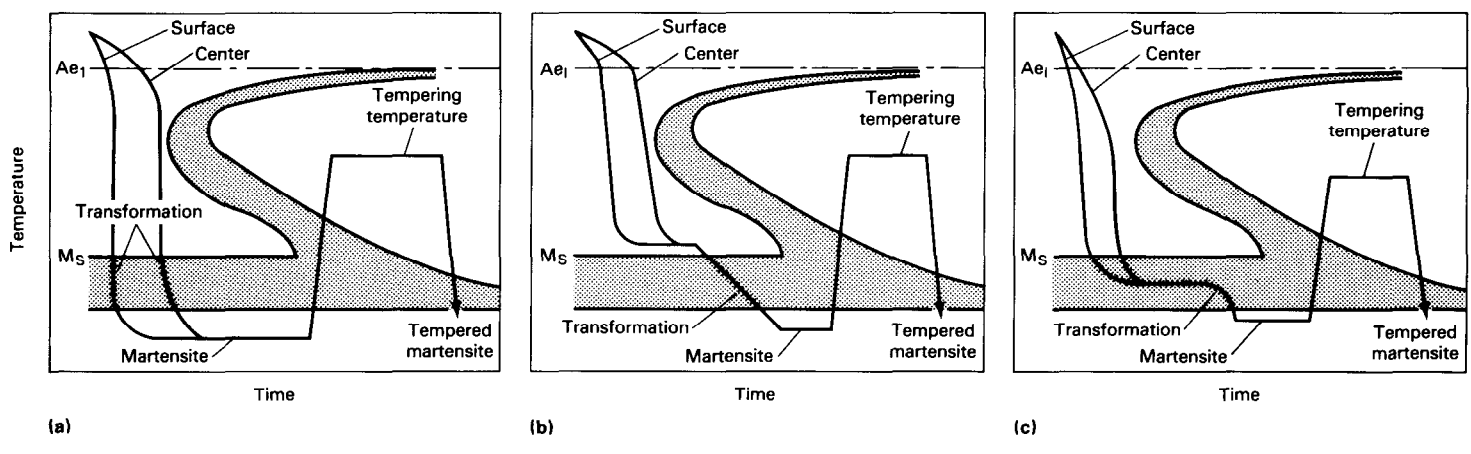
## Mechanical Properties of 1095 Steel Heat Treated by Two Methods

| Specimen number | Heat treatment | Hardness, HRC | Impact energy | | Elongation(a), % |
|---|---|---|---|---|---|
| | | | J | ft · lbf | |
| 1 | Water quench and temper | 53.0 | 16 | 12 | 0 |
| 2 | Water quench and temper | 52.5 | 19 | 14 | 0 |
| 3 | Martemper and temper | 53.0 | 38 | 28 | 0 |
| 4 | Martemper and temper | 52.8 | 33 | 24 | 0 |

(a) In 25 mm or 1 in.

Marquenching of wrought steel and cast iron consists of the following steps:

- Quenching from the austenitizing temperature into a hot fluid medium (oil, molten salt, molten metal, or a fluidized particle bed) at a temperature usually above the martensitic range ($M_s$ point)
- Holding in the quenching medium until the temperature throughout a part is uniform
- Cooling, usually in air, at a moderate rate to prevent large differences between temperatures on the outside and center of a section

During cooling to room temperature, the formation of martensite throughout a part is fairly uniform, which avoids excessive residual stresses. When the still-hot part is removed from the bath, it is easy to straighten or to form, and will hold its shape on subsequent cooling in a fixture, or in air cooling after removal from a forming die. Following marquenching, parts are tempered in the same manner as conventionally quenched parts. The time lapse between martempering and tempering is not so critical as it is in conventional quenching and tempering operations.

## Advantages of Martempering

Properties of steel treated in conventional water quenching and tempering and steel treated in martempering are compared in an adjoining Table.

In martempering residual stresses are lower than those developed in conventional quenching because the greatest thermal variations come while the steel is still in its relatively plastic austenitic condition and because final transformation and thermal changes occur throughout a part at essentially the same time.

Other advantages of the process:

- Susceptibility to cracking is reduced or eliminated
- When the austenitizing bath is a neutral salt and is controlled by the addition of methane or by proprietary rectifiers to maintain its neutrality, parts are protected with a residual coating of neutral salt until they are immersed in the marquench bath
- Problems with pollution and fire hazards are greatly reduced if nitrate-nitrite salts are used, rather than marquenching oils
- Quenching severity of molten salt is greatly enhanced by agitation and by water additions to the bath
- Martempering often eliminates the need for quenching fixtures, which are required to minimize distortion in conventional quenching

## Modified Martempering

The only difference between this process and standard martempering is the temperature of the quenching bath—it is below that of the $M_s$ point—which increases the severity of the quench (see c in Figure cited previously). This capability is important for steels with lower hardenability that require faster cooling to get greater depth of hardness.

When hot oil is used, the typical martempering temperature in this instance is 175 °C (345 °F). By comparison, molten nitrate-nitrite salt baths with water additions and agitation are effective at temperatures as low as 175 °C (345 °F). The molten salt method has some metallurgical and operational advantages.



**Cooling curves for 1045 steel cylinders quenched in salt, water, and oil.** Thermocouples were located at centers of specimens.
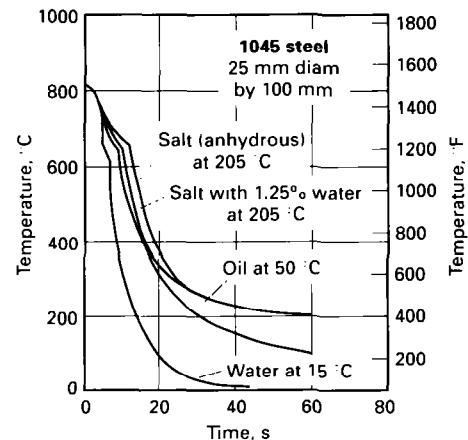
## Martempering Media

Molten salt and hot oil are widely used. Operating temperature is the most common deciding factor in choosing between salt and oil. For oil, the upper temperature is 205 °C (400 °F). Temperatures up to 230 °C (445 °F) are an occasional exception. The range for salt is 160 to 400 °C (320 to 750 °F).

**Composition and Cooling Power of Salt.** A commonly used salt contains 50 to 60% potassium nitrate, 37 to 50% sodium nitrite, and 0 to 10% sodium nitrate. This salt's melting point is approximately 140 °C (285 °F); its working range is 165 to 540 °C (330 to 1000 °F). Salts with a higher melting point (they cost less than the one just described) can be used to get higher operating temperatures. Their composition: 40 to 50% potassium nitrate, 0 to 30% sodium nitrite, and 20 to 60% sodium nitrate.

The cooling power of agitated salt at 205 °C (400 °F) is about the same as that of agitated oil in conventional oil quenching. Water additions increase the cooling power of salt, as indicated by cooling curves in an adjoining Figure and hardness values in a second Figure, in which the cooling power of water is compared with that of water and three types of oil.
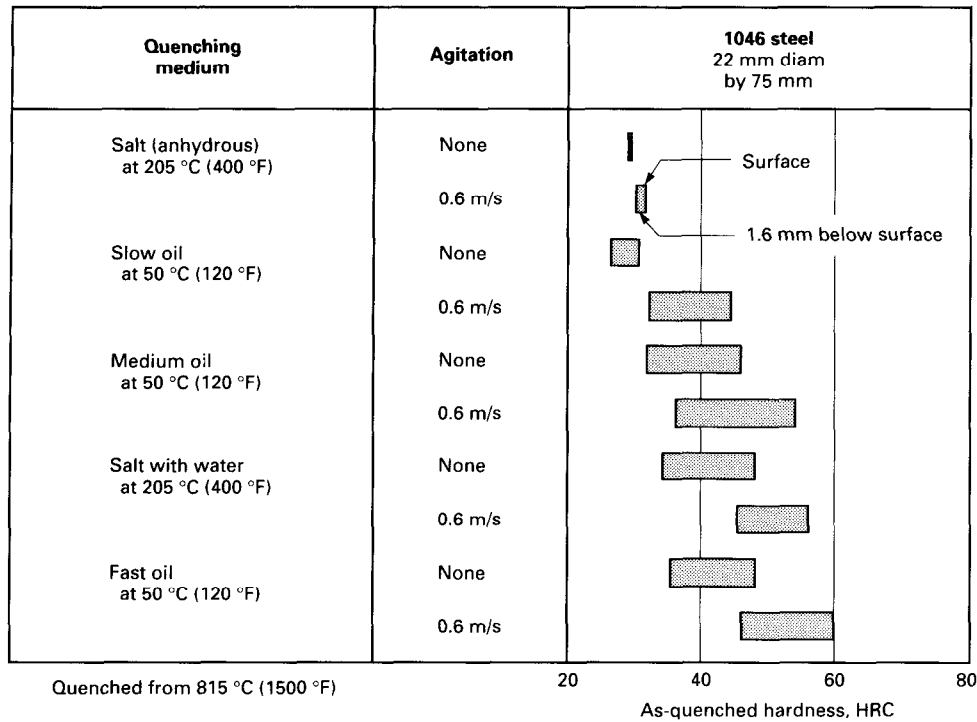
**Salt Vs. Oil.** Advantages of salt include the following:

- Changes in viscosity are slight over a wide temperature range
- Salt retains its chemical stability. Replenishment, usually, is needed only to replace dragout losses
- Salt is easily washed from work with plain water

**Disadvantages, salt vs. oil** include the following:

- Minimum operating temperature of salt is 160 °C (320 °F)
- Quenching from cyanide-based carburizing salt is hazardous because of possible explosion; explosion and splatter can occur if wet or oily parts

**Effects of quenchant and agitation on hardness of 1046 steel**

| Quenching medium | Agitation | 1046 steel 22 mm diam by 75 mm |
|---|---|---|
| Salt (anhydrous) at 205 °C (400 °F) | None | |
| | 0.6 m/s | |
| Slow oil at 50 °C (120 °F) | None | |
| | 0.6 m/s | |
| Medium oil at 50 °C (120 °F) | None | |
| | 0.6 m/s | |
| Salt with water at 205 °C (400 °F) | None | |
| | 0.6 m/s | |
| Fast oil at 50 °C (120 °F) | None | |
| | 0.6 m/s | |

Quenched from 815 °C (1500 °F)

As-quenched hardness, HRC

## Physical Properties of Two Oils Used for Martempering of Steel

| Property | Value, for oil with operating temperature of | |
|---|---|---|
| | 95 to 150 °C (200 to 300 °F)(a) | 150 to 230 °C (300 to 450 °F) |
| Flash point (min), °C (°F) | 210 (410) | 275 (525) |
| Fire point (min), °C (°F) | 245 (470) | 310 (595) |
| Viscosity, SUS, at: | | |
| 38 °C (100 °F) | 235-575 | ... |
| 100 °C (210 °F) | 50.5-51 | 118-122 |
| 150 °C (300 °F) | 36.5-37.5 | 51-52 |
| 175 °C (350 °F) | ... | 42-43 |
| 205 °C (400 °F) | ... | 38-39 |
| 230 °C (450 °F) | ... | 35-36 |
| Viscosity index (min) | 95 | 95 |
| Acid number | 0.00 | 0.00 |
| Fatty-oil content | None | None |
| Carbon residue | 0.05 | 0.45 |
| Color | Optional | Optional |

(a) Temperature range for modified martempering

are immersed in high-temperature salt; and there is potential for explosive reactions when atmosphere furnaces are connected to martempering salt quenches and atmospheres are sooty
• Quenching salt can be contaminated by high-temperature, neutral salt used for heating. To maintain quench severity, sludging is required

**Niche for Fluidized Beds.** Marquenching applications are limited. They have the advantage of equal heat transfer throughout the entire quenching temperature range. The quench rate is reproducible, does not degrade with time, and can be adjusted within wide limits.

## Oils For Martempering

Properties of two commonly used oils are listed in an adjoining Table. Compounded for the process, they provide higher rates of cooling than conventional oils during the initial stage of quenching.

At temperatures between 95 to 230 °C (205 to 445 °F) quenching oil requires special handling. It must be maintained under a protective atmosphere (reducing or neutral) to prolong its life. Exposure to air at elevated temperatures speeds up the deterioration of oil. For every 10 °C above 60 °C (18 above 140 °F) the oxidation rate approximately doubles, causing the formation of sludge and acid, which can affect the hardness and color of workpieces.

Oil life can be extended and the production of clean work can be maintained by using bypass or continuous filter units containing suitable filtering media (clay, cellulose cartridge, or waste cloth). Oils should be circulated at a rate no lower than 0.9 m/s (180 ft/min) to break up excessive vapor formed during quenching.

**Advantages of oil vs. salt** include the following:

• Oil can be used at lower temperatures
• Oil is easier to handle at room temperature
• Dragout is less

**Disadvantages of oil vs. salt** include the following:

• Maximum operating temperature of oil is 230 °C (445 °F)
• Oil deteriorates with usage
• Workpieces require more time to reach temperature equalization
• Oil, hot or cold, is a fire hazard
• Soap or emulsifier is needed to wash off oil. Washers must be drained and refilled periodically. Oil wastes present disposal problems

## Martempering Applications

Alloy steels generally are more adaptable than carbon steels to martempering (see Figure). In general, any steel that is normally quenched in oil can be martempered. Some carbon steels that are normally water quenched can be martempered at 205 °C (400 °F) in sections thinner than 5 mm

(0.1875 in.), using vigorous agitation of the martempering medium. In addition, thousands of gray cast iron parts are martempered on a routine basis.
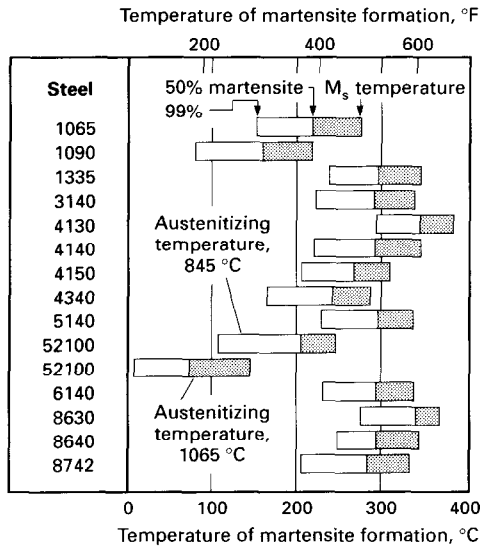
The grades of steel that are commonly martempered to full hardness include 1090, 4130, 4140, 4150, 4340, 300M (4340M), 4640, 5140, 6150, 8630, 8640, 8740, 8745, SAE 1141, and SAE 52100. Carburizing grades such as 3312, 4620, 5120, 8620, and 9310 also are commonly martempered after carburizing. Occasionally, higher-alloy steels such as type 410 stainless are martempered, but this is not a common practice.

Success in martempering is based on a knowledge of the transformation characteristics (TTT curves) of the steel being considered. The temperature range in which martensite forms is especially important.
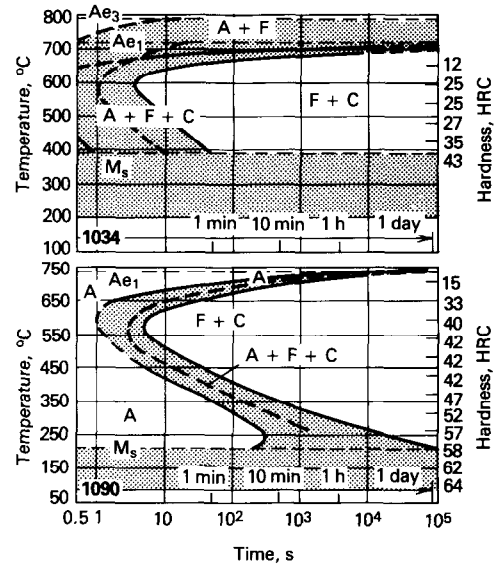
**Low-carbon and medium-carbon steels** 1008 through 1040 are too low in hardenability to be successfully martempered, except when carburized. The TTT curve for the 1034 steel in an adjoining Figure is characteristic of a steel that is unsuitable for martempering. Except in sections only a few thousandths of an inch thick, it would be impossible to quench the steel in hot salt or oil without encountering upper transformation products.

**Borderline Grades.** Some carbon steels higher in manganese content such as 1041 and 1141 can be martempered in thin sections. Low-alloy steels that have limited applications for martempering are listed (the lower-carbon grades are carburized before martempering): 1330 to 1345, 4012 to

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### Temperature ranges of martensite formation in 14 carbon and low-alloy steels



Temperature of martensite formation, °F

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### Approximate maximum diameters of bars that are hardenable by martempering, oil quenching, and water quenching.



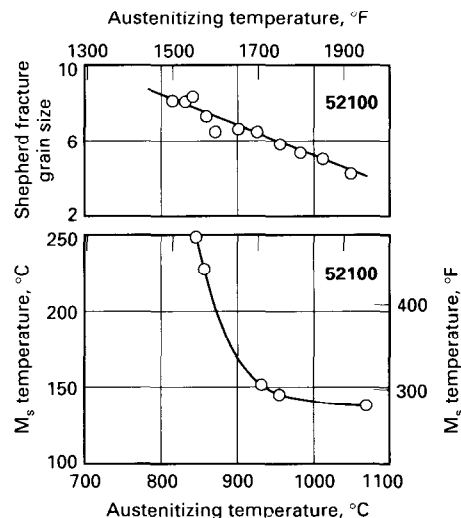Maximum diameter of bar that will harden to the center, in.

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### Time-temperature transformation diagrams for 1034 and 1090 steels. The 1090 steel was austenitized at 885 °C (1625 °F) and had a grain size of 4 to 5.



Time, s

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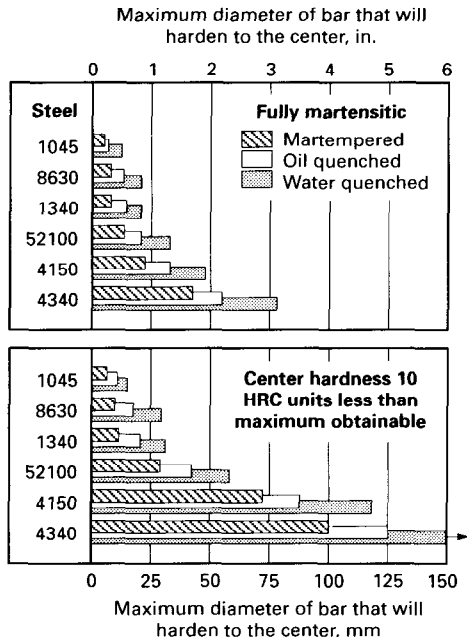
### Effects of austenitizing temperature on grain size and M$_s$ temperature of 52100 steel

4042, 4118 to 4137, 4422 and 4427, 4520, 5015 and 5046, 6118 and 6120, 8115.

Most of these alloy steels are suitable for martempering in section thicknesses of up to 16 to 19 mm (0.625 to 0.75 in.). Martempering at temperatures below 205 °C (400 °F) will improve hardening response, although greater distortion may result than in martempering at higher temperatures.

**Effect of Mass.** The limitation of section thickness or mass must be considered in martempering. With a given severity of quench, there is a limit to bar size beyond which the center of the bar will not cool fast enough to transform entirely to martensite. This is shown in an adjoining Figure, which compares the maximum diameter of bar that can be hardened by martempering, oil quenching, and water quenching for 1045 steel and five alloy steels in various hardenabilities.

For some applications, a fully martensitic structure is unnecessary and a center hardness 10 HRC units lower than the maximum obtainable value for a given carbon content may be acceptable. By this criterion, maximum bar diameter is 25 to 300% greater than the maximum diameter that can be made fully martensitic (see lower graph in Figure just cited). Non-martensitic transformation products (pearlite, ferrite, and bainite) were observed at the positions on end-quenched bars corresponding to this reduced hardness value, as follows:

| Steel | Transformation |
|---|---|
| 1045 | 15% pearlite |
| 8630 | 10% ferrite and bainite |
| 1340 | 20% ferrite and bainite |
| 52100 | 50% pearlite and bainite |
| 4150 | 20% bainite |
| 4340 | 5% bainite |

## Control of Process Variables

The success of martempering depends on close control of variables throughout the process. It is important that the prior structure of the material being austenitized be uniform. Also, use of a protective atmosphere (or salt) in austenitizing is required because oxide or scale will act as a barrier to uniform quenching in hot oil or salt.

Process variables that must be controlled include austenitizing temperature, temperature of martempering bath, time in martempering bath, salt contamination, water additions to salt, agitation, and rate of cooling from the martempering bath.

**Austenitizing temperature** is important because it controls austenitic grain size, degree of homogenization, and carbide solution, and because it affects the $M_s$ temperature and increases grain size. (See adjoining Figure.)

Temperature control during austenitizing is the same for martempering as for conventional quenching: a tolerance of ±8 °C (±14 °F) is common. The austenitizing temperatures most commonly used for several different steels are indicated in an adjoining Table.

In most instances, austenitizing temperatures for martempering are the same as those for conventional oil quenching. Occasionally, however, medium-carbon steels are austenitized at higher temperatures prior to martempering to increase as-quenched hardness.

**Salt Contamination.** When parts are carburized or austenitized in a salt bath, they can be directly quenched in an oil bath operating at the martempering temperature. However, if the parts are carburized or austenitized in salt containing cyanide, they must *not* be directly martempered in salt because the two types of salts are not compatible and explosions can occur if they are mixed. Instead, one of two procedures should be used: Either air cool from the carburizing bath, wash, reheat to the austenitizing temperature for case and/or core in a chloride bath, and then martemper; or quench from the cyanide-containing bath into a neutral chloride rinse bath maintained at the austenitizing temperature and then martemper.

**Temperature of the martempering bath** varies considerably, depending on composition of workpieces, austenitizing temperature, and desired results. In establishing procedures for new applications, many plants begin at 95 °C (205 °F) for oil quenching, or at about 175 °C (345 °F) for salt quenching, and progressively increase the temperature until the best combination of hardness and distortion is obtained. Martempering temperatures (for oil and salt) that represent the experience of several plants are listed in the Table previously cited.

## Typical Austenitizing and Martempering Temperatures for Various Steels

| | Austenitizing temperature | | Martempering temperature | | | |
| | | | Oil(a) | | Salt(b) | |
| Grade | °C | °F | °C | °F | °C | °F |
|---|---|---|---|---|---|---|
| **Through-hardening steels** | | | | | | |
| 1024 | 870 | 1600 | 135 | 275 | ... | ... |
| 1070 | 845 | 1550 | 175 | 350 | ... | ... |
| 1146 | 815 | 1500 | 175 | 350 | ... | ... |
| 1330 | 845 | 1550 | 175 | 350 | ... | ... |
| 4063 | 845 | 1550 | 175 | 350 | ... | ... |
| 4130 | 845 | 1550 | ... | ... | 205-260 | 400-500 |
| 4140 | 845 | 1550 | 150 | 300 | ... | ... |
| 4140 | 830 | 1525 | ... | ... | 230-275 | 450-525 |
| 4340, 4350 | 815 | 1500 | .. | ... | 230-275 | 450-525 |
| 52100 | 855 | 1575 | 190 | 375 | ... | ... |
| 52100 | 845 | 1550 | .. | .. | 175-245 | 350-475 |
| 8740 | 830 | 1525 | ... | ... | 230-275 | 450-525 |
| **Carburizing steels** | | | | | | |
| 3312 | 815 | 1500 | ... | ... | 175-190 | 350-375 |
| 4320 | 830 | 1525 | ... | . | 175-190 | 350-375 |
| 4615 | 955 | 1750 | 190 | 375 | ... | .. |
| 4720 | 845 | 1550 | ... | ... | 175-190 | 350-375 |
| 8617, 8620 | 925 | 1700 | 150 | 300 | ... | .. |
| 8620 | 855 | 1575 | ... | .. | 175-190 | 350-375 |
| 9310 | 815 | 1500 | ... | ... | 175-190 | 350-375 |

(a) Time in oil varies from 4 to 20 min, depending on section thickness. (b) Martempering temperature depends on shape and mass of parts being quenched; higher temperatures in range (and sometimes above range) are used for thinner sections and more intricate parts.

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**Time in the martempering bath** depends on section thickness and on the type, temperature, and degree of agitation of the quenching medium. The effects of section thickness and of temperature and agitation of the quench bath on immersion time are indicated in an adjoining Figure.

Because the object of martempering is to develop a martensitic structure with low thermal and transformation stresses, there is no need to hold the steel in the martempering bath for extended periods. Excessive holding lowers final hardness because it permits transformation to products other than martensite. In addition, stabilization may occur in medium-alloy steels that are held for extended periods at the martempering temperature.

The martempering time for temperature equalization in oil is about four to five times that required in anhydrous salt at the same temperature.

**Water Additions to Salt.** The quenching severity of a nitrate-nitrite salt can be increased significantly by careful addition of water. Agitation of the salt is necessary to disperse the water uniformly, and periodic additions are needed to maintain required water content. The water can be added with complete safety as follows:

- Water can be misted at a regulated rate into a vigorously agitated area of the molten bath
- In installations where the salt is pump circulated, returning salt is cascaded into the quench zone. A controlled fine stream of water can be injected into the cascade of returning salt
- The austempering bath can be kept saturated with moisture by introducing steam directly into the bath. The steam line should be trapped and equipped with a discharge to avoid emptying condensate directly into the bath
- Steam addition of water to the bath is done on baths with operating temperatures above 260 °C (500 °F)

**Martempering time versus section size and agitation of quench bath for 1045 steel bars.** Effects of bar diameter and agitation of quench bath on time required for centers of 1045 steel bars to reach martempering temperature when quenched from a neutral chloride bath at 845 °C (1555 °F) into anhydrous nitrate-nitrite martempering salt at 205, 260, and 315 °C (400, 500, and 600 °F). Length of each bar was three times the diameter.
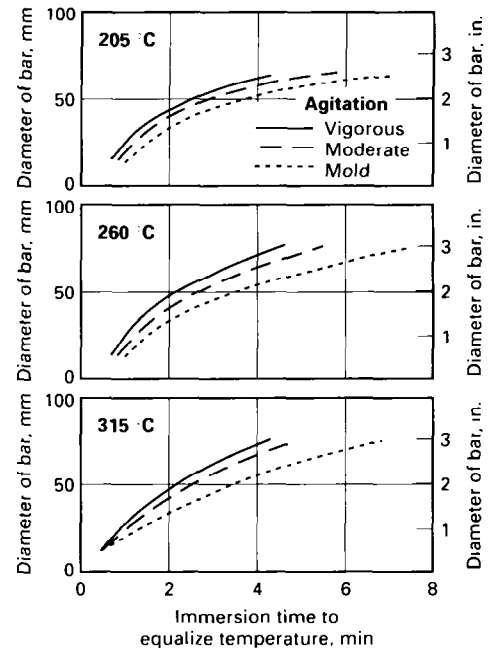


# Austempering of Steel

In this process, a ferrous alloy is isothermally quenched at a temperature below that of pearlite formation.

Workpieces are heated to a temperature within the austenitizing range, usually 790 to 915 °C (1455 to 1680 °F).

Quenching is in a bath maintained at a constant temperature, usually in a range of 260 to 400 °C (500 to 750 °F).

Parts are allowed to transform isothermally to bainite in this bath. Cooling to room temperature completes the process.

The basic differences between austempering and conventional quenching and tempering is shown schematically in an adjoining Figure. In true austempering, metal must be cooled from the austenitic temperature to the temperature of the austempering bath fast enough to ensure complete transformation of austenite to bainite.

Treatment of hardenable cast irons is another application. In this case, a unique acicular matrix of bainitic ferrite and stable high-carbon austenite is formed.

Advantages of austempering include higher ductility, toughness, and strength at a given hardness (see Table) and reduced distortion. In addition, the overall time cycle is the shortest needed to get through hardness within the range of 35 to 55 HRC.

## Quenching Media

Molten salt is the most commonly used. Formulations and characteristics of two typical baths are given in an adjoining Table. The high range of salt is suitable for only austempering, while the wide range type is suitable for austempering, martempering, and variations thereof. Quench severities under different conditions are compared in an adjoining Table.

The quenching severity of a nitrate-nitrite salt can be boosted significantly with careful additions of water. The salt must be agitated to disperse the water uniformly. Periodic additions are needed to maintain required water content.

Water usually is added by directing a stream onto the molten salt at the agitator vortex. A protective water shroud surrounds the water spray to prevent spattering. Turbulence of the water carries it into the bath without spattering, a hazard to the operator. Water should never be added from a pail or dipper. Water is continuously evaporating from the bath at a rate which increases as hot work is quenched. The amount of water added to an

**Compositions and characteristics of salts used for austempering**

|  | High range | Wide range |
|---|---|---|
| Sodium nitrate, % | 45-55 | 0-25 |
| Potassium nitrate, % | 45-55 | 45-55 |
| Sodium nitrite, % | ... | 25-55 |
| Melting point (approx), °C (°F) | 220 (430) | 150-165 (300-330) |
| Working temperature range, °C (°F) | 260-595 (500-1100) | 175-540 (345-1000) |

**Comparison of time-temperature transformation cycles for conventional quenching and tempering and for austempering**
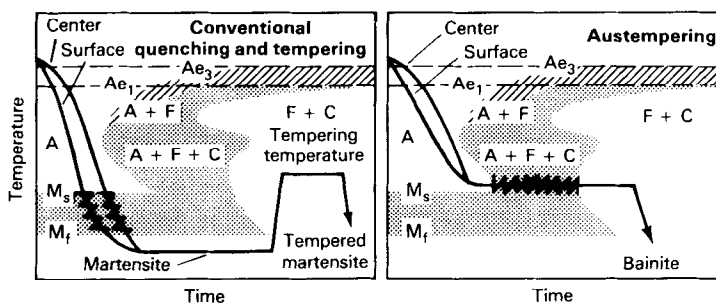


## Mechanical Properties of 1095 Steel Heat Treated by Three Methods

| Specimen No. | Heat treatment | Hardness, HRC | Impact strength | | Elongation in 25 mm, or 1 in., % |
|---|---|---|---|---|---|
| | | | J | ft · lbf | |
| 1 | Water quenched and tempered | 53.0 | 16 | 12 | ... |
| 2 | Water quenched and tempered | 52.5 | 19 | 14 | ... |
| 3 | Martempered and tempered | 53.0 | 38 | 28 | ... |
| 4 | Martempered and tempered | 52.8 | 33 | 24 | ... |
| 5 | Austempered | 52.0 | 61 | 45 | 11 |
| 6 | Austempered | 52.5 | 54 | 40 | 8 |

open bath varies with the operating temperature of the salt, as indicated by the following recommended concentrations:

| Temperature | | Water concentration, % |
|---|---|---|
| °C | °F | |
| 205 | 400 | ½ to 2 |
| 260 | 500 | ½ to 1 |
| 315 | 600 | ¼ to ½ |
| 370 | 700 | ¼ |

The presence of water can be visually detected by the operator because steam is released when hot work is immersed into the nitrate-nitrite salt.

**Oil as Quenching Media.** Usage is restricted to quenching below 245 °C (475 °F), because of oil's chemical instability, resulting in changes of viscosity at austempering temperatures.

## Austempering Steels

Selection is based on the transformation characteristics of a specific steel as indicated by time-temperature-transformation (TTT) diagrams. Three important considerations are:

- Location of the nose of the TTT curve and the speed of a quench
- Time needed for complete transformation of austenite to bainite at the austempering temperature
- Location of the $M_s$ point

Because of its transformation characteristics, 1080 carbon steel has limited applicability for austempering (see Figure). Cooling must take place in about 1 s to avoid the nose of the TTT curve to prevent transformation to pearlite on cooling. Because of this disadvantage, austempering of 1080 is limited to thin sections—the maximum is about 5 mm (0.2 in.).

On the other hand, 5140, a low-alloy steel, is well suited to the process (see TTT curves for 1080, 5140, 1034, and 9261 in an adjoining Figure). About 2 s are allowed to bypass the nose of the curve; transformation to bainite is completed within 1 to 10 min at 315 to 400 °C (600 to 750 °F). This means that sections thicker than those possible with 1080 steel are

### Quench severity comparison for salt quenches

| Agitation | Estimated Grossmann number ($H$) at temperature (a) | |
|---|---|---|
| | 180 °C (360 °F) | 370 °C (700 °F) |
| Still and dry | 0.15-0.20 | 0.15 |
| Agitated and dry | 0.25-0.35 | 0.20-0.25 |
| Agitated with 0.5% water | 0.40-0.50 | 0.30-0.40 |
| Agitated with 2% water | 0.50-0.60 | 0.50-0.60(a) |
| Agitated with 10% water | 0.90-1.3(b) | Not possible |

(a) See "Grossmann number ($H$)" in the "Glossary of Terms Related to Heat Treating." (b) Requires special enclosed quenching apparatus

feasible in treating 5140 and other steels with similar transformation characteristics.

## Other austempering steels include:

- Plain carbon steels containing 0.50 to 1.00% carbon and a minimum of 0.60% manganese
- High-carbon steels containing more than 0.90% carbon and, possibly, a little less than 0.60% manganese
- Some carbon steels, such as 1041, with less than 0.50% carbon and manganese in the range of 1.00 to 1.65%
- Certain low alloys, such as 5100 series alloys, that contain over 0.40% carbon, plus other steels such as 4140, 6145, and 9440

Some steels sufficient in carbon or alloy content to be hardenable are borderline or impractical because transformation at the nose of the TTT curve starts in less than 1 s, ruling out the quenching of all but thin sections in molten salt without forming some pearlite, or transformation takes excessively long times.

Chemical composition is the main determinant of the martensite start ($M_s$) temperature. Carbon is the most significant variable. Direct effects of other alloying elements are less pronounced, but carbide-forming elements such as molybdenum and vanadium can tie up carbon as alloy carbides and prevent complete solution of carbon.

**Time-temperature transformation diagram for 1080 steel, showing difference between conventional and modified austempering.** When applied to wire, the modification shown is known as patenting.
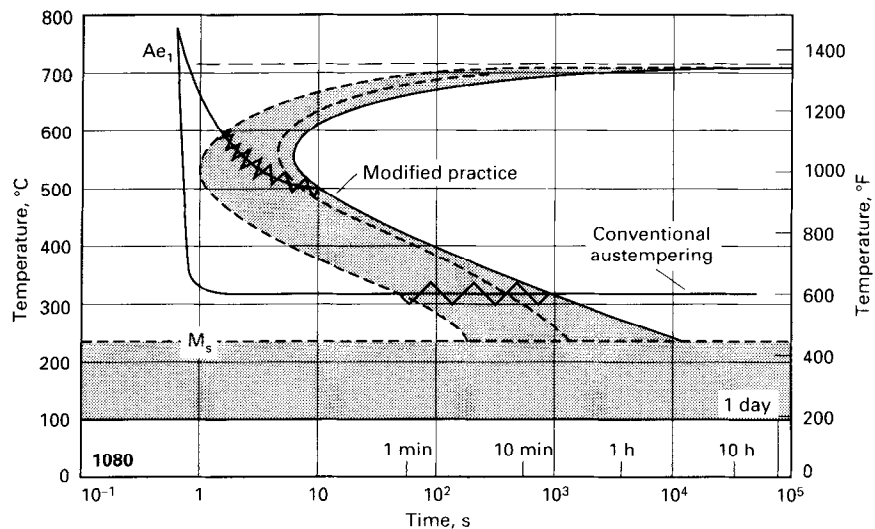


**Transformation characteristics of 1080, 5140, 1034, and 9261 steels, in relation to their suitability for austempering.** 1080, limited suitability for austempering because pearlite reaction starts too soon near 540 °C (1000 °F); 5140, well suited to austempering; 1034, impossible to austemper because of extremely fast pearlite reaction time at 540 to 595 °C (1000 to 1105 °F); 9261, not suited to austempering because of slow reaction to bainite at 260 to 400 °C (500 to 750 °F)
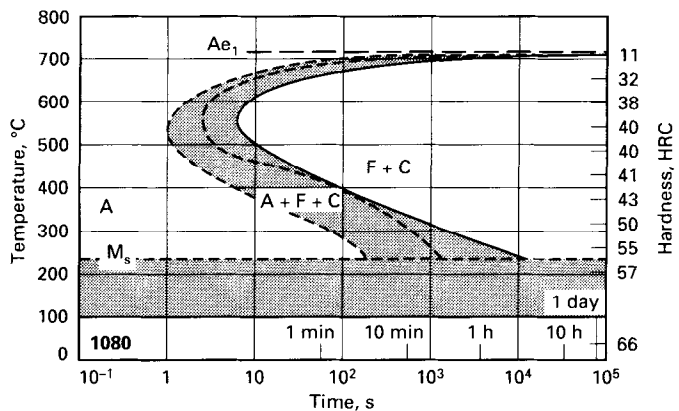


(a)
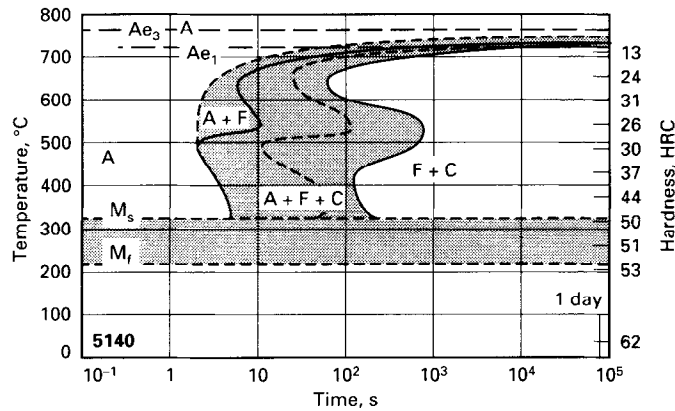
(b)
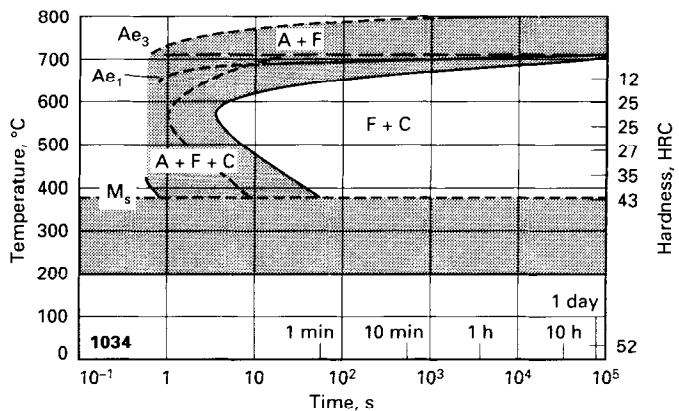
(c)

(d)

## Hardness of Various Steels and Section Sizes of Austempered Parts

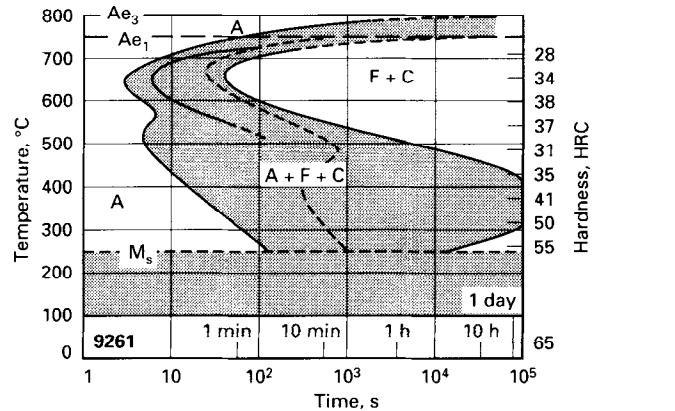| Steel | Section size mm | Section size in. | Salt temperature °C | Salt temperature °F | M, temperature(a) °C | M, temperature(a) °F | Hardness, HRC |
|---|---|---|---|---|---|---|---|
| 1050 | 3(b) | 0.125(b) | 345 | 655 | 320 | 610 | 41-47 |
| 1065 | 5(c) | 0.187(c) | (d) | (d) | 275 | 525 | 53-56 |
| 1066 | 7(c) | 0 281(c) | (d) | (d) | 260 | 500 | 53-56 |
| 1084 | 6(c) | 0.218(c) | (d) | (d) | 200 | 395 | 55-58 |
| 1086 | 13(c) | 0.516(c) | (d) | (d) | 215 | 420 | 55-58 |
| 1090 | 5(c) | 0.187(c) | (d) | (d) | ... | ... | 57-60 |
| 1090(e) | 20(c) | 0.820(c) | 315(f) | 600(f) | ... | ... | 44.5 (avg) |
| 1095 | 4(c) | 0.148(c) | (d) | (d) | 210(g) | 410(g) | 57-60 |
| 1350 | 16(c) | 0.625(c) | (d) | (d) | 235 | 450 | 53-56 |
| 4063 | 16(c) | 0.625(c) | (d) | (d) | 245 | 475 | 53-56 |
| 4150 | 13(c) | 0.500(c) | (d) | (d) | 285 | 545 | 52 max |
| 4365 | 25(c) | 1.000(c) | (d) | (d) | 210 | 410 | 54 max |
| 5140 | 3(b) | 0.125(b) | 345 | 655 | 330 | 630 | 43-48 |
| 5160(e) | 26(c) | 1.035(c) | 315(f) | 600(f) | 255 | 490 | 46.7 (avg) |
| 8750 | 3(b) | 0.125(b) | 315 | 600 | 285 | 545 | 47-48 |
| 50100 | 8(c) | 0.312(c) | (d) | (d) | ... | ... | 57-60 |

(a) Calculated. (b) Sheet thickness. (c) Diameter of section. (d) Salt temperature adjusted to give maximum hardness and 100% bainite. (e) Modified austempering: microstructure contained pearlite as well as bainite. (f) Salt with water additions. (g) Experimental value

## Typical Production Applications of Austempering

Parts listed in order of increasing section thickness

| Part | Steel | Maximum section thickness mm | Maximum section thickness in. | Parts per unit weight kg | Parts per unit weight lb | Salt temperature °C | Salt temperature °F | Immersion time, min | Hardness, HRC |
|---|---|---|---|---|---|---|---|---|---|
| **Plain carbon steel parts** | | | | | | | | | |
| Clevis | 1050 | 0.75 | 0.030 | 770/kg | 350/lb | 360 | 680 | 15 | 42 |
| Follower arm | 1050 | 0.75 | 0.030 | 412/kg | 187/lb | 355 | 675 | 15 | 42 |
| Spring | 1080 | 0.79 | 0.031 | 220/kg | 100/lb | 330 | 625 | 15 | 48 |
| Plate | 1060 | 0.81 | 0.032 | 88/kg | 40/lb | 330 | 630 | 6 | 45-50 |
| Cam lever | 1065 | 1.0 | 0.040 | 62/kg | 28/lb | 370 | 700 | 15 | 42 |
| Plate | 1050 | 1.0 | 0.040 | 0.5 kg | 1¼ lb | 360 | 675 | 15 | 42 |
| Type bar | 1065 | 1 0 | 0.040 | 141/kg | 64/lb | 370 | 700 | 15 | 42 |
| Tabulator stop | 1065 | 1.22 | 0.048 | 440/kg | 200/lb | 360 | 680 | 15 | 45 |
| Lever | 1050 | 1.25 | 0 050 | ... | ... | 345 | 650 | 15 | 45-50 |
| Chain link | 1050 | 1.5 | 0.060 | 573/kg | 260/lb | 345 | 650 | 15 | 45 |
| Shoe-last link | 1065 | 1.5 | 0.060 | 86/kg | 39/lb | 290 | 550 | 30 | 52 |
| Shoe-toe cap | 1070 | 1.5 | 0.060 | 18/kg | 8/lb | 315 | 600 | 60 | 50 |
| Lawn mower blade | 1065 | 3.18 | 0.125 | 1 5 kg | ⅔ lb | 315 | 600 | 15 | 50 |
| Lever | 1075 | 3.18 | 0.125 | 24/kg | 11/lb | 385 | 725 | 5 | 30-35 |
| Fastener | 1060 | 6.35 | 0.250 | 110/kg | 50/lb | 310 | 590 | 25 | 50 |
| Stabilizer bar | 1090 | 19 | 0.750 | 22 kg | 10 lb | 370 | 700 | 6-9 | 40-45 |
| Boron steel bolt | 10B20 | 6.35 | 0.250 | 100/kg | 45/lb | 420 | 790 | 5 | 38-43 |
| **Alloy steel parts** | | | | | | | | | |
| Socket wrench | 6150 | . | ... | 0.3 kg | ⅛ lb | 365 | 690 | 15 | 45 |
| Chain link | Cr-Ni-V(a) | 1.60 | 0 063 | 110/kg | 50/lb | 290 | 550 | 25 | 53 |
| Pin | 3140 | 1 60 | 0.063 | 5500/kg | 2500/lb | 325 | 620 | 45 | 48 |
| Cylinder liner | 4140 | 2.54 | 0.100 | 15 kg | 7 lb | 260 | 500 | 14 | 40 |
| Anvil | 8640 | 3.18 | 0.125 | 1 65 kg | ¾ lb | 370 | 700 | 30 | 37 |
| Shovel blade | 4068 | 3.18 | 0.125 | ... | ... | 370 | 700 | 15 | 45 |
| Pin | 3140 | 6.35 | 0.250 | 100/kg | 45/lb | 370 | 700 | 45 | 40 |
| Shaft | 4140(b) | 9.53 | 0 375 | 0.5 kg | 1¼ lb | 385 | 725 | 15 | 35-40 |
| Gear | 6150 | 12.7 | 0.500 | 4.4 kg | 2 lb | 305 | 580 | 30 | 45 |
| **Carburized steel parts** | | | | | | | | | |
| Lever | 1010 | 3.96 | 0.156 | 33 kg | 15 lb | 385 | 725 | 5 | 30-35(c) |
| Shaft | 1117 | 6.35 | 0.250 | 66/kg | 30/lb | 385 | 725 | 5 | 30-35(c) |
| Block | 8620 | 11.13 | 0.438 | 132/kg | 60/lb | 290-315 | 550-600 | 30 | 50(c) |

(a) Contains 0.65 to 0.75% C  (b) Leaded grade. (c) Case hardness

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**Effect of carbon content in plain carbon steel on the hardness of fine pearlite formed when the quenching curve intersects the nose of the time-temperature diagram for Isothermal transformation**



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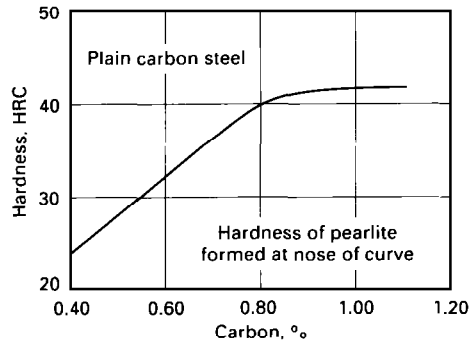
Austenitizing temperature has a significant effect on the time at which transformation begins. As this temperature rises above normal (for a given steel) the nose of the TTT curve shifts to the right because of grain coarsening. Use of standard austenitizing temperatures is recommended.

## Section Thickness Limitations

Maximum section thickness is important in determining if a part is a candidate for austempering. The maximum for a 1080 steel, for instance, is about 5 mm (0.2 in.), if the part requires a fully bainitic structure. Steels lower in carbon are restricted to proportionately less thicknesses. However, heavier sections can be handled if a low-carbon steel contains boron. Also, sections thicker than 5 mm (0.2 in.) are regularly austempered in production when some pearlite is tolerated (see Table that lists section thicknesses for specific steels).

## Applications

Austempering usually is substituted for conventional quenching and tempering for these reasons:

- To improve mechanical properties
- To reduce the likelihood of cracking and distortion
- To upgrade wear resistance at a given hardness
- To add resistance to subsequent embrittlement

At times, austempering is more economical than conventional quenching and tempering—most likely when small parts are treated in an automated setup in competition with conventional quenching and tempering, which is a three-step operation: austenitizing, quenching, and tempering. Austem-

pering is a two-step process: austenitizing and isothermal transformation in an austempering bath.

Generally, applications are limited to parts made from small-diameter bars or from sheet or strip which is small in cross section. The process is especially suitable for the treatment of thin section, carbon steel parts calling for exceptional toughness at hardnesses between 40 and 50 HRC.

Reduction in the area of austempered, carbon steel parts usually is much greater than it is for parts conventionally quenched and tempered, as indicated in the following tabulation for 5 mm (0.180 in.) bars of 0.85% carbon, plain carbon steel:

| Austempered mechanical properties | |
|---|---|
| Tensile strength, MPa (ksi) | 1780 (258) |
| Yield strength, MPa (ksi) | 1450 (210) |
| Reduction in area, % | 45 |
| Hardness, HRC | 50 |
| **Quenched and tempered mechanical properties** | |
| Tensile strength, MPa (ksi) | 1795 (260) |
| Yield strength, MPa (ksi) | 1550 (225) |
| Reduction in area, % | 28 |
| Hardness, HRC | 50 |

In commercial austempering practice, acceptable results are obtained with parts having less than 100% bainite. In some instances, 85% bainite is satisfactory. Representative practice in a dozen plants for a variety of parts and steels is summarized in an adjoining Table.

**Dimensional Control.** Dimensional change in austempering usually is less than that experienced in conventional quenching and tempering. The process may be the most effective way to hold close tolerances without excessive straightening or machining after heat treating.

**Modified Austempering.** Modifications of the process that result in mixed pearlite/bainite structures are quite common in commercial practice.

Patenting of wire is an example. Wire or rod is continuously quenched in a bath maintained at 510 to 540 °C (950 to 1000 °F) and held for periods ranging from 10 s (for small wire) to 90 s (for rod). Result: Moderately high strength combined with high ductility.

Modified practice varies from true austempering in that the quenching rate is different; instead of being rapid enough to avoid the nose of the TTT curve, it is sufficiently slow to intersect the nose, which results in the formation of fine pearlite.

Practice is similar for plain carbon steels at hardnesses between 30 and 42 HRC. In this instance, the hardness of steel quenched at a rate that intersects the nose of the TTT curve varies with carbon content (see Figure).