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Volume 4 of 4
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DEPARTMENT OF DEFENSE HANDBOOK

COMPOSITE MATERIALS HANDBOOK

VOLUME 4. METAL MATRIX COMPOSITES

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FOREWORD

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3. Every effort has been made to reflect the latest information on composite materials. The handbook is continually reviewed and revised to ensure its completeness and currentness. Documentation for the secretariat should be directed to: Materials Sciences Corporation, MIL-HDBK-17 Secretariat, 500 Office Center Drive, Suite 250, Fort Washington, PA 19034.

4. MIL-HDBK-17 provides guidelines and material properties for polymer (organic) and metal matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. The fourth volume currently focuses on metal matrix composites (MMC). Ceramic matrix composites (CMC) and carbon/carbon composites (C/C) will be covered in separate volumes as developments occur.

5. This standardization handbook has been developed and is being maintained as a joint effort of the Department of Defense and the Federal Aviation Administration.

6. The information contained in this handbook was obtained from materials producers, industry, reports on Government sponsored research, the open literature, and by contact with research laboratories and those who participate in the MIL-HDBK-17 coordination activity.

7. All information and data contained in this handbook have been coordinated with industry and the U.S. Army, U.S. Navy, U.S. Air Force, NASA, and Federal Aviation Administration prior to publication.

8. Copies of this document and revisions thereto may be obtained from the Defense Automated Printing Service (DAPS), 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094.

9. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Director, U.S. Army Research Laboratory, Weapons and Materials Research Directorate, ATTN: AMSRL-WM-M, Aberdeen Proving Ground, MD 21005-5069, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

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1. GUIDELINES

1.1 GENERAL INFORMATION

This handbook documents engineering methodologies for the development of standardized, statistically-based material property data for continuous and discontinuous metal matrix composite (MMC) materials. Also provided are data summaries for a number of relevant composite material systems for which available data meets specific MIL-HDBK-17 requirements for publication. Additionally, supporting engineering and manufacturing technologies and common practices related to composite materials are summarized.

1.1.1 INTRODUCTION

It is generally understood that standardized, statistically-based, material property data are essential to an efficient engineering development process; such data are needed by material suppliers, engineering users, and system end-users alike. Since the inherent properties of materials are independent of specific applications, data development methodologies and material property data are applicable to a wide variety of industries; they also form much of the technical basis for establishment of statistically-based design values acceptable to procuring or certifying agencies.[1] This evaluation of the inherent properties of composite materials, as shown in Figure 1.1.1, is the focus of MIL-HDBK-17.

[1]An example of a procuring agency is a branch of the U.S. Department of Defense (DoD). An example of a certifying agency is an office of the Federal Aviation Administration (FAA).

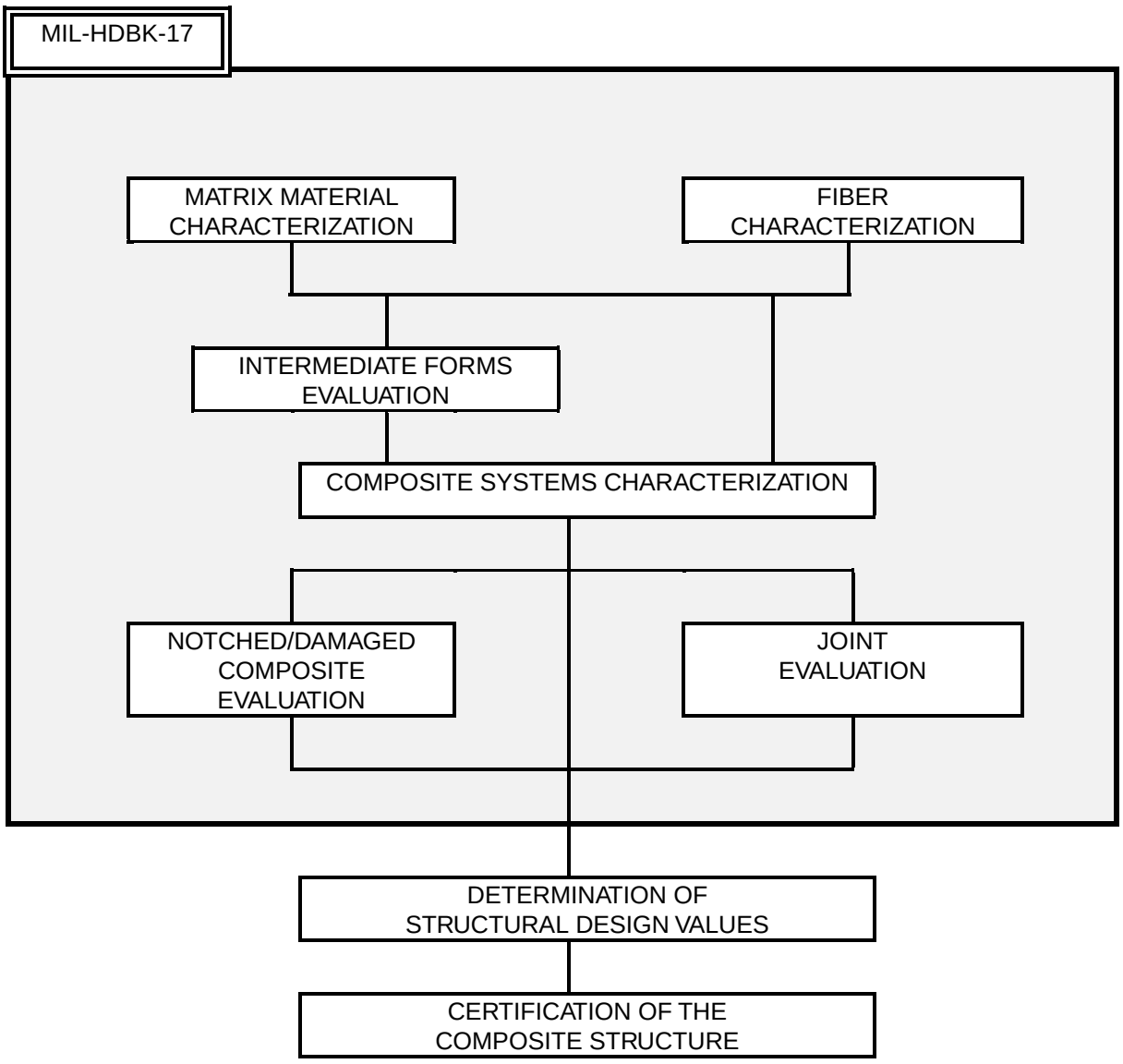

FIGURE 1.1.1 *Focus of MIL-HDBK-17 Volume 4 indicated by shaded block.*

1.1.2 PURPOSE

The primary purpose of MIL-HDBK-17 Volume 4 is the standardization of engineering data development methodologies related to characterization testing, data reduction, and data reporting of properties for metal matrix composite materials. In support of this objective MIL-HDBK-17 Volume 4 publishes properties on composite material systems for which data meeting specific requirements is available. In addition, MIL-HDBK-17 provides selected guidance on other technical topics related to composites, including material selection, material specification, material processing, design, analysis, quality control, and repair of typical metal matrix composite materials. Thus, MIL-HDBK-17 is published in three major sections, and serves as a source for the following:

- Section 1 - Guidelines: Documents material characterization data development methodology guidelines adaptable to a wide variety of needs, as well as specific requirements to be met by data published in the handbook. Most procuring and certifying agencies prefer, and some may require, that composite material systems used in critical applications either be characterized in accordance with Section 1 guidelines or selected from material systems published in Section 3.

- Section 2 - Utilization of Data: This section provides guidance on statistical analysis of metal matrix composite data. In addition, methodologies and recommendations for design, modeling, joining, structural reliability, and repair are given.

- Section 3 - Materials Property Data: Provides a repository of potential design data. The documented property summaries for material systems provide data meeting the criteria for any of the two MIL-HDBK-17 data documentation classes, (screening and fully approved).

1.1.3 SCOPE

Volume 4 of MIL-HDBK-17 serves as a general reference source for technical information on metal matrix composites, including:

1.1.3.1 Section 1: Guidelines

This volume contains guidelines for determining the properties of composite material systems, their constituents, and generic structural elements, including test planning, test matrices, sampling, conditioning, test procedure selection, data reporting, data reduction, statistical analysis, and other related topics. Special attention is given to the statistical treatment and analysis of data. Section 1 contains guidelines for general development of material characterization data as well as specific requirements for publication of metal matrix composite material data in MIL-HDBK-17.

It must be emphasized that this handbook differentiates between material basis values (material allowables) and design allowable values. Material basis values, being an intrinsic property of a composite material system, are the focus of this handbook. Design allowable values, while often rooted in material basis values, are application dependent, and consider and include specific additional considerations that may further affect the strength or stiffness of the structure. Also, when establishing application design values there may be additional certification or procurement agency requirements that go beyond MIL-HDBK-17.

1.1.3.2 Section 2: Utilization of data

[Materials Usage, Design, and Analysis Guidelines]

Section 2 provides methodologies and lessons learned for the design, manufacture, analysis, and supportability of composite structures, and for utilization of the material data provided in Section 3 consistent with the guidance provided in Section 1. Topics discussed in Section 2 include materials and processing, quality control, design and analysis, joints, reliability, and supportability.

1.1.3.3 Section 3: Material property data

Section 3 contains statistically-based data meeting specific MIL-HDBK-17 population sampling and data documentation requirements, covering constituents and material systems of general interest. Data published in Section 3 are under the jurisdiction of the Data Review Working Group and are approved by the overall Coordination Group (the MIL-HDBK-17 Coordination Group and Working Groups are discussed in Section 1.1.5). New material systems will be included and additional material data for existing systems will be added as data become available and are approved.

The material properties in Section 3 are defined over a range of potential use conditions, focusing, when possible, on the upper and lower material environmental limits so that application-specific environments do not limit use of the data. Data at intermediate environmental conditions, when available, provide additional definition of the relation between material response and environment.

While the process of establishing structural design values for specific applications can begin with the data contained in Section 3, most applications require collection of additional data, especially if there are requirements for data from the laminate or higher structural complexity levels (structural complexity level is discussed in 2.1.2.1). Also, the ability to manufacture material equivalent to that from which the data in Section 3 were obtained typically must be proven to the procuring or certifying agency, which usually involves limited testing and data comparison. The details of such an evaluation remain at the discretion of the procuring or certifying agency.

1.1.4 USE OF THE DOCUMENT AND LIMITATIONS

1.1.4.1 Source of information

The information contained in MIL-HDBK-17 Volume 4 is obtained from materials producers and fabricators, manufacturers, reports on government-sponsored research, the open literature, direct contacts with researchers, and from participants in MIL-HDBK-17 coordination activities. All information published in this document has been coordinated and reviewed by representatives from industry, the U.S. Army, U.S. Navy, U.S. Air Force, NASA, and Federal Aviation Administration. Every effort has been made to reflect the most up-to-date information on the use of composite materials, with particular emphasis on use of composites in structures. The handbook is continually reviewed and revised to keep current with the state-of-the-art and insure completeness and accuracy.

1.1.4.2 Use of data and guidelines in applications

All data contained herein are based on small-scale test specimens for specific environmental conditions, largely limited to uniaxial loading.[1] It is the user's responsibility to determine if handbook data is appropriate for a given application, and if selected, to translate or scale the data as necessary for use:

- in a multi-directional laminate,
- on a structure of different characteristic size and geometry,
- under a multi-directional stress state,
- when exposed to a different environment, and/or
- when subjected to non-static loading.

[1]Unless otherwise noted, tests were conducted in conformance with the particular test method noted. The emphasis is on data obtained from ASTM standard test methods for advanced composites, but where an ASTM test method has been deemed inappropriate or is not yet available, or when data from a nonstandard but commonly practiced test procedure is available, then data from a non-standard test method may have been accepted for publication. The specific test method used is noted in the data documentation. See also the statement on test method acceptance criteria in Section 1.3.2.1.

Further discussions of these and other issues are provided in Section 2. Specific uses of handbook data are beyond the scope and responsibility of MIL-HDBK-17, and applicability and interpretation of specific provisions of this handbook may require approval by an appropriate procurement or certification agency.

1.1.4.3 Strength properties and allowables terminology

The handbook intent is to provide guidelines for generating material property data, including statistically-based strength data at environmental extremes that bracket most intermediate application-specific environments. The philosophy is to avoid having application-specific issues govern generic material property characterization programs. If data are also available at intermediate environmental conditions, they can be used to more completely define the relationship between the property and the effect of the environment on that property. However, in some cases an environmental limit for a composite material system may be application dependent, and in others, data at environmental limits may not be available.

Available statistically-based strength data are useful as a starting point for establishing structural design allowable values when stress and strength analysis capabilities permit lamina-level margin-of-safety calculations. For such cases the MIL-HDBK-17 strength basis value may also be termed a material design allowable. Depending on the application, some structural design allowables may have to be empirically determined from additional laminate, element, or higher-level test data not provided by MIL-HDBK-17.

1.1.4.4 Use of references

While many references are provided at the end of each chapter, note that the information in these citations may not necessarily comply in every respect either with the general guidelines for data development or with the specific requirements for publication of data in the handbook. The references are simply intended to be helpful, but not necessarily complete or authoritative sources of additional related information on specific subject areas.

1.1.4.5 Use of tradenames and product names

Use of tradenames or proprietary product names does *not* constitute an endorsement of those products by the U.S. Government or by the MIL-HDBK-17 Coordination Group.

1.1.4.6 Toxicity, health hazards, and safety

Certain processing and test methods discussed in MIL-HDBK-17 may involve hazardous materials, operations, or equipment. These methods may not address safety problems, if any, associated with their use. It is the responsibility of the user of these methods to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use. The user is referred to the Advanced Composite Materials U.S. Army Interim Health and Safety Guidance for a discussion of the health and safety issues involved in the processing and use of composite materials. This document is generated by the U.S. Army Environmental Hygiene Agency, Aberdeen Proving Ground, MD. Material manufacturers, as well as various composites user groups, may also provide guidance on health and safety issues pertinent to composite materials.

1.1.4.7 Ozone depleting chemicals

Restrictions on the use of ozone depleting chemicals are detailed in the U.S. Clean Air Act of 1991.

1.1.5 APPROVAL PROCEDURES

The content of the handbook is developed and approved by the MIL-HDBK-17 MMC Coordination Group, which meets twice yearly to consider changes and additions to the handbook. This Group consists of the Coordination Group Co-Chairs, Coordinator, Secretariat, Working Group Chairs, and the active Working Group participants, which include representatives from various United States procuring and certifying agencies, in addition to the producing industries and academic and research institutions. MIL-HDBK-17

MMC Coordination Group meetings are announced on the MIL-HDBK-17 homepage (http://mil-17.udel.edu/).

While each of the Working Groups functions similarly, they are of three types: *Executive*, a single Working Group with oversight responsibility composed of the Working Group Chairs, the handbook Co-Chairs, Coordinator, and Secretariat; *Standing*, including Data Review, Materials and Processing, Statistics, and Testing Working Groups; and *Specialty*, which will be established as needed. The makeup and organization of the Coordination Group and Working Groups, as well as the procedures followed for document change approval, are summarized in the MIL-HDBK-17 homepage.

Proposals for addition to, deletion from, or modification to the handbook should be submitted to both the appropriate Working Group and the Secretariat well in advance of the announcement mailing date, and should include specific notation of the proposed changes and adequate documentation of supporting data or analytical procedures. Reproducible copies of figures, drawings, or photographs proposed for publication in the document should be furnished to the Secretariat. Following approval by the appropriate Working Group, the proposed changes are published in the next minutes of the Coordination Group, in a special section of the minutes called the "yellow pages", and all participants are allowed comment on the proposed changes. If no substantive comments are received on any individual item by the posted response date, then that item is considered approved by the Coordination Group and is considered effective as of that date. (Prior to publication in the next revision of the handbook the collected changes are reviewed by various branches of the U.S. DoD. Additional proposals for revision may result from this U.S. DoD review.)

Requests for inclusion of material property data into MIL-HDBK-17 should be submitted to either the Coordinator or the Secretariat, accompanied by the documentation specified in Section 1.3.2.5. A Data Source Information Package has been created to aid those considering submitting data for inclusion in MIL-HDBK-17, and is available from either the Coordinator or the Secretariat. The Secretariat reviews and analyzes each data submission and at the next available meeting of the Coordination Group presents a summary for evaluation by the Data Review Working Group. The choice of new materials to be included herein is governed by the MIL-HDBK-17 Coordination Group. Practical considerations preclude inclusion of all advanced composite materials, but reasonable attempts will be made to add new material systems of interest in a timely manner.

1.1.6 SYMBOLS, ABBREVIATIONS, AND SYSTEMS OF UNITS

This section defines the symbols and abbreviations which are used within MIL-HDBK-17 and describes the system of units which is maintained. Common usage is maintained where possible. References 1.1.6(a) through 1.1.6(c) served as primary sources for this information.

1.1.6.1 Symbols and abbreviations

The symbols and abbreviations used in this document are defined in this section with the exception of statistical symbols. These latter symbols are defined in Section 1.11. The lamina/laminate coordinate axes used for all properties and a summary of the mechanical property notation are shown in Figure 1.1.6.1.

- The symbols f and m, when used as either subscripts or superscripts, always denote fiber and matrix, respectively.
- The type of stress (for example, cy - compression yield) is always used in the superscript position.
- Direction indicators (for example, x, y, z, 1, 2, 3, and so on) are always used in the subscript position.
- Ordinal indicators of laminae sequence (for example, 1, 2, 3, and so on) are used in the superscript position and must be parenthesized to distinguish them from mathematical exponents.

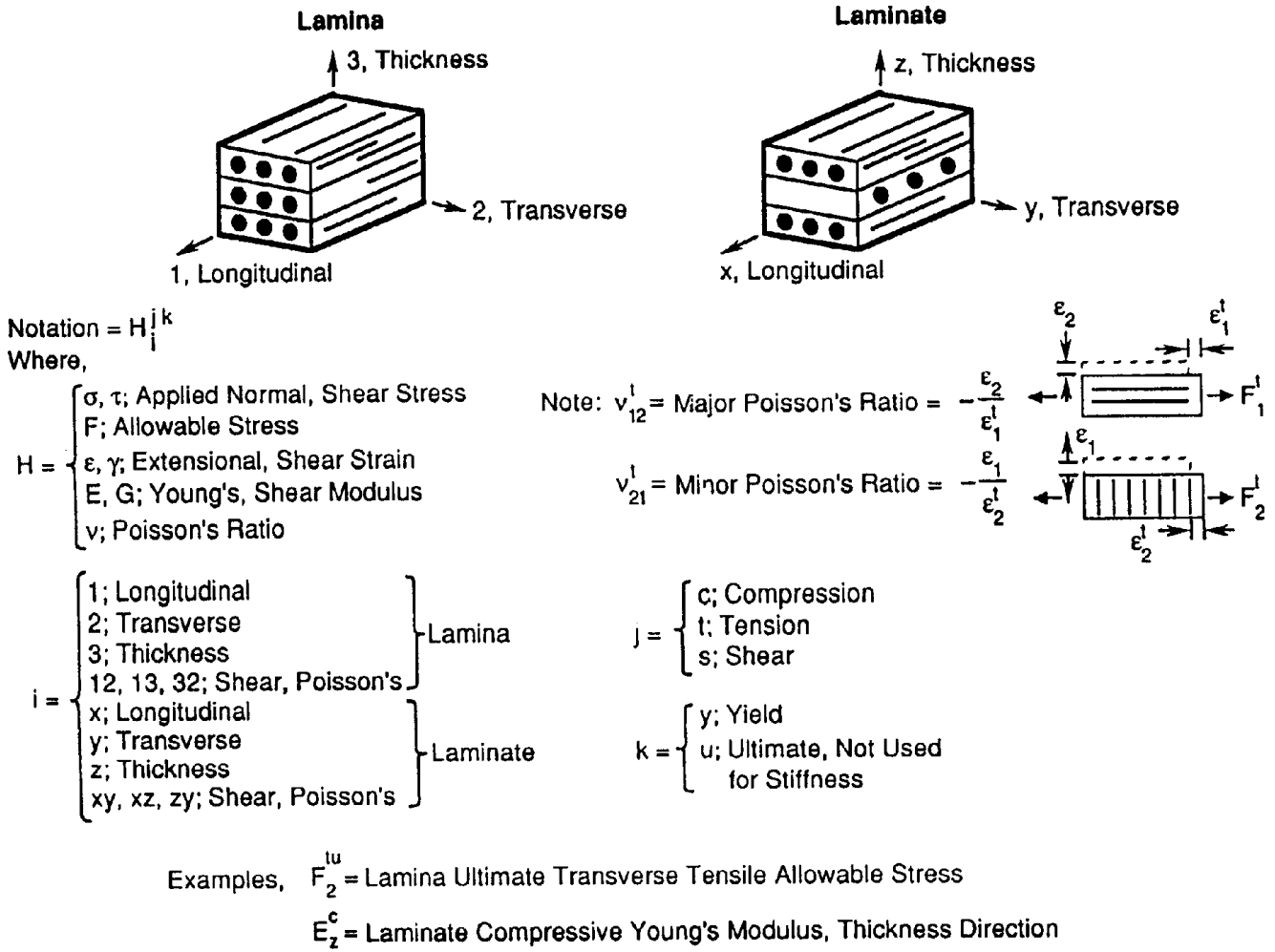

FIGURE 1.1.6.1 *Mechanical property notation.*

- Other indicators may be used in either subscript or superscript position, as appropriate for clarity.
- Compound symbols (such as, basic symbols plus indicators) which deviate from these rules are shown in their specific form in the following list.

The following general symbols and abbreviations are considered standard for use in MIL-HDBK-17. Where exceptions are made, they are noted in the text and tables.

A - (1) area (m^2,in^2)
- (2) ratio of alternating stress to mean stress
- (3) A-basis for mechanical property values

Ann - Annealed

a - (1) length dimension (mm,in)
- (2) acceleration (m/sec^2,ft/sec^2)
- (3) amplitude
- (4) crack or flaw dimension (mm, in.)

a_c - critical half crack length

a_o - initial half crack length

B - (1) B-basis for mechanical property values
- (2) biaxial ratio

Btu - British thermal unit(s)

BUS - individual or typical bearing ultimate strength

BYS - individual or typical bearing yield strength

b - (1) width dimension (mm, in.), for example, the width of a bearing or compression panel normal to load,
or breadth of beam cross-section
- (2) width of sections; subscript “bending”

br - subscript “bearing”

C - (1) specific heat (kJ/kg °C, Btu/lb °F)
- (2) Celsius

CC - center cracked

CEM - consumable electrode melted

CF - centrifugal force (N, lbf)

CPF - crossply factor

CG - (1) center of mass, "center of gravity"
- (2) area or volume centroid

$\mathbb{C}_L$ - centerline

CT - compact tension

c - column buckling end-fixity coefficient

cpm - cycles per minute

D - (1) diameter (mm, in.)
- (2) hole or fastener diameter (mm, in.)
- (3) plate stiffness (N-m, lbf-in)

d - mathematical operator denoting differential

E - modulus of elasticity in tension, average ratio of stress to strain for stress below proportional limit (GPa, Msi)

E_c - modulus of elasticity in compression, average ratio of stress to strain for stress below proportional limit (GPa, Msi)

E_c' - modulus of elasticity of honeycomb core normal to sandwich plane (GPa, Msi)

E^{sec} - secant modulus (GPa, Msi)

E^{tan} - tangent modulus (GPa, Msi)

ELI - extra low interstitial (grade of titanium alloy)

ER - equivalent round

ESR - electro-slag remelted

e - (1) minimum distance from a hole center to the edge of the sheet (mm, in.)
- (2) elongation in percent, a measure of the ductility of a material based on a tension test
- (3) unit deformation or strain
- (4) subscript “fatigue or endurance”

e/D - ratio of edge distance to hole diameter (bearing strength)

F - (1) stress (MPa, ksi)
- (2) Fahrenheit

F^{b} - bending stress (MPa, ksi)

F^{ccr} - crushing or crippling stress (upper limit of column stress for failure) (MPa, ksi)

F^{pl} - proportional limit (MPa, ksi)

F^{su} - ultimate stress in pure shear (this value represents the average shear stress over the cross-section) (MPa, ksi)

F^{tu} - ultimate stress in tension (MPa, ksi)

FV - fiber volume (%)

f - (1) internal (or calculated) stress (MPa, ksi)
- (2) stress applied to the gross flawed section (MPa, ksi)
- (3) creep stress (MPa, ksi)

f^{c} - internal (or calculated) compressive stress (MPa, ksi)

f_c - (1) maximum stress at fracture (MPa, ksi)
- (2) gross stress limit (for screening elastic fracture data (MPa, ksi)

ft - foot, feet

G - modulus of rigidity (shear modulus) (GPa, Msi)

GPa - gigapascal(s)

g - (1) gram(s)
- (2) acceleration due to gravity (m/s^2, ft/s^2)

H/C - honeycomb (sandwich)

h - height dimension (mm, in.) for example, the height of a beam cross-section

hr - hour(s)

I - area moment of inertia (mm^4, $in.^4$)

i - slope (due to bending) of neutral plane in a beam, in radians

in. - inch(es)

J - (1) torsion constant (= I_p for round tubes) (m^4, $in.^4$)
- (2) Joule

K - (1) Kelvin
- (2) stress intensity factor ($MPa\sqrt{m}$, $ksi\sqrt{in.}$)
- (3) coefficient of thermal conductivity (W/m °C, $Btu/ft^2/hr/in./°F$)
- (4) correction factor
- (5) dielectric constant

K_{app} - apparent plane strain fracture toughness or residual strength ($MPa\sqrt{m}$, $ksi\sqrt{in.}$)

K_c - critical plane strain fracture toughness, a measure of fracture toughness at point of crack growth instability ($MPa\sqrt{m}$, $ksi\sqrt{in.}$)

K_{Ic} - plane strain fracture toughness ($MPa\sqrt{m}$, $ksi\sqrt{in.}$)

K_N - empirically calculated fatigue notch factor

K_s - plate or cylinder shear buckling coefficient

K_t - (1) theoretical elastic stress concentration factor
- (2) t_w/c ratio in H/C sandwich

Kv - dielectric strength (KV/mm, V/mil)

K_x,K_y - plate or cylinder compression buckling coefficient

k - strain at unit stress (m/m, in./in.)

ksi - kips (1,000 pounds) per square inch

L - cylinder, beam, or column length (mm, in.)

L' - effective column length (mm, in.)

LT - long transverse (grain direction)

lb. - pound
ℓ_o - gage length
M - applied moment or couple (N-m, in.-lbf)
Mg - megagram(s)
MIG - metal-inert-gas (welding)
MPa - megapascal(s)
MS - military standard
M.S. - margin of safety
MW - molecular weight
MWD - molecular weight distribution
m - (1) mass (kg, lb.)
- (2) number of half wave lengths
- (3) metre
- (4) slope
mm - millimetre(s)
N - (1) number of fatigue cycles to failure
- (2) number of laminae in a laminate
- (3) distributed in-plane forces on a panel (lbf/in.)
- (4) Newton
- (5) normalized
NA - neutral axis
n - (1) number of times in a set
- (2) number of half or total wavelengths
- (3) number of fatigue cycles endured
- (4) subscript “normal”;
- (5)cycles applied to failure
- (6) shape parameter for the standard stress-strain curve (Ramberg-Osgood parameter)
P - (1) applied load (N, lbf)
- (2) exposure parameter
- (3) probability
- (4) specific resistance (Ω)
P^u - test ultimate load, (N, lb. per fastener)
P^y - test yield load, (N, lb per fastener)
p - normal pressure (Pa, psi)
psi - pounds per square inch
Q - area static moment of a cross-section (mm^3, $in.^3$)
Q&T - quenched and tempered
q - shear flow (N/m, lbf/in.)
R - (1) algebraic ratio of minimum load to maximum load in cyclic loading
- (2) reduced ratio
RA - reduction of area
R.H. - relative humidity
RMS - root-mean-square
RT - room temperature
r - (1) radius (mm, in.)
- (2) root radius (mm, in.)
- (3) reduced ratio (regression analysis)
S - (1) shear force (N, lbf)
- (2) nominal stress in fatigue (MPa, ksi)
- (3) S-basis for mechanical property values
S_a - stress amplitude in fatigue (MPa, ksi)
S_e - fatigue limit (MPa, ksi)
S_m - mean stress in fatigue (MPa, ksi)
S_{max} - highest algebraic value of stress in the stress cycle (MPa, ksi)
S_{min} - lowest algebraic value of stress in the stress cycle (MPa, ksi)

S_R - algebraic difference between the minimum and maximum stresses in one cycle (MPa, ksi)
S.F. - safety factor
SCC - stress-corrosion cracking
ST - short transverse (grain direction)
STA - solution treated and aged
S-N - stress vs. fatigue life
s - (1) arc length (mm, in.)
- (2) H/C sandwich cell size (mm, in.)
T - (1) temperature (°C, °F)
- (2) applied torsional moment (N-m, in.-lbf)
TIG - tungsten-inert-gas (welding)
T_F - exposure temperature
T_F - exposure temperature (°C, °F)
T_m - melting temperature (°C, °F)
t - (1) thickness (mm, in.)
- (2) exposure time (s)
- (3) elapsed time (s)
V - (1) volume (mm^3, $in.^3$)
- (2) shear force (N, lbf)
W - (1) weight (N, lbf)
- (2) width (mm, in.)
- (3) Watt
x - distance along a coordinate axis
Y - nondimensional factor relating component geometry and flaw size
y - (1) deflection (due to bending) of elastic curve of a beam (mm, in.)
- (2) distance from neutral axis to given point
- (3) distance along a coordinate axis
Z - section modulus, I/y (mm^3, $in.^3$)
z - distance along a coordinate axis
α - coefficient of thermal expansion (m/m/°C, in./in./°F)
γ - shear strain (m/m, in./in.)
Δ - difference (used as prefix to quantitative symbols)
Φ - angular deflection
δ - elongation or deflection (mm, in.)
ε - strain (m/m, in./in.)
ε_e - elastic strain (m/m, in./in.)
ε_p - plastic strain (m/m, in./in.)
μ - permeability
η - plasticity reduction factor
ν - Poisson's ratio
ρ - (1) density (g/cm^3, $lb/in.^3$)
- (2) radius of gyration (mm, in.)
- (3) radius of gyration; Neuber constant (block length)
ρ'_c - H/C sandwich core density (kg/m^3, $lb/in.^3$)
Σ - total, summation
σ - standard deviation
σ_{ij}, τ_{ij} - stress in j direction on surface whose outer normal is in i direction (i, j = 1, 2, 3 or x, y, z) (MPa, ksi)
T - applied shear stress (MPa, ksi)
ω - angular velocity (radians/s)
∞ - infinity

1.1.6.1.1 Constituent properties

The following symbols apply specifically to the constituent properties of a typical composite material.

E^f - Young's modulus of fiber (MPa, ksi)
E^m - Young's modulus of matrix material (MPa, ksi)
E^R - Young's modulus of reinforcement (MPa, ksi)
G^f - shear modulus of fiber (MPa, ksi)
G^m - shear modulus of matrix (MPa, ksi)
G^R - shear modulus of reinforcement (MPa, ksi)
G'_{cx} - shear modulus of sandwich core along X-axis (MPa, ksi)
G'_{cy} - shear modulus of sandwich core along Y-axis (MPa, ksi)
ℓ - fiber length (mm, in.)
α^f - coefficient of thermal expansion for fiber material (m/m/°C, in./in./°F)
α^m - coefficient of thermal expansion for matrix material (m/m/°C, in./in./°F)
ν^f - Poisson's ratio of fiber material
ν^m - Poisson's ratio of matrix material
σ - applied axial stress at a point, as used in micromechanics analysis (MPa, ksi)
τ - applied shear stress at a point, as used in micromechanics analysis (MPa, ksi)

1.1.6.1.2 Laminae and laminates

The following symbols, abbreviations, and notations apply to composite laminae and laminates.

A_{ij} (i,j = 1,2,6) - extensional rigidities (N/m, lbf/in.)
B_{ij} (i,j = 1,2,6) - coupling matrix (N, lbf)
C_{ij} (i,j = 1,2,6) - elements of stiffness matrix (Pa, psi)
D_x, D_y - flexural rigidities (N-m, lbf-in.)
D_{xy} - twisting rigidity (N-m, lbf-in.)
D_{ij} (i,j = 1,2,6) - flexural rigidities (N-m, lbf-in.)
E_1 - Young's modulus of lamina parallel to fiber or warp direction (GPa, Msi)
E_2 - Young's modulus of lamina transverse to fiber or warp direction (GPa, Msi)
E_x - Young's modulus of laminate along x reference axis (GPa, Msi)
E_y - Young's modulus of laminate along y reference axis (GPa, Msi)
G_{12} - shear modulus of lamina in 12 plane (GPa, Msi)
G_{xy} - shear modulus of laminate in xy reference plane (GPa, Msi)
h_i - thickness of i^{th} ply or lamina (mm, in.)
M_x, M_y, M_{xy} - bending and twisting moment components (N-m/m, in.-lbf/in. in plate and shell analysis)
n_f - number of fibers per unit length per lamina
Q_x, Q_y - shear force parallel to z axis of sections of a plate perpendicular to x and y axes, respectively (N/m, lbf/in.)
Q_{ij} (i,j = 1,2,6) - reduced stiffness matrix (Pa, psi)
u_x, u_y, u_z - components of the displacement vector (mm, in.)
u_x^o, u_y^o, u_z^o - components of the displacement vector at the laminate's midsurface (mm, in.)
V_v - void content (% by volume)
V_f - fiber content or fiber volume (% by volume)
V_m - matrix content (% by volume)
V_x, V_y - edge or support shear force (N/m, lbf/in.)
W_f - fiber content (% by weight)
W_m - matrix content (% by weight)
W_s - weight of laminate per unit surface area (N/m^2, $lbf/in.^2$)
α_1 - lamina coefficient of thermal expansion along 1 axis (m/m/°C, in./in./°F)
α_2 - lamina coefficient of thermal expansion along 2 axis (m/m/°C, in./in./°F)

α_x - laminate coefficient of thermal expansion along general reference x axis (m/m/°C, in./in./°F)
α_y - laminate coefficient of thermal expansion along general reference y axis (m/m/°C, in./in./°F)
α_{xy} - laminate shear distortion coefficient of thermal expansion (m/m/°C, in./in./°F)
θ - angular orientation of a lamina in a laminate, that is, angle between 1 and x axes (°)
λ_{xy} - product of ν_{xy} and ν_{yx}
ν_{12} - Poisson's ratio relating contraction in the 2 direction as a result of extension in the 1 direction[1]
ν_{21} - Poisson's ratio relating contraction in the 1 direction as a result of extension in the 2 direction[1]
ν_{xy} - Poisson's ratio relating contraction in the y direction as a result of extension in the x direction[1]
ν_{yx} - Poisson's ratio relating contraction in the x direction as a result of extension in the y direction[1]
ρ_c - (1) density of a single lamina (g/cm^3, lb/in.^{3})
- (2) density of a laminate (g/cm^3, lb/in.^{3})
ϕ - (1) general angular coordinate, (°)
- (2) angle between x and load axes in off-axis loading (°)

1.1.6.1.3 Subscripts

The following subscript notations are considered standard in MIL-HDBK-17.

1, 2, 3 - laminae natural orthogonal coordinates (1 is fiber)
A - axial
a - (1) adhesive
- (2) alternating
app - apparent
byp - bypass
c - (1) composite system, specific fiber/matrix composition.
- (2) critical
- (3) compression
cf - centrifugal force
e - fatigue or endurance
eff - effective
eq - equivalent
f - fiber
H - hoop
i - ith position in a sequence
L - lateral
m - (1) matrix
- (2) mean
max - maximum
min - minimum
n - (1) nth (last) position in a sequence
- (2) normal
p - polar
s - symmetric
st - stiffener
T - transverse

[1]The convention for Poisson's ratio should be checked before comparing different sources as different conventions are used.

t - value of parameter at time t
x, y, z - general coordinate system
$\sum$ - total, or summation
o - initial or reference datum
( ) - format for indicating specific, temperature associated with term in parentheses. RT - room temperature (21°C, 70°F); all other temperatures in °F unless specified.

1.1.6.1.4 Superscripts

The following superscript notations are considered standard in MIL-HDBK-17.

b - bending
br - bearing
c - (1) compression
- (2) creep
cc - compression crippling
cr - compression buckling
e - elastic
f - fiber
(i) - i^{th} ply or lamina
lim - limit, used to indicate limit loading
m - matrix
ohc - open hole compression
oht - open hole tension
p - plastic
pl - proportional limit
rup - rupture
s - shear
scr - shear buckling
sec - secant (modulus)
so - offset shear
T - temperature or thermal
t - tension
tan - tangent (modulus)
u - ultimate
y - yield
' - secondary (modulus), or denotes properties of H/C core when used with subscript c

1.1.6.1.5 Acronyms

The following acronyms are used in MIL-HDBK-17.

AISI - American Iron and Steel Institute
AMS - Aerospace Materials Specification
ANOVA - analysis of variance
ARL - U.S. Army Research Laboratory
ASTM - American Society for Testing and Materials
CTA - cold temperature ambient
CTD - cold temperature dry
CTE - coefficient of thermal expansion
CV - coefficient of variation
CVD - chemical vapor deposition
DCB - double cantilever beam
DLL - design limit load
DoD - Department of Defense

EDM - electric discharge machining
ENF - end notched flexure
ETW - elevated temperature wet
FAA - Federal Aviation Administration
IITRI - Illinois Institute of Technology Research Institute
LPT - laminate plate theory
LSS - laminate stacking sequence
MMB - mixed mode bending
MMC - metal matrix composite
NAS - National Aerospace Standard
NASA - National Aeronautics and Space Administration
NDI - nondestructive inspection
RH - relative humidity
RT - room temperature
RTA - room temperature ambient
RTD - room temperature dry
SAE - Society of Automotive Engineers
SEM - scanning electron microscopy
SI - International System of Units (Le Système Interational d'Unités)
TEM - transmission electron microscopy
TMC - titanium matrix composite
VNB - V-notched beam

1.1.6.2 Material system codes

The materials systems codes which are used in the handbook consist of a fiber system code and a matrix material code separated by a virgule (/), for example, AIO/Al for alumina reinforced aluminum. The codes for the fiber and matrix materials appear in Table 1.1.6.2(a) and (b).

TABLE 1.1.6.2(a) *Fiber system codes*.

AlO	Alumina
B	Boron
BC	Boron carbide
C	Carbon
Gr	Graphite
SiC	Silicon Carbide
Fe	Steel
W	Tungsten

TABLE 1.1.6.2(b) *Matrix material codes.*

Al	Aluminum
Cu	Copper
Mg	Magnesium
Ti	Titanium

1.1.6.3 System of units

To comply with Department of Defense Instructive 5000.2, Part 6, Section M, "Use of the Metric System," dated February 23, 1991, the data in MIL-HDBK-17 are generally presented in both the International System of Units (SI units) and the U. S. Customary (English) system of units. ASTM E380, Standard for Metric Practice, provides guidance for the application for SI units which are intended as a basis for worldwide standardization of measurement units (Reference 1.1.6.3(a)). Further guidelines on the use of the SI system of units and conversion factors are contained in the following publications (References 1.1.6.3(b) through 1.1.6.3(f)):

(1) DARCOM P 706-470, “Engineering Design Handbook: Metric Conversion Guide”, July 1976.

(2) NBS Special Publication 330, "The International System of Units (SI)”, National Bureau of Standards, 1986 edition.

(3) NBS Letter Circular LC 1035, "Units and Systems of Weights and Measures, Their Origin, Development, and Present Status”, National Bureau of Standards, November 1985.

(4) NASA Special Publication 7012, "The International System of Units Physical Constants and Conversion Factors", 1964.

(5) IEEE SI 10, “International System of Units (SI): The Modern Metric System”, Institute of Electrical and Electronic Engineers (IEEE), November 1997.

English to SI conversion factors pertinent to MIL-HDBK-17 data are contained in Table 1.1.6.3.

TABLE 1.1.6.3 *English to SI conversion factors.*

To convert from	to	Multiple by*
Btu (thermochemical)/in.^{2}-s	watt/meter^2 (W/m^2)	1.634 246 E+06
Btu-in/(s-ft^2-°F)	W/(m K)	5.192 204 E+02
Btu/lb.-F	Joule/gram-Kelvin	4.1868**
(or Btu·lb.$^{-1}$·F^{-1})	(J/g·K) or J·g^{-1}·K^{-1})	
Btu/[(hr)(ft^2)(F)/ft]	Watt/metre-Kelvin	1.7307
(or Btu·hr^{-1}·ft^{-2}·F^{-1}·ft)	W/(m·K) or W·m^{-1}·K^{-1})	
degree Fahrenheit	degree Celsius (°C)	T = (T - 32)/1.8
degree Fahrenheit	kelvin (K)	T = (T + 459.67)/1.8
foot	meter (m)	3.048 000 E-01
ft^2	m^2	9.290 304 E-02
foot/second	meter/second (m/s)	3.048 000 E-01
ft/s^2	m/s^2	3.048 000 E-01
inch	meter (m)	2.540 000 E-02
in.^{2}	meter^2 (m^2)	6.451 600 E-04
in.^{3}	m^3	1.638 706 E-05
in./in./F	Metre/metre/Kelvin	1.8
(or in.·in.$^{-1}$·F^{-1})	m/(m·K) or (m·m^{-1}·K·$^{-1}$)	
kilogram-force (kgf)	newton (N)	9.806 650 E+00
kgf/m^2	pascal (Pa)	9.806 650 E+00
kip (1000 lbf)	newton (N)	4.448 222 E+03
ksi (kip/in.^{2})	MPa	6.894 757 E+00
ksi√in.	megapascal √meter (MPa·m 1/2)***	1.0989
lbf-in.	N-m	1.129 848 E-01
lbf-ft	N-m	1.355 818 E+00
lbf/in.^{2} (psi)	pascal (Pa)	6.894 757 E+03
lb./in.^{2}	gm/m^2	7.030 696 E+05
lb./in.^{3}	kg/m^3	2.767 990 E+04
Msi (10^6 psi)	GPa	6.894 757 E+00
pound-force (lbf)	newton (N)	4.488 222 E+00
pound-mass (lb. avoirdupois)	kilogram (kg)	4.535 924 E-01
torr	pascal (Pa)	1.333 22 E+02

*The letter “E” following the conversion factor stands for exponent and the two digits after the letter “E” indicate the power of 10 by which the number is to be multiplied.
**One Pascal (Pa) = one newton/metre^2.
***Conversion factor is exact.

1.1.7 DEFINITIONS

The following definitions are used within MIL-HDBK-17. This glossary of terms is not totally comprehensive but it does represent nearly all commonly used terms. Where exceptions are made, they are noted in the text and tables. For ease of identification the definitions have been organized alphabetically.

A-Basis (or A-Value) -- A statistically-based material property; a 95% lower confidence bound on the first percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 99% of a specified population.

Accuracy -- The degree of conformity of a measured or calculated value to some recognized standard or specified value. Accuracy involves the systematic error of an operation.

ADK -- Notation used for the k-sample Anderson-Darling statistic, which is used to test the hypothesis that k batches have the same distribution.

Aging -- The effect, on materials, of exposure to an environment for a period of time; the process of exposing materials to an environment for an interval of time.

Ambient -- The surrounding environmental conditions such as pressure or temperature.

Angleply -- Lamina orientation not coinciding with load axis.

Anisotropic -- Not isotropic; having mechanical and/or physical properties which vary with direction relative to natural reference axes inherent in the material.

Aspect Ratio -- In an essentially two-dimensional rectangular structure (for example, a panel), the ratio of the long dimension to the short dimension. However, in compression loading, it is sometimes considered to be the ratio of the load direction dimension to the transverse dimension. Also, in fiber micromechanics, it is referred to as the ratio of length to diameter.

B-Basis (or B-Value) -- A statistically-based material property; a 95% lower confidence bound on the tenth percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 90% of a specified population. (See Volume 1, Section 8.1.4)

Balanced Laminate -- A composite laminate in which all laminae at angles other than 0 degrees and 90 degrees occur only in ± pairs (not necessarily adjacent).

Bearing Area -- The product of the pin diameter and the specimen thickness.

Bearing Load -- A compressive load on an interface.

Bearing Yield Strength -- The bearing stress at which a material exhibits a specified limiting deviation from the proportionality of bearing stress to bearing strain.

Bend Test -- A test of ductility by bending or folding, usually with steadily applied forces. In some instances the test may involve blows to a specimen having a cross section that is essentially uniform over a length several times as great as the largest dimension of the cross section.

Binomial Random Variable -- The number of successes in independent trials where the probability of success is the same for each trial.

Buckling (Composite) -- A mode of structural response characterized by an out-of-plane material deflection due to compressive action on the structural element involved. In advanced composites, buckling may take the form not only of conventional general instability and local instability but also a micro-instability of individual fibers.

Bundle -- A general term for a collection of essentially parallel fibers or fibers.

Censoring -- Data is right (left) censored at M, if, whenever an observation is less than or equal to M (greater than or equal to M), the actual value of the observation is recorded. If the observation exceeds (is less than) M, the observation is recorded as M.

Coefficient of Linear Thermal Expansion -- The change in length per unit length resulting from a one-degree rise in temperature.

Coefficient of Variation -- The ratio of the population (or sample) standard deviation to the population (or sample) mean.

Collimated -- Rendered parallel.

Composite Class -- As used in the handbook, a major subdivision of composite construction in which the class is defined by the fiber system and the matrix class, for example, organic-matrix filamentary laminate.

Composite Material -- Composites are considered to be combinations of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Confidence Coefficient -- See **Confidence Interval**.

Confidence Interval -- A confidence interval is defined by a statement of one of the following forms:

$$(1)\ P\{a<\theta\}\leq 1-\alpha$$
$$(2)\ P\{\theta<b\}\leq 1-\alpha$$
$$(3)\ P\{a<\theta<b\}\leq 1-\alpha$$

where $1\text{-}\alpha$ is called the confidence coefficient. A statement of type (1) or (2) is called a one-sided confidence interval and a statement of type (3) is called a two-sided confidence interval. In (1) a is a lower confidence limit and in (2) b is an upper confidence limit. With probability at least $1\text{-}\alpha$, the confidence interval will contain the parameter θ.

Constituent -- In general, an element of a larger grouping. In advanced composites, the principal constituents are the fibers and the matrix.

Continuous fiber -- A yarn or strand in which the individual fibers are substantially the same length as the strand.

Continuous Fiber - A fiber which spans the dimension of the test specimen.

Creep -- The time dependent part of strain resulting from an applied stress.

Creep, Rate Of -- The slope of the creep-time curve at a given time.

Critical Value(s) -- When testing a one-sided statistical hypothesis, a critical value is the value such that, if the test statistic is greater than (less than) the critical value, the hypothesis is rejected. When testing a two-sided statistical hypothesis, two critical values are determined. If the test statistic is either less than the smaller critical value or greater than the larger critical value, then the hypothesis is rejected. In both cases, the critical value chosen depends on the desired risk (often 0.05) of rejecting the hypothesis when it is true.

Crossply -- Any filamentary laminate which is not uniaxial. Same as Angleply. In some references, the term crossply is used to designate only those laminates in which the laminae are at right angles to one another, while the term angleply is used for all others.

Cumulative Distribution Function -- See Volume 1, Section 8.1.4.

Debond -- A deliberate separation of a bonded joint or interface, usually for repair or rework purposes. Any separation of an interface between constituents in a composite.

Deformation -- The change in shape of a specimen caused by the application of a load or force.

Degradation -- A deleterious change in chemical structure, physical properties or appearance.

Delamination -- The separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes.

Denier -- A direct numbering system for expressing linear density, equal to the mass in grams per 9000 meters of yarn, fiber, fiber, or other textile strand.

Density -- The mass per unit volume.

Deviation -- Variation from a specified dimension or requirement, usually defining the upper and lower limits.

Distribution -- A formula which gives the probability that a value will fall within prescribed limits. (See **Normal**, **Weibull**, and **Lognormal Distributions**, also Volume 1, Section 8.1.4).

Dry -- a material condition of moisture equilibrium with a surrounding environment at 5% or lower relative humidity.

Ductility -- The ability of a material to deform plastically before fracturing.

Elasticity -- The property of a material which allows it to recover its original size and shape immediately after removal of the force causing deformation.

Elongation -- The increase in gage length or extension of a specimen during a tension test, usually expressed as a percentage of the original gage length.

End -- A single fiber, strand, roving or yarn being or already incorporated into a product. An end may be an individual warp yarn or cord in a woven fabric. In referring to aramid and glass fibers, an end is usually an untwisted bundle of continuous fibers.

Extensometer -- A device for measuring linear strain.

F-Distribution -- See Volume 1, Section 8.1.4.

Fiber -- A general term used to refer to filamentary materials. Often, fiber is used synonymously with fiber. It is a general term for a fiber of finite length. A unit of matter, either natural or manmade, which forms the basic element of fabrics and other textile structures.

Fiber Content -- The amount of fiber present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.

Fiber Count -- The number of fibers per unit width of ply present in a specified section of a composite.

Fiber Direction -- The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.

Fiber System -- The type and arrangement of fibrous material which comprises the fiber constituent of an advanced composite. Examples of fiber systems are collimated fibers or fiber yarns, woven fabric, randomly oriented short-fiber ribbons, random fiber mats, whiskers, and so on

Filament -- The smallest unit of a fibrous material. The basic units formed during spinning and which are gathered into strands of fiber, (for use in composites). Filaments usually are of extreme length and of very small diameter. Filaments normally are not used individually. Some textile filaments can function as a yarn when they are of sufficient strength and flexibility.

Filamentary Composites -- A major form of advanced composites in which the fiber constituent consists of continuous filaments. Specifically, a filamentary composite is a laminate comprised of a number of laminae, each of which consists of a nonwoven, parallel, uniaxial, planar array of filaments (or filament yarns) embedded in the selected matrix material. Individual laminae are directionally oriented and combined into specific multiaxial laminates for application to specific envelopes of strength and stiffness requirements.

Fixed Effect -- A systematic shift in a measured quantity due to a particular level change of a treatment or condition. (See Volume 1, Section 8.1.4.)

Flash -- Excess material which forms at the parting line of a mold or die, or which is extruded from a closed mold.

Fracture Ductility -- The true plastic strain at fracture.

Gage Length -- the original length of that portion of the specimen over which strain or change of length is determined.

Graphite Fibers -- See **Carbon Fibers**.

Hand Lay-up -- A process in which components are applied either to a mold or a working surface, and the successive plies are built up and worked by hand.

Hardness -- Resistance to deformation; usually measured by indention. Types of standard tests include Brinell, Rockwell, Knoop, and Vickers.

Heterogeneous -- Descriptive term for a material consisting of dissimilar constituents separately identifiable; a medium consisting of regions of unlike properties separated by internal boundaries. (Note that all nonhomogeneous materials are not necessarily heterogeneous).

Homogeneous -- Descriptive term for a material of uniform composition throughout; a medium which has no internal physical boundaries; a material whose properties are constant at every point, in other words, constant with respect to spatial coordinates (but not necessarily with respect to directional coordinates).

Horizontal Shear -- Sometimes used to indicate interlaminar shear. This is not an approved term for use in this handbook.

Humidity, Relative -- The ratio of the pressure of water vapor present to the pressure of saturated water vapor at the same temperature.

Hybrid -- A composite laminate comprised of laminae of two or more composite material systems. Or, a combination of two or more different fibers such as carbon and glass or carbon and aramid into a structure (tapes, fabrics and other forms may be combined).

Hysteresis -- The energy absorbed in a complete cycle of loading and unloading.

Inclusion -- A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but in a noticeably different manner from the parent material.

Integral Composite Structure -- Composite structure in which several structural elements, which would conventionally be assembled by bonding or with mechanical fasteners after separate fabrication, are instead laid up and cured as a single, complex, continuous structure; for example, spars, ribs, and one stiffened cover of a wing box fabricated as a single integral part. The term is sometimes applied more loosely to any composite structure not assembled by mechanical fasteners.

Interface -- The boundary between the individual, physically distinguishable constituents of a composite.

Interlaminar -- Descriptive term pertaining to some object (for example, voids), event (for example, fracture), or potential field (for example, shear stress) referenced as existing or occurring between two or more adjacent laminae.

Interlaminar Shear -- Shearing force tending to produce a relative displacement between two laminae in a laminate along the plane of their interface.

Intermediate Bearing Stress -- The bearing stress at the point on the bearing load-deformation curve where the tangent is equal to the bearing stress divided by a designated percentage (usually 4%) of the original hole diameter.

Intralaminar -- Descriptive term pertaining to some object (for example, voids), event (for example, fracture), or potential field (for example, temperature gradient) existing entirely within a single lamina without reference to any adjacent laminae.

Isotropic -- Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.

k-Sample Data -- A collection of data consisting of values observed when sampling from k batches.

Lamina -- A single ply or layer in a laminate made up of a series of layers or unidirectional ply(ies).

Laminae -- Plural of lamina.

Laminate -- A product made by bonding together two or more laminae non-unidirectionally.

Laminate Orientation -- The configuration of a crossplied composite laminate with regard to the angles of crossplying, the number of laminae at each angle, and the exact sequence of the lamina lay-up.

Lay-up -- A process of fabrication involving the assembly of successive layers of fiber matrix.

Lognormal Distribution -- A probability distribution for which the probability that an observation selected at random from this population falls between a and b ($0 < a < b < B$) is given by the area under the normal distribution between log a and log b. The common (base 10) or the natural (base e) logarithm may be used. (See Volume 1, Section 8.1.4.)

Lot – A reinforcement, matrix or composite formed during the same manufacturing process. A composite lot by definition is made up of the same lots of reinforcements and matrix.

Lower Confidence Bound -- See **Confidence Interval**.

Macro -- In relation to composites, denotes the gross properties of a composite as a structural element but does not consider the individual properties or identity of the constituents.

Macrostrain -- The mean strain over any finite gage length of measurement which is large in comparison to the material's interatomic distance.

Material Acceptance -- The testing of incoming material to ensure that it meets requirements.

Material Qualification -- The procedures used to accept a material by a company or organization for production use.

Material System -- A specific composite material made from specifically identified constituents in specific geometric proportions and arrangements and possessed of numerically defined properties.

Material System Class -- As used in this handbook, a group consisting of material systems categorized by the same generic constituent materials, but without defining the constituents uniquely; for example, the carbon/epoxy class.

Material Variability -- A source of variability due to the spatial and consistency variations of the material itself and due to variation in its processing.

Matrix -- The essentially homogeneous material in which the fiber system of a composite is embedded.

Mean -- See **Sample Mean** and **Population Mean**.

Mechanical Properties -- The properties of a material that are associated with elastic and inelastic reaction when force is applied, or the properties involving the relationship between stress and strain.

Median -- See **Sample Median** and **Population Median**.

Micro -- In relation to composites, denotes the properties of the constituents, that is, matrix and reinforcement and interface only, as well as their effects on the composite properties.

Microstrain -- The strain over a gage length comparable to the material's interatomic distance.

Modulus, Chord -- The slope of the chord drawn between any two specified points on the stress-strain curve.

Modulus, Initial -- The slope of the initial straight portion of a stress-strain curve.

Modulus, Secant -- The slope of the secant drawn from the origin to any specified point on the stress-strain curve.

Modulus, Tangent -- The ratio of change in stress to change in strain derived from the tangent to any point on a stress-strain curve.

Modulus, Young's -- The ratio of change in stress to change in strain below the elastic limit of a material. (Applicable to tension and compression).

Modulus of Rigidity (also Shear Modulus or Torsional Modulus) -- The ratio of stress to strain below the proportional limit for shear or torsional stress.

Modulus of Rupture, in Bending -- The maximum tensile or compressive stress (whichever causes failure) value in the extreme fiber of a beam loaded to failure in bending. The value is computed from the flexure equation:

$$F^b = \frac{Mc}{I} \qquad 1.1.7(a)$$

where M = maximum bending moment computed from the maximum load and the original moment arm,
c = initial distance from the neutral axis to the extreme fiber where failure occurs,
I = the initial moment of inertia of the cross section about its neutral axis.

Modulus of Rupture, in Torsion -- The maximum shear stress in the extreme fiber of a member of circular cross section loaded to failure in torsion calculated from the equation:

$$F^s = \frac{Tr}{J} \qquad 1.1.7(b)$$

where T = maximum twisting moment,
r = original outer radius,
J = polar moment of inertia of the original cross section.

Monolayer -- The basic laminate unit from which crossplied or other laminates are constructed.

NDE -- Nondestructive evaluation. Broadly considered synonymous with NDI.

NDI -- Nondestructive inspection. A process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties.

NDT -- Nondestructive testing. Broadly considered synonymous with NDI.

Neat Matrix – Unreinforced matrix manufactured similar to the composite.

Necking -- A localized reduction in cross-sectional area which may occur in a material under tensile stress.

Negatively Skewed -- A distribution is said to be negatively skewed if the distribution is not symmetric and the longest tail is on the left.

Nominal Specimen Thickness -- The nominal ply thickness multiplied by the number of plies.

Nominal Value -- A value assigned for the purpose of a convenient designation. A nominal value exists in name only.

Normal Distribution -- A two parameter (μ,σ) family of probability distributions for which the probability that an observation will fall between a and b is given by the area under the curve between a and b. (See Volume 1, Section 8.1.4.)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[- \frac{(x-\mu)^2}{2\sigma^2} \right] \qquad 1.1.7(c)$$

Normalization -- A mathematical procedure for adjusting raw test values for fiber-dominated properties to a single (specified) fiber volume content.

Normalized Stress -- Stress value adjusted to a specified fiber volume content by multiplying the measured stress value by the ratio of specimen fiber volume to the specified fiber volume. This ratio may be obtained directly by experimentally measuring fiber volume, or indirectly by calculation using specimen thickness and fiber areal weight.

Observed Significance Level (OSL) -- The probability of observing a more extreme value of the test statistic when the null hypotheses is true.

Offset Shear Strength --- (from valid execution of a material property shear response test) the value of shear stress at the intersection between a line parallel to the shear chord modulus of elasticity and the shear stress/strain curve, where the line has been offset along the shear strain axis from the origin by a specified strain offset value.

One-Sided Tolerance Limit Factor -- See **Tolerance Limit Factor**.

Orthotropic -- Having three mutually perpendicular planes of elastic symmetry.

PAN Fibers -- Reinforcement fiber derived from the controlled pyrolysis of poly(acrylonitrile) fiber.

Parallel Laminate -- A laminate of woven fabric in which the plies are aligned in the same position as originally aligned in the fabric roll.

pH -- A measure of acidity or alkalinity of a solution, with neutrality represented by a value of 7, with increasing acidity corresponding to progressively smaller values, and increasing alkalinity corresponding to progressively higher values.

Pitch Fibers -- Reinforcement fiber derived from petroleum or coal tar pitch.

Plied Yarn -- A yarn formed by twisting together two or more single yarns in one operation.

Poisson's Ratio -- The absolute value of the ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material.

Population -- The set of measurements about which inferences are to be made or the totality of possible measurements which might be obtained in a given testing situation. For example, "all possible ultimate tensile strength measurements for carbon/epoxy system A, conditioned at 95% relative humidity and room temperature". In order to make inferences about a population, it is often necessary to make assumptions about its distributional form. The assumed distributional form may also be referred to as the population. (See Volume 1, Section 8.1.4.)

Population Mean -- The average of all potential measurements in a given population weighted by their relative frequencies in the population. (See Volume 1, Section 8.1.4.)

Population Median -- That value in the population such that the probability of exceeding it is 0.5 and the probability of being less than it is 0.5. (See Volume 1, Section 8.1.4.)

Population Variance -- A measure of dispersion in the population.

Porosity -- A condition of trapped pockets of air, gas, or vacuum within a solid material, usually expressed as a percentage of the total nonsolid volume to the total volume (solid plus nonsolid) of a unit quantity of material.

Positively Skewed -- A distribution is said to be positively skewed if the distribution is not symmetric and the longest tail is on the right.

Precision -- The degree of agreement within a set of observations or test results obtained. Precision involves repeatability and reproducibility.

Preform -- An assembly of fibers which has been prepared for one of several different infiltration methods. A preform may be stitched or stabilized in some other way to hold its shape.

Pressure -- The force or load per unit area.

Probability Density Function -- See Volume 1, Section 8.1.4.

Proportional Limit -- The maximum stress that a material is capable of sustaining without any deviation from the proportionality of stress to strain (also known as Hooke's law).

Quasi-Isotropic Laminate -- A laminate approximating isotropy by orientation of plies in several or more directions.

Random Effect -- A shift in a measured quantity due to a particular level change of an external, usually uncontrollable, factor.

Random Error -- That part of the data variation that is due to unknown or uncontrolled factors and that affects each observation independently and unpredictably.

Reduction of Area -- The difference between the original cross sectional area of a tension test specimen and the area of its smallest cross section, usually expressed as a percentage of the original area.

Room Temperature Ambient (RTA) -- 1) an environmental condition of 73±5°F (23±3°C) at ambient laboratory relative humidity; 2) a material condition where, immediately following consolidation/cure, the material is stored at 73±5°F (23±3°C) and at a maximum relative humidity of 60%.

Roving -- A number of strands, tows, or ends collected into a parallel bundle with little or no twist. In spun yarn production, an intermediate state between sliver and yarn.

S-Basis (or S-Value) -- The mechanical property value which is usually the specified minimum value of the appropriate government specification or SAE Aerospace Material Specification for this material.

Sample -- A small portion of a material or product intended to be representative of the whole. Statistically, a sample is the collection of measurements taken from a specified population.

Sample Mean -- The arithmetic average of the measurements in a sample. The sample mean is an estimator of the population mean.

Sample Median -- Order the observation from smallest to largest. Then the sample median is the value of the middle observation if the sample size is odd; the average of the two central observations if n is even. If the population is symmetric about its mean, the sample median is also an estimator of the population mean.

Sample Standard Deviation -- The square root of the sample variance.

Sample Variance -- The sum of the squared deviations from the sample mean, divided by $n-1$.

Sandwich Construction -- A structural panel concept consisting in its simplest form of two relatively thin, parallel sheets of structural material bonded to, and separated by, a relatively thick, light-weight core.

Shear Fracture (for crystalline type materials) -- A mode of fracture resulting from translation along slip planes which are preferentially oriented in the direction of the shearing stress.

Short Beam Strength (SBS) -- A test result from valid execution of ASTM test method D2344.

Significant -- Statistically, the value of a test statistic is significant if the probability of a value at least as extreme is less than or equal to a predetermined number called the significance level of the test.

Significant Digit -- Any digit that is necessary to define a value or quantity.

Skewness -- See **Positively Skewed, Negatively Skewed**.

Slenderness Ratio -- The unsupported effective length of a uniform column divided by the least radius of gyration of the cross-sectional area.

Sliver -- A continuous strand of loosely assembled fiber that is approximately uniform in cross-sectional area and has no twist.

Specific Gravity -- The ratio of the weight of any volume of a substance to the weight of an equal volume of another substance taken as standard at a constant or stated temperature. Solids and liquids are usually compared with water at 39°F (4°C).

Specific Heat -- The quantity of heat required to raise the temperature of a unit mass of a substance one degree under specified conditions.

Specimen -- A piece or portion of a sample or other material taken to be tested. Specimens normally are prepared to conform with the applicable test method.

Standard Deviation -- See **Sample Standard Deviation**.

Staple -- Either naturally occurring fibers or lengths cut from fibers.

Strain -- The per unit change, due to force, in the size or shape of a body referred to its original size or shape. Strain is a nondimensional quantity, but it is frequently expressed in inches per inch, meters per meter, or percent.

Strand -- Normally an untwisted bundle or assembly of continuous fibers used as a unit, including slivers, tow, ends, yarn, and so on

Strength -- The maximum stress which a material is capable of sustaining.

Stress -- The intensity at a point in a body of the forces or components of forces that act on a given plane through the point. Stress is expressed in force per unit area (pounds-force per square inch, megapascals, and so on).

Stress Relaxation -- The time dependent decrease in stress in a solid under given constraint conditions.

Stress-Strain Curve (Diagram) -- A graphical representation showing the relationship between the change in dimension of the specimen in the direction of the externally applied stress and the magnitude of the applied stress. Values of stress usually are plotted as ordinates (vertically) and strain values as abscissa (horizontally).

Structural Element -- a generic element of a more complex structural member (for example, skin, stringer, shear panels, sandwich panels, joints, or splices).

Symmetrical Laminate -- A composite laminate in which the sequence of plies below the laminate midplane is a mirror image of the stacking sequence above the midplane.

Tenacity -- The tensile stress expressed as force per unit linear density of the unstrained specimen that is, grams-force per denier or grams-force per tex.

Tex -- A unit for expressing linear density equal to the mass or weight in grams of 1000 meters of fiber, yarn or other textile strand.

Thermal Conductivity -- Ability of a material to conduct heat. The physical constant for quantity of heat that passes through unit cube of a substance in unit time when the difference in temperature of two faces is one degree.

Tolerance -- The total amount by which a quantity is allowed to vary.

Tolerance Limit -- A lower (upper) confidence limit on a specified percentile of a distribution. For example, the B-basis value is a 95% lower confidence limit on the tenth percentile of a distribution.

Tolerance Limit Factor -- The factor which is multiplied by the estimate of variability in computing the tolerance limit.

Toughness -- A measure of a material's ability to absorb work, or the actual work per unit volume or unit mass of material that is required to rupture it. Toughness is proportional to the area under the load-elongation curve from the origin to the breaking point.

Tow -- An untwisted bundle of continuous fibers. Commonly used in referring to man-made fibers, particularly carbon and graphite fibers, in the composites industry.

Transformation -- A transformation of data values is a change in the units of measurement accomplished by applying a mathematical function to all data values. For example, if the data is given by x, then $y = x + 1$, x , $1/x$, $\log x$, and $\cos x$ are transformations.

Transversely Isotropic -- Descriptive term for a material exhibiting a special case of orthotropy in which properties are identical in two orthotropic dimensions, but not the third; having identical properties in both transverse directions but not the longitudinal direction.

Twist -- The number of turns about its axis per unit of length in a yarn or other textile strand. It may be expressed as turns per inch (tpi) or turns per centimeter (tpcm).

Twist, Direction of -- The direction of twist in yarns and other textile strands is indicated by the capital letters S and Z. Yarn has S twist if, when held in a vertical position, the visible spirals or helices around its central axis are in the direction of slope of the central portion of the letter S, and Z twist is in the other direction.

Typical Basis -- A typical property value is a sample mean. Note that the typical value is defined as the simple arithmetic mean which has a statistical connotation of 50% reliability with a 50% confidence.

Unidirectional Laminate -- A laminate with all layers laid up in the same direction.

Unstructured Data -- See Volume 1, Section 8.1.4.

Upper Confidence Limit -- See **Confidence Interval**.

Variance -- See **Sample Variance**.

Void -- A physical and mechanical discontinuity occurring within a material or part which may be two-dimensional (for example, disbonds, delaminations) or three-dimensional (for example, vacuum-, air-, or gas-filled pockets). Porosity is an aggregation of micro-voids. Voids are essentially incapable of transmitting structural stresses or nonradiative energy fields. (See **Inclusion**.)

Weibull Distribution (Two - Parameter) -- A probability distribution for which the probability that a randomly selected observation from this population lies between a and b ($0 < a < b < \infty$) is given by Equation 1.1.7(d) where α is called the scale parameter and β is called the shape parameter. (See Volume 1, Section 8.1.4.)

$$\exp\left[-\left(\frac{a}{\alpha}\right)^{\beta}\right]-\exp\left[-\left(\frac{b}{\alpha}\right)^{\beta}\right] \qquad 1.1.7(d)$$

Whisker -- A short single fiber. Whisker diameters range from 1 to 25 microns, with aspect ratios between 100 and 15,000.

Yarn -- A generic term for strands or bundles of continuous fibers, usually twisted and suitable for making textile fabric.

Yarn, Plied -- Yarns made by collecting two or more single yarns together. Normally, the yarns are twisted together though sometimes they are collected without twist.

Yield Strength -- The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. (The deviation is expressed in terms of strain such as 0.2 percent for the Offset Method or 0.5 percent for the Total Extension Under Load Method.)

X-Axis -- In composite laminates, an axis in the plane of the laminate which is used as the 0 degree reference for designating the angle of a lamina.

X-Y Plane -- In composite laminates, the reference plane parallel to the plane of the laminate.

Y-Axis -- In composite laminates, the axis in the plane of the laminate which is perpendicular to the x-axis.

Z-Axis -- In composite laminates, the reference axis normal to the plane of the laminate.

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1.2 INTRODUCTION TO MMC MATERIALS

1.2.1 INTRODUCTION

This Materials and Processes, M&P, Section 1.2, is intended to provide a condensed, designer oriented, introduction and overview of the various MMC materials (including their constituent matrices and reinforcements) and the typical processes used in their consolidation and subsequent fabrication.

The emphasis in Section 1.2 is on making clear the distinctions between the various M&P considerations in MMC and polymer matrix composites (PMC) and ceramic matrix composites (CMC). Just as there are very significant differences between the monolithic unreinforced metals and monolithic polymers and ceramics, similar differences exist between MMC and PMC and CMC. Such differences are manifested in: a.) the nature and type of constituents, b.) the consolidation and processing approaches and c.) their resulting engineering physical and mechanical property attributes and liabilities.

Although MMCs are relative newcomers to the regime of modern engineered materials for advanced design, one can expect continuing improvements in both the understanding and predictability of their design and performance characteristics. Improvements in their affordability and availability will also lead to significant future design utilization.

The scope of MMCs included in this Section 1.2 includes all MMC materials either currently available commercially or under advanced development and of current or anticipated future design interest. Not included in this section are those "model" system MMC materials developed for basic research and not intended for commercialization and technology transfer/implementation in their present form.

1.2.2 MMC SYSTEMS

1.2.2.1 Systems definitions

1.2.2.2 Distinction from other materials/composites

1.2.3 MATRIX MATERIALS

Metals are extremely versatile engineering materials. A metallic material can exhibit a wide range of readily controllable properties through appropriate selection of alloy composition and thermomechanical processing method. The extensive use of metallic alloys in engineering reflects not only their strength and toughness but also the relative ease and low cost of fabrication of engineering components by a wide range of manufacturing processes. The development of MMCs has reflected the need to achieve property combinations beyond those attainable in monolithic metals alone. Thus, tailored composites resulting from the addition of reinforcements to a metal may provide enhanced specific stiffness coupled with improved fatigue and wear resistance, or perhaps increased specific strength combined with desired thermal characteristics (for example, reduced thermal expansion coefficient and conductivity) in the resulting MMC. However, the cost of achieving property improvements remains a challenge in many potential MMC applications.

MMCs involve distinctly different property combinations and processing procedures as compared to either PMCs or CMCs. This is largely due to the inherent differences among metals, polymers and ceramics as matrix materials and less so to the nature of the reinforcements employed. Pure metals are opaque, lustrous chemical elements and are generally good conductors of heat and electricity. When polished, they tend to reflect light well. Also, most metals are ductile but are relatively high in density. These characteristics reflect the nature of atom bonding in metals, in which the atoms tend to lose electrons; the resulting free electron "gas" then holds the positive metal ions in place. In contrast, ceramic and polymeric materials are chemical compounds of elements. Bonding in ceramics and intramolecular bonding in polymers is characterized by either sharing of electrons between atoms or the transfer of electrons from one atom to another. The absence of free electrons in ceramics and polymers (no free electrons are formed in

polymers due to intermolecular van der Waals bonding) results in poor conductivity of heat and electricity, and lower deformability and toughness in comparison to metallic materials.

1.2.3.1 Role of matrix materials

The choice of a matrix alloy for an MMC is dictated by several considerations. Of particular importance is whether the composite is to be continuously or discontinuously reinforced. The use of continuous fibers as reinforcements may result in transfer of most of the load to the reinforcing filaments and hence composite strength will be governed primarily by the fiber strength. The primary roles of the matrix alloy, then are to provide efficient transfer of load to the fibers and to blunt cracks in the event that fiber failure occurs and so the matrix alloy for a continuously reinforced MMC may be chosen more for toughness than for strength. On this basis, lower strength, more ductile, and tougher matrix alloys may be utilized in continuously reinforced MMCs. For discontinuously reinforced MMCs, the matrix may govern composite strength. Then, the choice of matrix will be influenced by consideration of the required composite strength and higher strength matrix alloys may be required.

Additional considerations in the choice of the matrix include potential reinforcement/matrix reactions, either during processing or in service, that might result in degraded composite performance; thermal stresses due to thermal expansion mismatch between the reinforcements and the matrix; and the influence of matrix fatigue behavior on the cyclic response of the composite. Indeed, the behavior of MMCs under cyclic loading conditions is an area requiring special consideration. In MMCs intended for use at elevated temperatures, an additional consideration is the difference in melting temperatures between the matrix and the reinforcements. A large melting temperature difference may result in matrix creep while the reinforcements remain elastic, even at temperatures approaching the matrix melting point. However, creep in both the matrix and reinforcement must be considered when there is a small melting point difference in the composite.

1.2.3.2 Forms of matrix materials

Metals are routinely available in a wide variety of product forms intended for subsequent manufacturing operations. These forms include remelting stock for casting, wrought materials including wire, foil, sheet, bar, plate, a wide variety of extruded shapes, and powder. Many of these different forms are employed in the manufacturing of MMCs. Melt processing methods such as liquid metal infiltration require remeltable compositions. Foil/fiber/foil methods require matrix foil in appropriate thicknesses (typically 0.1 mm or 0.004 inch); in general, foil refers to a flat rolled product of thickness less than 0.012 inch (0.3 mm). Such thickness is readily attainable by rolling of many ductile matrix alloys but may require special rolling methods for less workable alloys. Most metals can be reduced to powder by a variety of methods.

1.2.3.3 Types of matrix materials

Many MMC applications involve considerations other than strength alone - for example, electrical contacts - and so there are corresponding requirements for many types of matrix materials. Pure metals generally are soft and weak as well as being high in electrical and thermal conductivity. This is because the factors which result in easy plastic deformation and low strength with high ductility also allow for ready motion of free electrons and, therefore, high electrical and thermal conductivity. Thus, applications requiring high thermal or electrical conductivity combined with high strength and resistance to wear, for example, contact points, may employ pure metal matrices with ceramic reinforcements.

In recent years there has been a growing emphasis on alloy compositions near to those of certain intermetallic compounds such as Titanium Aluminides. Such intermetallic compounds and the alloys based on them often exhibit attractive combinations of low density, high melting point and high strength at elevated temperatures. On the other hand, the ductility of such compounds is generally poor since bonding is often covalent or ionic in character rather than metallic.

Matrix alloys are also classified according to melting temperature. Exceptionally high melting temperatures such as found with Mo, Nb, and W are termed refractory, meaning difficult to melt. Metals such as Fe, Ni, and Cu are considered to exhibit ordinary melting behavior while Al and Mg are relatively lower temperature melting materials.

Many different metals have been employed in MMCs and the choice of matrix material provides the basis for further classification of these composites. Alloy systems including aluminum, copper, iron (steels), magnesium, nickel, and titanium have been utilized as matrices and each of these are discussed further in following sections.

1.2.3.3.1 Aluminum

A wide range of aluminum alloys in various forms have been incorporated in MMCs. The density of most aluminum alloys is near that of pure aluminum, approximately 0.1 lb/in^3 (2698 kg/m^3). Pure aluminum melts at 1220°F (660°C); this relatively low melting temperature in comparison to most other potential matrix metals facilitates processing of Al-based MMCs by solid state routes, such as powder metallurgy, and by casting methods. Aluminum alloys are broadly classified as either wrought or cast materials; furthermore, many wrought compositions are also available in powder form. The term “wrought” indicates that the material is available primarily in the form of mechanically worked products such as rolled sheet, plate or foil, various extruded shapes, tubing, forgings, wire, rod, or bar. The ready availability of aluminum alloy foils and relatively low processing temperatures allowed the foil-fiber-foil method to be successfully developed and utilized during the 1970s to produce aluminum alloys reinforced with continuous boron or SiC-coated boron fibers for aerospace applications. The 6061 Al-Mg-Si alloy in foil form was employed in many instances and this same alloy composition has also been used in cast form as the matrix in continuously reinforced Al-graphite composites. Many wrought aluminum alloy compositions are well suited for extrusion and most discontinuously reinforced aluminum (DRA) MMCs, whether initially consolidated via powder metallurgy or casting methods, are processed in this manner. Aluminum alloys intended for use in production of castings are generally available as ingots of varying size or in other forms suitable for remelting. Applications of such cast materials have included the production of cast components using DRA, with stirring to suspend particles in the liquid metal prior to casting and solidification of the article.

The designation schemes for both wrought and cast alloys are based on the major alloying additions. Wrought alloys are designated by four digits while cast compositions are designated by three digits (Table 1.2.3.3.1). Further details of compositions are available from many sources. Both wrought and cast alloy compositions may be further classified according to the method of obtaining mechanical properties: heat treatable or non-heat treatable. Heat treatable refers to alloys that can be strengthened by thermal treatment. Wrought alloys of the 2XXX, 6XXX and 7XXX series are generally heat treatable and those that contain major additions of lithium (for example, some 8XXX alloys) are also heat treatable. Typical heat treatment operations may include solution heat treatment, quenching in a liquid medium and subsequent aging. A temper designator is appended to the alloy designation to describe the resulting condition of heat treatment. Thus, -T4 refers to material allowed to naturally age at room temperature following solution heat treatment and quenching, while -T6 describes artificial aging to the peak strength. Additional digits may be used to indicate further details of processing such as straightening operations. Further details of heat treatments and their effect on properties are available in numerous references. The addition of reinforcements (especially particles and whiskers) has been shown to have a significant effect on the aging response of the matrix composition for many DRA MMCs. The aging response may be either accelerated or retarded and the effect is both material and process specific. For this reason the aging treatment for a MMC with a heat treatable matrix alloy may differ significantly from that for the unreinforced matrix. Furthermore, most wrought alloys contain minor alloy additions. For example, Zr is added to various alloys to control recrystallization during hot working. However, the presence of reinforcing particles in an MMC may also aid in grain refinement and obviate the need for some of the minor additions often found in wrought alloys.

TABLE 1.2.3.3.1 *Designations for Aluminum Alloys (Aluminum Association - AA and American National Standards Institute - ANSI).*

Designation		
		Major Alloying Element(s)
Wrought	Cast	
1XXX	1XX	None
2XXX	2XX	Cu
3XXX	----	Mn
	3XX	Si + Mg; Si +Cu; Si + Mg +Cu
4XXX	4XX	Si
5XXX	5XX	Mg
6XXX	----	Mg + Si
7XXX	7XX	Zn
8XXX	----	Other than above
	8XX	Sn

Non-heat treatable alloys are those that are not appreciably strengthened by heat treatment. The strength of the material is determined by the presence of alloying elements present in solid solution and by the extent of any cold working. Wrought alloys of the 1XXX, 3XXX, 4XXX and 5XXX series are generally non-heat treatable. The appended temper designators for these alloys are generally either -O, referring to a fully annealed and softened condition, or -H (with additional digits). The H refers to the use of plastic deformation, typically by cold rolling, to strengthen the material, and the additional digits describe the extent of strain hardening and related annealing treatments to control strength, ductility and susceptibility to stress corrosion. Temper designators similar to those employed with wrought heat treatable alloys are employed with heat treatable (2XX, 3XX, 7XX and 8XX series) casting alloys. Since castings will not experience appreciable mechanical deformation in manufacture, the non-heat treatable 1XX, 4XX and 5XX series cast aluminum alloys are either designated -F (as-cast) or -O (cast and annealed for stress relief). Aluminum-silicon alloys (3XX and 4XX series) are predominant among cast aluminum alloys because they generally exhibit high fluidity when molten and, thus, are well suited for complex shapes and thin sections. Such fluidity is an important consideration in selection of matrix compositions for cast MMCs where, for example, it may be necessary to completely fill the mold volume. The presence of silicon in aluminum significantly lessens the tendency of aluminum to react chemically and reduce SiC and form Al_4C. This latter compound severely embrittles SiC-reinforced Al MMCs even when present in small quantities. For this reason cast aluminum MMCs incorporating SiC particles as reinforcements utilize alloys such as AA 359 as the matrix material. Alternatively, SiC can be incorporated into aluminum alloys by powder metallurgy methods; lower processing temperatures in the solid state reduce the tendency to formation of Al_4C and this affords a wider range of choice of matrix composition.

1.2.3.3.2 Copper

This section is reserved for future use.

1.2.3.3.3 Iron

This section is reserved for future use.

1.2.3.3.4 Magnesium

This section is reserved for future use.

1.2.3.3.5 Nickel

This section is reserved for future use.

1.2.3.3.6 Titanium

Titanium matrix composites have been successfully produced from a wide range of beta, alpha-beta and alpha-phase titanium alloy compositions. Since titanium alloys range in density from approximately 0.18 lb/in^3 (4317 kg/m^3), they are typically 60% higher in density than aluminum alloys and 40% lower in density than low alloy steels at strength levels comparable to annealed steel. Titanium alloys typically maintain good structural properties and oxidation resistance at temperatures up to 315°C (600°F). Since these alloys will provide higher matrix property contributions to a composite system than previously observed in continuous fiber reinforced aluminum composites, there is a greater interest in specific alloy selection.

Although titanium alloys are available in most wrought product forms, its high (approximately 3200°F (1750°C)) melting temperature and work hardening characteristics make some alloys more difficult to process than others. In general, beta-phase alloys can be mechanically worked to higher reduction ratios than alpha-beta alloys, while alpha-beta alloys exhibit greater elevated temperature strength retention. In addition, titanium is a highly reactive element and, therefore, difficult to handle and process at elevated temperatures. Titanium melting/pouring and rapid solidification operations must be performed in vacuum environments.

Titanium alloys are typically identified by their major alloying constituents (for example, Ti-6Al-4V, Ti-15V-3Cr-3Al-3Sn), although several specific alloys have registered trade names (for example, Timetal-21, Ti-1100). The most common alloys used in titanium compositing have been Ti-6-4, Ti-15-3-3-3, Ti-6-2-4-2 and Timetal-21. There has been significant interest in a variety of titanium aluminide alloys, including alpha-2, super alpha-2, gamma, and most recently orthorhombic alloys. These alloys offer higher elevated temperature strength, creep strength, and microstructural stability and are attractive for some gas turbine engine applications, however, low ductility and low tolerance for interstitial contaminants makes processing much more difficult.

1.2.4 REINFORCEMENT MATERIALS

Reinforcement materials in MMCs are second phase additions to a metallic matrix that result in some net property improvement, a typical one being an increase in strength. Generally, most reinforcement materials for MMCs are ceramics (oxides, carbides, nitrides, and so on) which are characterized by their high strength and stiffness both at ambient and elevated temperatures. Examples of common MMC reinforcements are SiC, Al_2O_3, TiB_2, B_4C, and graphite. Metallic reinforcements are used less frequently.

1.2.4.1 Types of reinforcement

Reinforcements can be divided into two major groups, particulates and fibers. Fiber reinforcements can be further divided into continuous and discontinuous fibers. Fibers enhance strength in the direction of orientation. Low strength in the direction perpendicular to the fiber orientation is characteristic of continuous fiber reinforced MMCs. Particulate reinforced MMCs, on the other hand, display more isotropic characteristics.

1.2.4.2 Role of reinforcement

The role of the reinforcement varies with its type in structural MMCs. In particulate and whisker reinforced MMCs, the matrix is the major load bearing constituent. The role of the reinforcement is to strengthen and stiffen the composite by preventing matrix deformation by mechanical restraint. This restraint is generally a function of the interparticle spacing-to-diameter ratio. In continuous fiber reinforced MMCs, the reinforcement is the principal load bearing constituent, the metallic matrix serves to bond the reinforcement and transfer and distributes the load. Discontinuous fiber reinforced MMCs display characteristics between that of continuous fiber and particulate reinforced composites. Typically, reinforcement increases the strength, stiffness and temperature capability of MMCs. When combined with a metallic matrix of higher density, the reinforcement also serves to reduce the density of the composite, thus enhancing properties such as specific strength.

1.2.5 REINFORCEMENT COATINGS

1.2.5.1 Role of coatings

In many MMCs, it is necessary to apply a thin coating on the reinforcements prior to their incorporation into the metal matrix.

In general, coatings on the fibers offer the following advantages:

1. Protection of fiber from reaction and diffusion with the matrix by serving as a diffusion barrier
2. Prevention of direct fiber-fiber contact
3. Promotion of wetting and bonding between the fiber and the matrix
4. Relief of thermal stresses or strain concentrations between the fiber and the matrix
5. Protection of fiber during handling

In some instances particulates are coated to enhance composite processing by enhancing wetting and reducing interfacial reactions.

1.2.5.2 Types of coatings

Given the major role of coatings, there are several techniques available for the deposition of thin coatings on long fibers and, to a much lesser extent, on short fiber and particulate reinforcement. One such process is chemical vapor deposition (CVD). In this process, hot fiber is traversed through a reaction zone in which a vaporized species either decomposes thermally or reacts with another vapor so as to form a deposit on the fiber. Sometimes, the deposition process is enhanced by generating an electric discharge plasma (plasma-assisted CVD). Physical vapor deposition (PVD), plating and spraying are some of the other techniques used to produce fiber coatings. When the objective is to increase wettability, the integrity and structure of the coating is less of a concern than if it were to be used as a protective layer. Barrier coatings to protect fibers from chemical attack by the matrix must, in addition to having thermodynamic stability, impair transport of reactants through it. Fluxing action by a reactive salt coating such as K_2ZrF_6 have been found to promote wettability particularly for C and SiC fibers in aluminum. Sizing of tow based ceramic fibers may be used to enhance handling characteristics.

1.2.6 MANUFACTURING PROCESSES

1.2.6.1 Overview and General Information

Choice of the primary manufacturing process for the fabrication of any MMC is dictated by many factors, the most important of which are:

1. Preservation of reinforcement strength
2. Minimization of reinforcement damage

3. Promotion of wetting and bonding between the matrix and reinforcement
4. Flexibility that allows proper backing, spacing and orientation of the reinforcements within the matrix

These primary industrial manufacturing processes can be classified into liquid phase and solid state processes. Liquid phase processing is characterized by intimate interfacial contact and hence strong bonding, but can lead to the formation of a brittle interfacial layer. Solid state processes include powder blending followed by consolidation, diffusion bonding and vapor deposition. Liquid phase processes include squeeze casting and squeeze infiltration, spray deposition, slurry casting (compocasting), and reactive processing (in-situ composites).

1.2.6.2 Assembly and consolidation

1.2.6.2.1 Powder blending and consolidation

Powder blending and consolidation is a commonly used method for the preparation of discontinuously reinforced MMCs. In this process, powders of the metallic matrix and reinforcement are first blended and fed into a mold of the desired shape. Blending can be carried out dry or in liquid suspension. Pressure is then applied to further compact the powder (cold pressing). The compact is then heated to a temperature which is below the melting point but high enough to develop significant solid state diffusion (sintering). After blending, the mixture can also be consolidated directly by hot pressing or hot isostatic pressing (HIP) to obtain high density. The consolidated composite is then available for secondary processing. Achieving a homogeneous mixture during blending is a critical factor because the discontinuous reinforcement tends to persist as agglomerates with interstitial spaces too small for penetration of matrix particles.

1.2.6.2.2 Consolidation diffusion bonding

This method is normally used to manufacture fiber reinforced MMCs from sheets, foils, powder, powder tape or wire of matrix material, or matrix coated fibers. The methods of assembling reinforcement fibers and matrix alloys depend upon fiber type and fiber array preform method. In the case of monofilaments, such as SiC and boron, parallel arrays with controlled fiber-to-fiber spacing are generated via drum winding, weaving with metallic ribbons, or feeding one or more filaments into a continuous process. Tow-based fibers, such as alumina or graphite (carbon), are typically drum wound or creeled for continuous payout. Matrix materials can be supplied to the composite assembly as separate constituents (for example, foils, powder mat or tape, wires) or applied directly to the fiber array (for example, vapor deposition, plasma spray). The composite elements (plies) are assembled by layering (or wrapping for cylindrical or ring shapes) the fiber array and matrix plies to achieve a predetermined fiber orientation and composite thickness. Composite consolidation is achieved by applying a high pressure in a direction normal to the ply surfaces and a temperature sufficient to produce atomic diffusion of the applicable matrix alloy. This process is performed in a vacuum environment.

1.2.6.2.3 Vapor deposition

Prominent among the vapor deposition techniques for the fabrication of MMCs is electron beam/physical vapor deposition (EB/PVD). This process involves continuous passage of fiber through a region of high partial vapor pressure of the metal to be deposited, where condensation takes place so as to produce a relatively thick coating on the fiber. The vapor is produced by directing a high power (~ 10kW) electron beam onto the end of a solid bar feedstock. One advantage of this technique is that a wide range of alloy compositions can be used. Another advantage worth noting is that there is little or no mechanical disturbance of the interfacial region which may be quite significant when the fibers have a diffusion barrier layer or a tailored surface chemistry. Composite fabrication is usually completed by assembling the coated fibers into a bundle or array and consolidating in a hot press or HIP operation.

1.2.6.2.4 Squeeze casting and squeeze infiltration

Porous preforms of reinforcement material are infiltrated by molten metal under pressure to produce metal matrix composites. Reinforcement materials include carbon, graphite, and ceramics, such as oxides, carbides, or nitrides. Reinforcement forms include continuous fiber, discontinuous fiber, and particulate. Metals used include aluminum, magnesium, copper, and silver. The volume fraction of reinforcement in the metal matrix composites varies from 10 to 70 v/o depending on the particular application for the material.

Generally, the preform, which is shaped to match the contours of the mold, is not wet by the molten metal and must be infiltrated under pressure. In squeeze casting, a hydraulically activated ram applies a low controlled pressure to the molten metal to attain infiltration of the preform without damaging it. Infiltration may or may not be vacuum assisted. Once infiltration is complete, a high pressure is applied to eliminate the shrinkage porosity that can occur when the liquid metal contracts as it transforms into the solid state. This complete consolidation, or absence of porosity, provides the squeeze cast metal matrix composite materials with excellent mechanical properties.

1.2.6.2.5 Spray deposition

A number of processes have evolved under this category in which a stream of metal droplets impinges on a substrate in such a way as to build up a composite. If the reinforcement is particulate, it can be fed into the spray. Matrix only spray can be applied to an array of fibers. The techniques employed fall into two distinct classes, depending on whether the droplet stream is produced from the molten bath (for example, the Osprey process), or by continuous feeding of cold metal into a zone of rapid heat injection (for example, thermal spray processes). In general, spray deposition methods are characterized by rapid solidification, low oxide contents, and significant porosity levels. Depositions of this type are typically consolidated to full density in subsequent processing.

1.2.6.2.6 Slurry casting (compocasting)

Liquid metal is stirred as solid reinforcement particles are added to the melt to produce a slurry. Stirring continues as the melt is cooled until the metal itself becomes semi-solid and traps the reinforcement particles in a uniform dispersion. Further cooling and solidification then takes place without additional stirring. The slurry may be transferred directly to a shaped mold prior to complete solidification, or it may be allowed to solidify in billet or rod shape so that it can be reheated to the slurry form for further processing by techniques, such as die casting.

1.2.6.2.7 Reactive processing (in-situ composites)

There are several different processes that would fall under this category. Directional solidification of eutectics in which one of the phases solidifies in the form of fibers is one such process. Inherent limitations in the nature and volume fraction of the reinforcement and the morphological instabilities associated with thermal gradients have resulted in a decrease in the interest in these types of composites. Exothermic reactions, such as directed metal oxidation, are one family of processes for the production of in-situ composites. The major advantage of this class of composites is that the in-situ reaction products are thermodynamically stable.

1.2.6.3 Thermomechanical processing

1.2.6.4 Near net shape manufacturing processes

1.2.7 PRODUCT FORMS

1.2.7.1 Intermediate

1.2.7.2 Standard

1.2.7.3 Selectively reinforced components

1.2.8 SECONDARY MANUFACTURING PROCESSES

1.2.8.1 Overview and general information

1.2.8.2 Forming

1.2.8.3 Machining

1.2.8.4 Joining

In order to fabricate structures from MMCs, effective joining methods must be developed to join MMCs to the same or different materials. This section reviews the potential adaptability of standard joining practices used for monolithic metals to the joining of MMCs. Since MMCs utilize a variety of non-metallic reinforcements such as silicon carbide, graphite, aluminum-oxide, boron-carbide, and so on, these reinforcements will impose limitations and may require some modifications to standard joining methods for monolithic metals. This section provides a brief summary of the candidate joining methods and a qualitative assessment of their joint performances.

1.2.8.4.1 Qualitative assessment for MMC joining methods

1.2.8.4.1.1 Qualitative performance assessment

As a general rule, the adaptability of conventional joining techniques to MMCs will depend on the combination of the following factors: (1) the volume percent and types of reinforcements, (2) metal matrix melting temperatures, and (3) the thermal energy management control. A brief summary of these three factors is given as follow:

Factor 1: Since MMCs utilize a variety of non-metallic reinforcements, the higher the reinforcement volume fraction, the less likely for standard metal joining techniques to adapt to the MMC. Discontinuously reinforced MMCs are easier to join than continuously reinforced MMCs.

Factor 2: The prolonged contact between a molten metal matrix and a reinforcement can lead to undesirable chemical reactions which are accelerated as the molten metal temperature is increased. Therefore, the metal matrix-reinforcement chemical compatibility is a material and temperature dependent factor. For this reason, the higher the metal matrix melting temperature, the less likely fusion welding techniques will be applicable.

Factor 3: Although high thermal energy is required for many conventional joining processes, excessive thermal energy input is undesirable. Therefore, the use of an automated joining process or a special joining method which can offer a well controlled thermal energy input in a minimum process time will likely improve the joining adaptability for MMCs.

1.2.8.4.1.2 Joint adaptability, applications and selection

A qualitative estimate of the adaptability of 17 monolithic joining practices to MMCs is shown in Table 1.2.8.4.1.2. Further details of each process and classification are provided in subsequent sections. It is important to realize that MMC joining is not a mature technology and many important joining technical details are still lacking. Consequently, the precise knowledge of the adaptability for a specific joining method is a specific material and process dependent factor which must be determined experimentally. However, as a general observation, the use of solid state and other low temperature processes are often more adaptable for joining of MMCs than the use of high temperature fusion processes.

From the designer's viewpoint, selecting a joining method can be qualitatively accomplished by using a set of criteria for joint applications, in conjunction with its adaptability for joining MMCs. Table 1.2.8.4.1.2 shows the proposed criteria for joint applications which are grouped into 8 categories such as joint's stiffness, strength, thermal and electrical conductivity, and so on Each of these joint performance criteria is qualitatively rated in terms of high, medium, or low. From this table, the designer could qualitatively select a candidate joining method which is adaptable for MMCs and has the highest rating score for a particular joining application.

TABLE 1.2.8.4.1.2 *Qualitative rating for joining adaptability, applications and selection.*

	Joint Applications								
Joining Methods	strength driven	stiffness driven	high temperature	thermal conduction	electrical conduction	dimensional stable	complex shapes	dissimilar materials	**Adaptability for MMCs**
Inertia Friction Welding	○	○	○	○	○	○	●	○	○
Friction Stir Welding	○	○	○	○	○	○	○	○	○
Ultrasonic Welding	○	○	○	○	○	○	●	○	○
Diffusion Bonding	○	○	○	○	○	○	○	○	○
Transient Liquid Phase	○	○	○	○	○	○	○	○	○
Rapid Infrared Joining	○	○	○	○	○	○	○	○	○
Laser Beam Welding	○	○	○	○	○	○	○	●	●
Electron Beam Welding	○	○	○	○	○	○	○	●	●
Gas Metal Arc Welding	○	○	○	○	○	○	○	●	●
Gas Tungsten Arc Welding	○	○	○	○	○	○	○	●	●
Resistance Spot Welding	○	○	○	○	○	○	○	●	●
Capacitor Discharge Welding	○	○	○	○	○	○	○	●	○
Brazing	○	○	○	○	○	○	○	○	○
Soldering	○	○	●	○	○	○	○	○	○
Adhesive Bonding	○	○	●	●	●	○	○	○	○
Mechanical Fastening	○	○	○	○	○	○	○	○	○
Cast-insert Joining	○	○	○	○	○	○	○	○	○

Joint Performance Rating: ○ High ○ Medium ● Low

1.2.8.4.2 Potential issues in joining MMCs

In general, MMCs utilize a variety of non-metallic reinforcements with a typical volume fraction ranging from 5% to 60%. For this reason, there are a number of potential joining issues that are peculiar to MMCs.

1.2.8.4.2.1 Solidification effects

For discontinuously reinforced MMCs, most non-metallic reinforcements have different densities from the metal matrix and this can lead to pronounced particle segregation effects when the matrix is in the molten state. In general, the composite weld pool has a higher viscosity and does not flow as well as the unreinforced metal matrix. High viscosity can often lead to a lower heat transfer by convection mechanism in the weld pool which can affect the resulting microstructures and the stress distributions in the MMCs. Techniques which avoid reinforcement material dissolution and non-uniform packing density due to migration of the reinforcement into the welded regions should be employed.

1.2.8.4.2.2 Chemical reactions

In general, the joining process temperature and time must be carefully controlled such that the contact between molten metal matrix and the reinforcements during joining will not lead to dissolution of the reinforcement material, interdiffusion, and the formation of undesirable metallurgical phases. The chemical stability of the metal matrix-reinforcement for a specific joining method is material and process specific. Consequently, final process parameters for a specific process must be experimentally determined.

1.2.8.4.2.3 Joint preparation

Because of their non-metallic reinforcements, most MMCs have very high wear resistance and are brittle to cut using standard steel-cutting tools and saw blades in the preparation of the joint. Cutting and drilling operations must be carefully controlled in order to avoid composite panel edge tear out problems and excessive damage to the continuous fiber reinforcements.

1.2.8.4.2.4 Post-joining heat treatment

To achieve maximum properties following joint fabrication, a post-joining heat treatment should be considered.

1.2.8.4.3 Classification and discussion of selected joining methods

MMC joining methods can be classified into three main groups: solid state, fusion, and other processes. In solid state processes, joining occurs at temperatures below melting of the base metals by the use of either mechanical deformation or the diffusion mechanism. A solid state process often results in the elimination of the original joint interface. In fusion processes, the joining is achieved by melting the base metals of substantially similar compositions and allow the molten metal mixture to solidify. A fusion weld can be fundamentally considered as a miniature casting with different boundary conditions. In other processes, joining usually occurs at temperatures below the melting of the base metals being joined with the use of intermediate filler materials. For processes such as brazing and soldering, special alloys or filler materials are placed in the clearance between the base materials to be joined. A variety of means may be used to heat the assembly. When the resulting filler materials become liquid, they coat the base metal and form a metallurgical bond. MMCs may also be joined by adhesives, mechanical inserts, and fasteners.

MMC joining is not yet a mature technology and many important details are still being developed. Therefore, the applicability of a specific MMC joining method depends on the types of MMC materials being joined. This section provides a qualitative review of selected joining methods, performed mostly for aluminum MMCs, that are described in the open literature as shown in Figure 1.2.8.4.3.

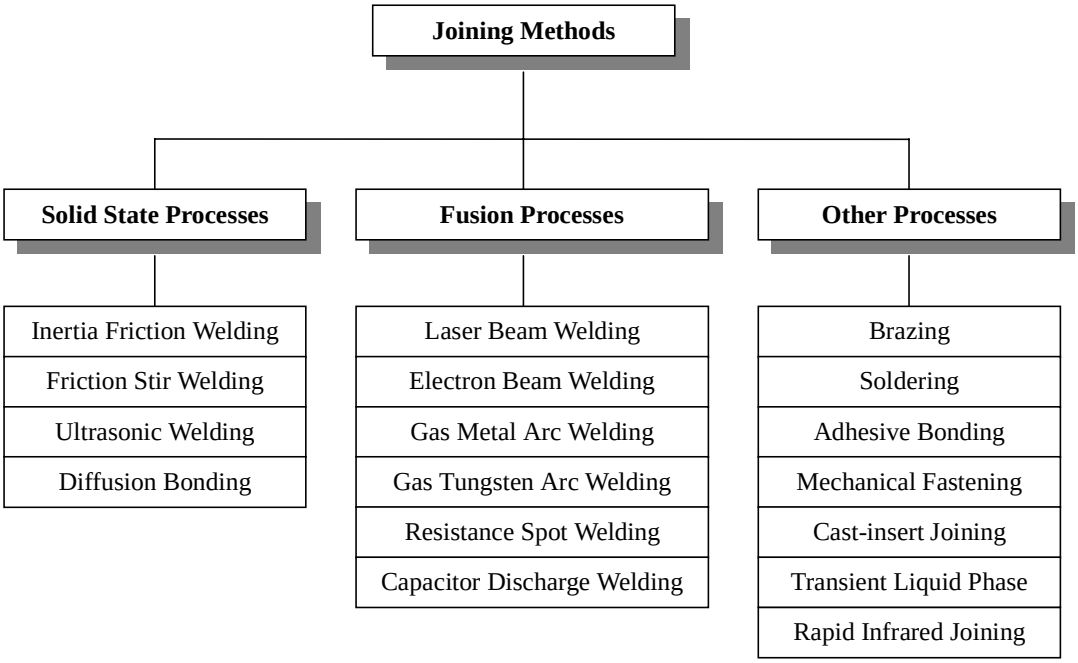

FIGURE 1.2.8.4.3 *Classification of selected joining methods for MMCs.*

1.2.8.4.3.1 Inertia friction (IF) welding

Friction welding produces a joint by using the friction force between components to generate heat. There are two conventional versions of this process: the direct drive and inertia friction welding. In general, conventional friction welding is applicable only to certain types of component sizes and shapes with appropriate joint cross-sectional geometries. Friction welding has been proven successful in making sound joints for discontinuously reinforced MMCs (References 1.2.8.4.3.1(a) and (b)). In IF welding, a part attached to a rapidly rotating flywheel is forced into contact with a part held stationary. A soft layer of material is formed at the interface due to frictional heating. This is the bonding layer that exists between the two components and the bond is normally allowed to cool under the contact pressure. IF welding is a solid state welding process and the processing temperature is lower than the melting temperature of the matrix materials. For these reasons, the welding technique does not tend to produce undesirable chemical reactions and may even promote a uniform particulate distribution at the friction weld interface. Joint formation is accompanied by upset forging and extrusion of materials from the interface. For joining of MMCs, the applied force is usually higher than for conventional alloys since the reinforcement particles substantially increase the flow stress of the MMCs.

1.2.8.4.3.2 Friction stir (FS) welding

Friction stir welding is a special type of conventional friction welding and was invented by The Welding Institute (Reference 1.2.8.4.3.2(a)) from the U.K. in 1991. FS welding is a relatively new technique even for the joining of monolithic materials. Although the technique is still in the development stage, it has a potential for joining some dissimilar materials and MMCs (References 1.2.8.4.3.2(b) and (c)). In FS welding, the parts to be joined are clamped to a backing plate in order to prevent the joint faces from being forced apart. A specially profiled cylindrical tool is rotated and slowly plunged into the joint line to produce a plasticized material zone around the tool through frictional heating. As the tool continues to rotate and moves slowly forward in the direction of welding, plasticized material surrounding the tool is forced to move from the front to the back of the tool thus forming a weld on consolidation. FS welding is a solid state welding which enables the retention of chemistry and uniform distribution of reinforcement materials in the matrix. The welding occurs at temperatures lower than the melting of the matrix and thus minimizes the

potential for matrix-reinforcement chemical reactions. Proper fixturing is required. For joining of MMCs, the applied force is usually higher than conventional alloys since the reinforcement particles substantially increase the flow stress. The FS welding's tool must be made from materials of high strength, high wear resistance, and toughness.

1.2.8.4.3.3 Ultrasonic (US) welding

Ultrasonic welding produces a joint by applying high frequency vibration to the weldment as it is held under a moderately high clamping force without significant melting of the base materials. In contrast with the friction welding which has a high localized plastic deformation at the joint interface, US welding is a mechanically fused joint that may not provide enough localized plastic deformation for joining of some MMCs. However, the induced thermal energy from ultrasonic welding is relatively low such that it will not promote unwanted reinforcement-to-matrix chemical reactions. For some continuously reinforced MMCs, the clamping pressures can result in fiber damage and face sheet delamination. On the other hand, welding may not be achieved if the clamping forces are reduced in order to minimize composite damage. US welding can induce fiber bundle damage from the shearing action of the high frequency vibration (References 1.2.8.4.3.3(a) and (b)). In general, conventional US welding is a low temperature process that has limited application for joining MMCs.

1.2.8.4.3.4 Diffusion bonding (DFB)

Diffusion bonding is a solid state process which is commonly referred to by trade names such as Activated Diffusion Bonding (ADB) and Activated Diffusion Healing (ADH). In each case, the result is actually a diffusion bond. A critical aspect of DFB is that an extensive diffusion penetration of the metallic filler into the base metal must occur and is only achieved with correct joint preparation and cleanliness. For this reason, the DFB process often results in the elimination of the original joint interface. In ADB, chemical compatibility between the MMCs and the metallic filler must be chosen to prevent liquid metal embrittlement (LME) effects. ADB can produce high joint strength for high temperature applications if LME effects are not encountered. Temperature and time must be minimized to control the formation of undesirable chemical reactants. Joint properties are material dependent and DFB joints can offer high thermal and electrical conductivity. DFB is commonly used for heat transfer applications such as heat pipes, fins, radiators, and heat exchangers. However, high temperature DFB may degrade the mechanical properties of some MMCs and may also induce some structural thermal distortion (References 1.2.8.4.3.4(a) and (b)).

1.2.8.4.3.5 Laser beam (LB) welding

Laser beam welding is a rapid thermal joining process that minimizes re-distribution of reinforcements and results in a very fine metal matrix grain size. The LB welding focuses the thermal energy into a very narrow beam resulting in a very narrow weld and heat-affected-zone (HAZ). Microstructural analysis of this region of high heat flux has shown that some reinforcements such as SiC and graphite are completely reacted to form undesirable metal-carbide phases. Other reinforcement types such as B_4C and Al_2O_3, do not present a similar problem. Experimental data suggested that the laser energy is preferentially absorbed by most non-metallic reinforcements in MMCs, relative to the metal matrices. Therefore, mechanically sound joints are not easily obtained by LB welding for most MMC materials containing SiC, carbon or graphite as reinforcement (References 1.2.8.4.3.3(b) and 1.2.8.4.3.4(a)).

1.2.8.4.3.6 Electron beam (EB) welding

This technique usually requires the electron beam and focusing devices, as well as the workpieces, to be placed in a vacuum chamber. The welding quality for MMCs obtained from the EB welding is somewhat similar to those obtained from the LB welding. Both EB and LB welding processes are fusion processes capable of providing very rapid thermal cycles and localized heating. In contrast with LB welding which can be performed in air, EB welding is more complex to set up due to vacuum requirements. Faster electron beam travel and sharper beam focus would tend to produce less aluminum-carbide phases. Generally, EB welding process produces somewhat less unwanted phases than the LB welding using the

same welding speed. EB welding has had limited success with aluminum and titanium-based MMCs which are reinforced by silicon-carbide (References 1.2.8.4.3.3(b) and 1.2.8.4.3.6). However, some improvement in joining quality may be achieved through the use of high speed and temperature controlled welding automation.

1.2.8.4.3.7 Gas-tungsten arc (GTA) welding

GTA is an arc welding process wherein heat is produced by an arc between a single tungsten electrode and the workpiece. Filler metal, if used, is preplaced in the weld joint or fed into the arc from an external source during welding. An arc weld involves a significant melting of the parent materials. Consequently, some degradation of the microstructures and properties of MMCs are often observed. In general, GTA is not easily applied to continuous fiber reinforced MMCs. However for discontinuously reinforced MMCs, the GTA welding process offers a commercially viable joining process. Butt joints, rather than lap joints, can be produced readily using GTA in these systems (References 1.2.8.4.3.3(b) and 1.2.8.4.3.7).

1.2.8.4.3.8 Gas-metal arc (GMA) welding

GMA is an arc welding process which is similar to the GTA, except that a consumable filler metal electrode (either monolithic alloy or MMC) is used instead of the tungsten electrode. The consumable electrode is fed through the welding torch and provides filler metal for making the weld joint. GMA welding process is often automated with high welding speed and has been found to be somewhat more adaptable for MMCs welding than the GTW. For discontinuous reinforcement, GMA welding has proven fairly successful in joining Al-MMCs reinforced with alumina particulates (References 1.2.8.4.3.4(b) and 1.2.8.4.3.8). For multi-pass welds, removing surface contaminant and degassing the MMCs may be required in order to reduce porosity and defects in the heat affected zone. The GMA welding process offers a commercially viable joining process for MMCs.

1.2.8.4.3.9 Resistance spot (RS) welding

A process wherein the heat at the joint interface is generated by a short time flow of low voltage but very high electrical current. An external force is usually applied during the application of the current to assure a continuous electrical contact and to forge the heated parts together to form a joint. RS welding for MMCs typically requires substantially less electrical current than non-reinforced metals due to the increase in bulk electrical resistivity associated with the non-metallic reinforcements. Because the thermal input is very localized, RS produces minimal unwanted reactions. For some continuously reinforced MMCs, the clamping pressures could induce the migration of reinforcement fibers into the weld nugget. This could be a favorable effect in weld nugget reinforcement by enhancing the fiber bundle-to-face sheet peel strength. However, fiber motion is often unpredictable and may lead to complex stress distributions. Important RS welding parameters to control weld nugget cracking are current density, clamping force, contact time between two components and post-forge cycles (References 1.2.8.4.3.3(b) and 1.2.8.4.3.6).

1.2.8.4.3.10 Capacitor discharge (CD) welding

CD is a welding technique similar to electrical resistance welding in that thermal energy is imported to the workpiece by direct electrical contact. In CD welding, the energy is introduced by the rapid discharge of electrical capacitors while force is applied. This assures a continuous electrical circuit and to forge the heated parts together to form a joint. Because capacitive discharge rates are short (on the order of 5 to 25 miliseconds), the process may produce fewer unwanted reactions and provide slightly better properties than interface resistance spot welding (RSW). In the CD welding process, some localized expulsion of molten metal from the interface is common and must be considered in the selection of this process. Experimental work on CD welding has shown that aluminum-carbide compound formation can be precluded on several types of silicon-carbide aluminum MMCs (Reference 1.2.8.4.3.10).

1.2.8.4.3.11 Brazing (BZ)

The two most common production brazing methods are vacuum furnace brazing and dip brazing. Vacuum brazing is somewhat limited to flat-on-flat applications where a large normal pressure can be applied to the surface during the braze cycle. Dip brazing is accomplished with chemical fluxes, and is best suited to self-fixturing assemblies. All brazing processes occur at elevated temperatures which may induce some structural thermal distortion. Long contact times at high process temperatures may cause degradation of joint properties due to the formation of deleterious phases. Surface oxidation must be removed prior to brazing aluminum MMCs. The chemical compatibility between the MMCs and the metallic brazing alloy must be considered to prevent the occurrence of liquid metal embrittlement (LME). Brazing can offer superior thermal and electrical conductivity due to use of a thin metallic filler. Brazing processes are commonly used for thermal applications such as joining of metallic heat pipes, radiators and heat exchangers (References 1.2.8.4.3.3(b) and 1.2.8.4.3.11).

1.2.8.4.3.12 Soldering (SD)

This is a relatively low temperature joining process in comparison with brazing, DFB, and fusion welding, but will result in much lower joint strength. However, a lower processing temperature may be beneficial in the fabrication of a dimensionally stable structure. Low temperature soldering will not degrade aluminum MMCs in the heat treated condition. The tenacious oxide layer formed on the metal matrix must be removed to allow a metallurgical bonding between the solder and the base metals. In general, highly corrosive chemical fluxes are commonly used to enhance surface wetting. Care must be taken to remove these chemical fluxes because they can cause in-service galvanic corrosion and liquid metal embrittlement (LME), if allowed to remain in the joint. Therefore, it is preferred to use solder along with a flux removal technique or a fluxless soldering process (References 1.2.8.4.3.4(a) and 1.2.8.4.3.12).

1.2.8.4.3.13 Adhesive bonding (AB)

This technique offers the lowest risk against potential physical damage of MMCs during joining. LME and metallic corrosion effects associated with joining of MMCs are not encountered when using the AB process. Since most curing temperatures for adhesives will be below 350°F (180°C), adhesive bonding is applicable to aluminum MMCs in the heat treated conditions. In general, strong chemical bonds can be achieved using standard adhesive bonding procedures with appropriate MMCs surface preparation. As with all adhesive bonding applications, outgassing of adhesive compound is a consideration. Vacuum outgassing could contaminate optical mirrors and photonic sensitive equipment if they are mounted onto an MMC adhesively bonded structure. AB technique is not recommended for applications with high thermal or electrical conductivity across the adhesive joint interface. High conductivity joints are more likely to be achieved with thin metal fillers as commonly used in soldering, brazing, and diffusion bonding (References 1.2.8.4.3.3(b) and 1.2.8.4.3.4(a)).

1.2.8.4.3.14 Mechanical fastening (MF)

This is a joining process using a non-melting agent such as mechanical inserts, bolts, nuts, and fasteners. Although mechanical fastening is easy to apply, this method has some disadvantages. For instance, high temperature MMC applications are often sensitive to thermal stresses resulting from the differences in the thermal expansion between the MMC and the fasteners. The size and location of fastener holes in relation to the composite's panel edges and corners must be carefully chosen to avoid panel edge tear out problems during fastener hole machining. It is important to minimize the damage to adjacent fibers when cutting holes through the composite structure. For discontinuous fiber reinforced MMCs, panel delamination and edge tearout problems are usually not encountered for MF. However, fastener sizes and the threshold torque for fastening should be selected to prevent delamination and deformation from overtightening the fasteners. MF is not recommended for the assembly of very low distortion, high dimensionally stable structures and high stiffness MMCs components (References 1.2.8.4.3.14(a) and (b)). DRMMCs have very high pin bearing properties and readily lend themselves to mechanical fastening.

1.2.8.4.3.15 Cast-insert joining (CI)

Cast-insert joining is a method of near net shape casting of MMC components with built-in metallic inserts to provide a site for joining with conventional techniques. Moreover, the inserts can be designed to transfer the imposed load to the fiber reinforcements which may result in stronger and stiffer cast MMC structures. The metallic insert's thermal expansion must be compatible with the cast MMC's to minimize thermal stress during casting (Reference 1.2.8.4.3.15).

1.2.8.4.3.16 Transient liquid phase (TLP) bonding

TLP bonding is a process which employs a filler material to produce a transient liquid layer at the interface to be joined. Since bonding of the joint occurs as a result of diffusion, surface oxides must be removed from the joined areas to facilitate wetting. This process generally requires the application of pressure to improve the interlayer-substrate contact. Process time and temperature must be minimized to prevent microstructural damage. In general, joint quality is material dependent. TLP joints can offer high thermal and electrical conductivity. However, high temperature TLP bonding may degrade the mechanical properties of some MMCs and induce structural thermal distortion. TLP bonding has been demonstrated for joining aluminum MMCs reinforced with silicon carbide and aluminum oxide particulates (References 1.2.8.4.3.16(a) and (b)).

1.2.8.4.3.17 Rapid infrared (RI) joining

This is a relatively new MMC joining process that can produce heating and cooling rates on the order of 212°F/second (100°C/second). Such rapid rates of thermal input could decrease the adverse effects associated with prolonged heating for MMC joining. This technique was developed to minimize the processing time in the transient-liquid-phase joining of high temperature titanium MMCs (Reference 1.2.8.4.3.17). RI process requires that MMC parts, with a metallic filler material, are placed in a special infrared furnace in an appropriate joint configuration. During the entire RIJ process an inert gas, such as argon, is purged through the heating chamber to prevent oxidation. After joining, the MMC parts are cooled naturally in the protective atmosphere. Similar to most diffusion bonding processes, RI can offer high thermal and electrical conductivity.

1.2.8.5 Thermal treatment

1.2.8.6 Coatings and surface treatments

1.2.9 QUALITY ASSURANCE

1.2.9.1 Constituents

1.2.9.2 Preform

1.2.9.3 Final product

1.2.9.4 Statistical process control

1.2.10 REPAIR

1.2.10.1 In-process

1.2.10.2 In-service

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1.3 TEST PLANS FOR MATERIALS CHARACTERIZATION

1.3.1 INTRODUCTION

1.3.1.1 Objective

The objective of these guidelines is to make recommendations regarding minimum handbook properties data that are required for establishing A-Basis, B-Basis and S-Basis mechanical properties for MMC systems. These recommendations cover the composites in final form, the constituents, and intermediate forms.

One of the benefits of composite materials is the ability to tailor their properties to meet design criteria for specific applications. For this reason, the recommendations which follow have been developed to provide flexibility in selecting the applicable test matrices, and number of tests. However, the need remains for statistically valid data in all critical orientations under the anticipated temperature and stress regime for each component.

It is recommended that specific end-use data be reported even if it covers only a small portion of the plans defined in the handbook. Frequently, testing outside that listed is completed. This data can provide very useful information and should be reported. In instances where testing methods used are not referenced in this handbook, the specimens and test methods should be described in detail.

1.3.1.2 Classes of data

1.3.2 REQUIREMENTS

1.3.2.1 Test method selection

Specific test method criteria apply when submitting data to MIL-HDBK-17 for consideration for inclusion in Section 3 of the Handbook, based on the following concepts. Ideally, a test method should have undergone a rigorous review of its applicability, precision and bias by an independent voluntary consensus standards organization that may include representatives from material suppliers, end-users, academia, or government. This review, and the test method, should be available in a referenceable, open-literature publication, and include interlaboratory (round robin) testing. Many times test methods meeting the above criteria are not available, and methods which meet less rigorous criteria (2 below) must be selected for data submittal.

The MIL-HDBK-17 MMC Coordination Group has identified specific test methods to be used when submitting data for consideration for inclusion in Section 3 of the Handbook. These methods are designated or described in Sections 1.4 through 1.10, and meet one or more of the following criteria:

1. Methods, applicable to advanced composites and in common use, which have completed the following:
   - Round robin testing under sponsorship of a recognized standards-making organization
   - Rigorous review of precision and bias
   - Publication in the open literature of a recognized standards-making organization

2. Where no standards meeting the above criteria exist for specific structures or process/product forms, other test methods may have been selected by consensus of the MIL-HDBK-17 MMC Coordination Group. Such methods may have been developed within the MIL-HDBK-17 Working Groups, or by other organizations, and will have begun the process toward formal standardization.

The test methods used for generating data submitted to the handbook must meet the handbook recommendations, current at the time the tests were performed.

1.3.2.2 Test conditions selection

The selection of conditions at which testing is performed is driven by many factors. In general, testing is best performed under the actual service conditions for which the material will be used. However, testing at each and every set of service conditions is cost and time prohibitive. Therefore, a compromise must be made which covers the usable range of the material, yet minimizes testing. This is usually accomplished by testing at the extremes of the application for the material, allowing the user to interpolate for applications between these extremes. This assumes that the properties vary somewhat linearly between these extremes. This is not always the case, as local maxima or minima are sometimes observed (for example, ductility minimum). If such anomalies occur, then an additional set of tests should be conducted at those conditions.

In addition to service conditions, there are other goals which may influence the choice of test conditions selection. If testing is performed to characterize a model, then that specific model should dictate the types of tests and conditions at which to conduct the tests. Testing is sometimes performed beyond the useful range of the material capabilities in order to understand the material behavior under extreme service conditions (that is, overloads, overtemperatures, and so on). Therefore, testing may be performed under conditions where the material incurs excessive amounts of creep, plasticity, oxidation, or other forms of damage. An excessive amount of testing should not be performed in ranges where the material is nominally elastic, where no thermal effects apply, or where limited damage accumulates.

1.3.2.3 Specimen number and sampling

General: Generation of design allowables for metal matrix composite systems usually imply that data have been pooled from different batches, locations, or even slightly different processes. For computational purposes, the definition of a population must be sufficiently restrictive to ensure that the calculated design variables are realistic and useful. A homogeneous population for data pooling should not include more than one composite system of fiber and matrix constituents, heat treat condition, test temperature, fiber orientation, fiber volume fraction, and test method. Statistical analysis of the pooled data should then be performed to confirm that they represent the same population. A decision will then be made after discussions with the certifying agency or, for MIL-HDBK-17, by the Data Review Group.

Sampling for Continuous Fiber Reinforced Metal Matrix Composites

For all continuous fiber reinforced metal matrix composites, samples should be taken from every panel to ensure that there is a homogeneity of properties in the entire batch or lot. The sample should be obtained from randomly selected areas of the panel so as to accurately represent the rest of the material. At least one specimen needs to be taken from each panel that is 6” x 6” (15 cm x 15 cm) or less. For composite panels larger that 6” x 6”, at least two specimens should be removed. A test method should be chosen by mutual agreement between the manufacturer and the end user. Tensile or low cycle fatigue are often used for such screening tests. These screening tests are in addition to the testing requirements outlined in Sections 1.3.3 and 1.3.4 of the Handbook.

1.3.2.4 Specimen preparation

This description is for the machining of composite test specimens. These test specimens will be subjected to cyclic and monotonic loads in order to characterize the behavior of these advanced, state-of-the-art materials. The mechanical properties of the materials will then be used to characterize models and provide data for design. Therefore, it is imperative that the machining process does not introduce any damage that will adversely affect the properties of the material.

These materials are usually supplied in plate form approximately one sq. ft. in size. Portions of the plate may be delivered if specimens have previously been machined from them. The thicknesses of the plates vary from 0.04" (0.1 cm) (for a 4-ply composite) to 0.30" (0.8 cm) (for a 32-ply composite). These materials are very expensive (approx. $10,000/sq. ft.) and require long lead times to purchase. The con-

cern, therefore, is to get good quality specimens from these plates with no mistakes and minimal material waste. Due to the inhomogeneity (that is, hard ceramic fibers and soft matrix) and the extreme anisotropy of these materials, they are not easily machined. This is exacerbated by the fact that the plates are often slightly warped due to the high residual stresses (due to the CTE mismatch between the fibers and the matrix, as well as from irregular lay-ups, that is, fiber misalignment, non-uniform matrix layers) from manufacturing of the plates. For these reasons, conventional machining practices do not work. Non-conventional machining methods have been successfully used for these materials.

There are three ways in which these materials have typically been machined: wire electro-discharge machining, abrasive water-jet machining, or diamond cutting/grinding of the entire specimen. All of these methods have been used successfully for thinner materials (8-ply or less). For thicker materials, abrasive water-jet cutting does not have a sufficient force to cut through the material and maintain accurate geometries; therefore, one of the other machining methods must be used. The machining method chosen should be maintained throughout the entire test program, if possible, to eliminate machining as a possible lurking variable in the data.

When preparing 0° specimens, care must be taken to ensure that the fibers are aligned parallel to the coupon axis. Likewise, when preparing specimens with off-axis or cross-ply fiber orientations, good alignment should also be maintained between the coupon axis and the desired orientation. Large deviations could result in errors in the mechanical properties. Typically, an alignment of ±1° is desired. Larger deviations in alignment should be reported.

If damage on the edge of the gage section (this is a machined surface) is of concern either because it is too rough to support an extensometer, too irregular to get an accurate measurement of the cross-sectional area, or because there is a concern with machining damage influencing the test results, then the specimens can be cut oversized by approximately 0.020 inches (0.050 cm) in the gage and radius sections and be subsequently diamond ground to final dimensions. Final grinding passes should be done in the longitudinal direction (that is, the direction of loading) to avoid scratches that may initiate damage (cracks).

Specimen edges (that is, machined surfaces) may be polished to aid in the viewing of cracks either by optical or replicative means. The faces of the specimen, which consist of a layer of matrix material above the outer most plies of fibers, are usually not prepared in any way. The reason for this is that the matrix face layer is often thin, and there is a good chance that through the preparation process, fibers will be exposed to the surface. This could damage the fibers, or at the least will provide an easy access for the environment into the material (note that the fiber coating on the SCS-6 fiber is an easy diffusion path for oxygen). In either case, the mechanical properties could be compromised. However, polishing may be required to facilitate matrix-crack detection during fatigue and fatigue crack growth testing. If polishing of the faces of the specimen is required, care should be taken to remove a minimum of matrix material. Light polishing can be conducted with the following procedure: 320, 400, then 600 grit abrasive paper followed by 6 and 3 micron diamond paste.

A sample of typical machining instructions is given in Figure 1.3.2.4(a) for the sample geometry given in Figure 1.3.2.4(b). This sample design is used for uniaxial loading. Its design originated from a finite element analysis, constructed to prevent failure in the transition area by minimizing and separating the shear and axial stress concentrations which occur at the transition between the radius and the gage section (Reference 1.3.2.4(a)). This geometry is proposed in the revision of ASTM Standard D3552-77 (the latest version is ASTM D3552/D3552M-96), Test Method for Tensile Properties of Fiber-Reinforced Metal Matrix Composites, as the recommended design for specimens of unidirectional composites. Other sample geometries may be used. Figure 1.3.2.4(c) shows a dogbone-shaped specimen which has been used successfully and has the added advantage that it uses less material. The key to an adequate specimen design is that the specimen must fail in the gage section. If failure frequently occurs in the transition, radius or grip areas, then the data from these specimens should be labeled as suspect and a new specimen geometry sought.

Rectangular cross-section gage

1) Wire EDM material approximately 0.020" oversized on gage and radius cuts before grinding.

2) Diamond grind on gage and radius to final dimensions as per detail dimensions shown.

3) Remove final stock with a series of light passes to minimize the depth of damage and work hardening.

4) Material supplied is unique and not easily replaced; therefore, take extra care to set up correct dimensions before making any cuts.

5) The reduced gage section width (0.390") should be centered relative to the width (0.500") of the specimen ends within ± 0.001".

6) The reduced gage section should be also centered with respect to the length (6”) of the specimen within ± 0.001”

7) Cut surfaces marked **A** [gage edge and end edge] should be true and square. Also, **A** surfaces should be parallel to specimen centerline within ± 0.001".

8) All radii must blend without undercuts or steps.

9) Number each specimen with permanent ink and identify the unique position of the plate from which it came.

10) The one inch straight gage section and the radii must have a 32 rms finish or better.

11) Thickness as supplied

12) Return ALL material and scraps. Protect ground surfaces of specimen from damage.

FIGURE 1.3.2.4(a) *Machining instructions.*

For specimens which contain off-axis plies, there is an additional factor in determining the gage width/length of the specimen. A study has shown that when off-axis fibers in the gage begin, end, or begin and end in either the radius or the grips, there is additional constraint on the specimen, thus affecting at least the room temperature tensile properties (Reference 1.3.2.4(b)). Thus, while the gage width may maintain a value identical to that of the unidirectional specimens, the gage width-to-length must be sized such that there are few fibers from the gage ending in either the radius or grips. In other words, the fibers in the gage section should begin and end in the straight gage section. Depending on the inclination of the fibers with respect to the specimen axis, this may necessitate a longer gage section.

Specimens will often require a heat treatment to either age the *in-situ* matrix or to simulate some thermomechanical treatment which the component may experience. The heat treatment should be performed after machining for several reasons. First, the heat treatment may help relieve machining residual stresses. Second, if only a few specimens are heat treated at a time and if there is a problem with the heat treatment, then only a few specimens will be ruined and not the entire plate. Lastly, due to the high residual stresses in the composite, the specimens may warp when cut out of the plate. This can be cured by subsequent heat treating of the specimen under weight for creep flattening. It should be noted that due to the high residual stresses in the composite, initially flat specimens may not come out of the heat treat furnace as flat. In some cases, specimens have been observed to be so severely bent and warped that they were rendered useless. Again, weighting the specimens during heat treatment should solve this problem.

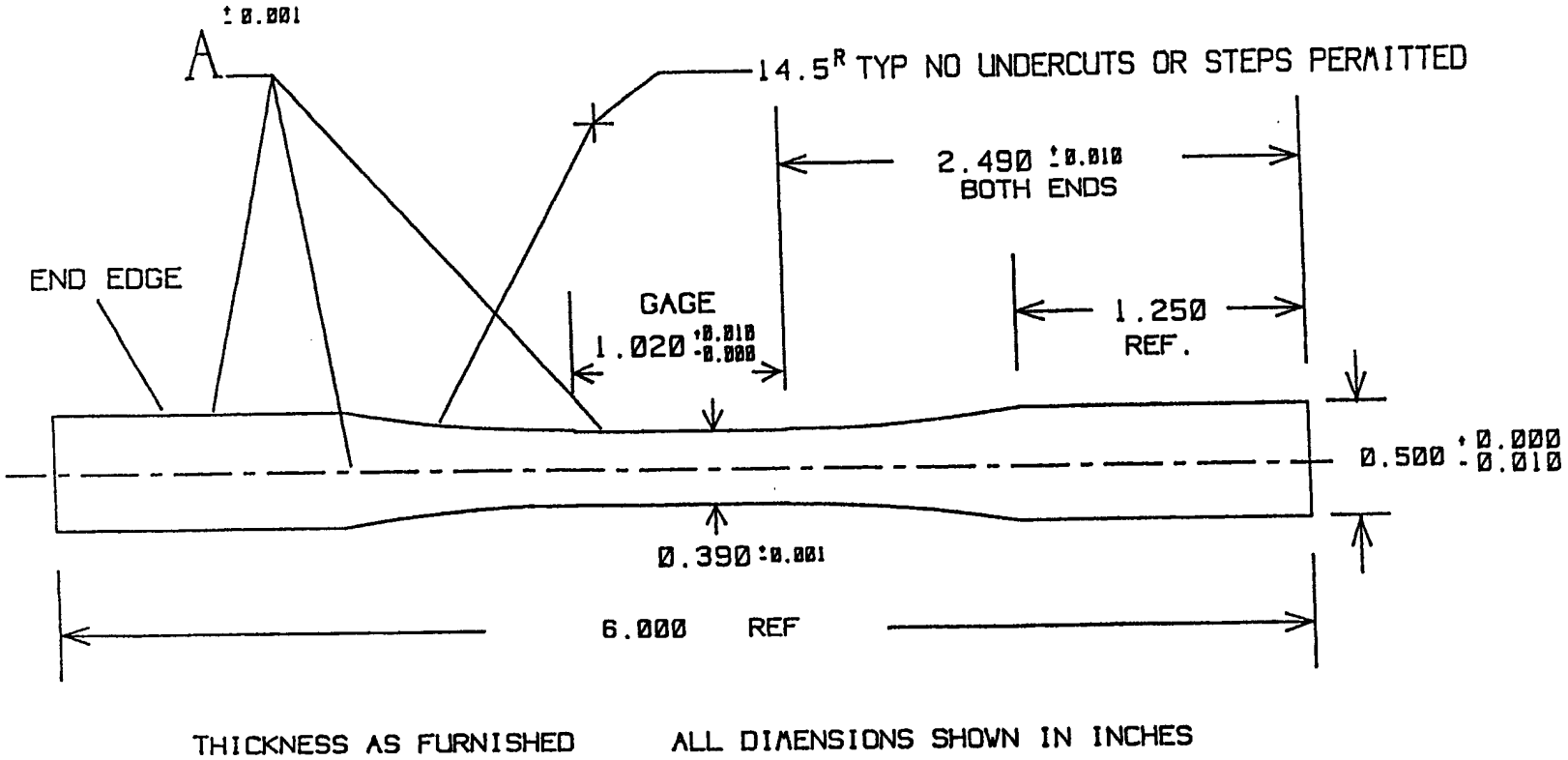
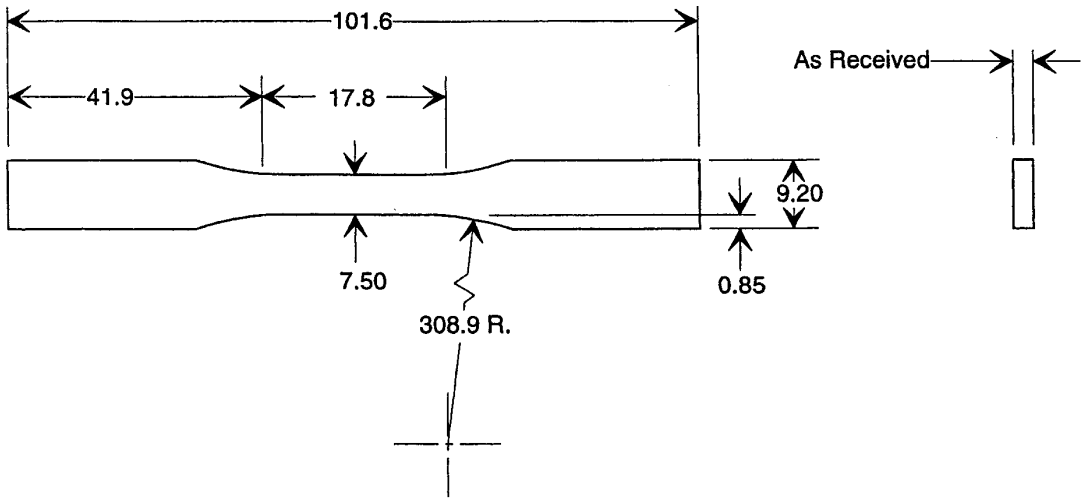


FIGURE 1.3.2.4(b) *MMC/IMC dogbone specimen - 14.5" radius.*



PART NAME: Flat Dogbone Specimen		
MATERIAL: SCS-6/Ti-6Al-4V		
HEAT TREATMENT: N/A		
FINISH: N/A		
TOLERANCES - ULESS OTHERWISE NOTED: x.x ± 0.3, x.xx ± 0.05, x.xxx ± 0.005		FRAC.
SCALE: 1 : 1	UNITS: millimeters	REVISION: --
FILE NAME: 1732.DSF		QUANTITY
DRAWN BY: David Maxwell	DATE: 08/07/96	SHT 2 of 2

FIGURE 1.3.2.4(c) *Flat dogbone specimen.*

1.3.2.5 Data documentation

Data Documentation Requirements Checklist

Material Name: _____

Data Submitted by: _____

Date Submitted: _____

Does Data meet MIL-HDBK-17 requirements for fully approved data? ____ Yes ____ No
For fully approved data, the requirements listed in Volume 4, Section 1.3.4 (Continuous Fiber Reinforced MMC Constituent Material Properties) or Section 1.3.5 (Discontinuous Reinforced MMC & Constituent Material Properties) must be fulfilled. In addition, all the items listed below marked by an arrow must be provided either on the Submitter's data tables or on this checklist in order to meet the handbook's Full Documentation Requirements. Otherwise, the data will be considered as Screening Data if those items marked by an arrow are not supplied.

Name (POC): _____

Organization: _____

Telephone: _____

_____

MATERIAL IDENTIFICATION

☐ ➨ Reinforcement ID _____

☐ ➨ Matrix ID _____

☐ ➨ Continuous or Discontinuous _____

REINFORCEMENT INFORMATION

☐ ➨ Chemical Composition _____

☐ ➨ Form (fiber, whisker, particulate, and so on) _____

☐ ➨ Commercial Name _____

☐ ➨ Manufacturer _____

☐ ➨ Diameter _____

☐ ➨ Aspect Ratio (If Discontinuous) _____

☐ Shape (If Discontinuous) _____

☐ ➨ Size Distribution (If Discontinuous) _____

☐ ➨ Lot Number(s) _____

➨ = For Full Documentation Requirements

Material Name: _____

Data Submitted by: _____

Date Submitted: _____

REINFORCEMENT INFORMATION (Continued)

- ☐ Reinforcement Nominal Density _____
- ☐ ➨ Nominal Filament Count (If Applicable) _____
- ☐ ➨ Fiber Alignment Material (crossweave) _____
- ☐ ➨ Fiber, Tow, or Yarn Count (per inch) _____

MATRIX INFORMATION

- ☐ ➨ Matrix Composition _____
- ☐ ➨ Matrix Supplier _____
- ☐ ➨ Matrix Heat No. _____

CONSOLIDATION PROCESS INFORMATION

- ☐ ➨ Manufacturer _____
- ☐ Manufacture Date _____
- ☐ ➨ Process Sequence Description _____
- ☐ ➨ Process Temperature/Pressure/Time _____

COMPOSITE INFORMATION

- ☐ ➨ Product Form _____
- ☐ ➨ Material Lot/Serial/Part No. _____
- ☐ Product Form Dimensions _____
- ☐ ➨ Reinforcement Volume Fraction _____
- ☐ ➨ Lay-Up & Ply Count (If Applicable) _____
- ☐ ➨ Nominal Density (g/cc) _____
- ☐ ➨ Void Content (If Cast Process) _____

➨ = For Full Documentation Requirements

Material Name: _____

Data Submitted by: _____

Date Submitted: _____

SPECIMEN INFORMATION

- ☐ ➨ Machining Method _____
- ☐ ➨ Specimen Geometry _____
- ☐ ➨ Specimen Dimensions (including thickness) _____
- ☐ ➨ Surface Condition _____
- ☐ ➨ Specimen Orientations _____
- ☐ ➨ Pre-Test Exposure _____
- ☐ ➨ Tabbing Method (If Applicable) _____

MECHANICAL TESTING

- ☐ ➨ Type of Test(s) _____
- ☐ ➨ Test Method/Procedure _____
- ☐ ➨ Number of Specimens _____
- ☐ Test Date _____
- ☐ ➨ Test Temperature _____
- ☐ ➨ Test Environment _____
- ☐ ➨ Failure Mode ID and Location _____

➨ = For Full Documentation Requirements

Static Property Data Documentation

For static properties, the following quantities should be provided for each specimen in tabular (spreadsheet) form as shown on the data table templates provided by MIL-HDBK-17 Secretariat:

- ☐ Specimen No.
- ☐ Fiber v/o
- ☐ Lot I.D. (Plate No.)
- ☐ Test Temp. (°F)
- ☐ Strain rate (1/s)
- ☐ E^{t} (Msi)
- ☐ Proportional Limit (ksi)
- ☐ $F^{ty0.02}$ (ksi)
- ☐ $F^{ty0.2}$ (ksi)
- ☐ F^{tu} (ksi)
- ☐ ε^{tu} (%)
- ☐ Test Date
- ☐ Failure Location
- ☐ Failure Mode
- ☐ Stress-Strain Data

In addition, the supplier of data should include any other quantities they have readily available for each specimen Add columns to the standard data table at the far right as needed. Examples of such quantities are:

- ☐ Reduction of Area (%)
- ☐ Elongation (%)
- ☐ Area (in^2)
- ☐ Load @ 0.2% Offset (lbs)
- ☐ Poisson's Ratio, ν
- ☐ Ultimate Load (lbs)
- ☐ Gage Width (in)
- ☐ Gage Thickness (in)
- ☐ Gage Length (in)

1.3.3 MATERIALS PEDIGREE

When submitting data to the Handbook, a complete set of pedigree information is required. This is to establish the validity of a manufacturer's material system's physical, chemical, and mechanical property database. The requirements are necessary to establish justification for the inclusion of data into MIL-HDBK-17. Documentation requirements ensure complete traceability and control of the database development process from material production through procurement, fabrication, machining, heat treating, gaging, and testing.

Data submitted must include a completed Data Documentation Checklist (see Section 1.3.2.5). Test methods used must meet handbook recommendations at the time the tests were performed. All items in this checklist are desired. Items marked with arrows are required for full approval. All information should be traceable and available to the Secretariat. The Data Documentation Checklist is based on the information necessary for composite level mechanical property testing. The information required for other tests or material levels is similar.

1.3.3.1 Reinforcement

1.3.3.2 Reinforcement sizing

1.3.3.3 Reinforcement coatings

1.3.3.4 Matrix

1.3.3.5 Intermediate forms characterization

1.3.3.5.1 Metallized fibers

1.3.3.5.2 Monotapes

1.3.3.5.3 Lamina other than monotapes

1.3.3.5.4 Specialized forms

1.3.3.6 Composite materials

1.3.4 CONTINUOUS FIBER REINFORCED MMC CONSTITUENT MATERIAL PROPERTIES

1.3.4.1 Screening

1.3.4.2 Acceptance testing of composite materials

This section recommends tests for the submission of fully approved data to the Handbook. The test matrices are for data generation on composites, fiber, and matrix materials. The test matrices were designed to allow a statistical analysis to be performed and to account for the anisotropic nature of these materials. However, due to the high cost of these materials, the overall number of recommended tests was kept at a minimum. All testing should follow the testing standards given in the Handbook.

1.3.4.2.1 Composite static properties tests

TABLE 1.3.4.2.1 *Composite static property tests.*

Test	Fiber Directionality	Number of Lots	Samples per Lot	Number of Tests per Condition
Tensile	L	5	6	30
Tensile	T	5	6	30
Compression	L	5	6	30
Compression	T	5	6	30
Shear (in-plane)	L	5	6	30
Shear (in-plane)	T	5	6	30
Pin-Bearing Tensile	L	5	6	30
Pin-Bearing Tensile	T	5	6	30

L is longitudinal and T is transverse.

1.3.4.2.2 Composite fatigue properties tests

TABLE 1.3.4.2.2 *Composite fatigue tests.*

Test	Fiber Directionality	Number of Lots	Stress Levels	Replicates	Number of Tests per Condition
High-Cycle Fatigue	L	3	5	2	30
High-Cycle Fatigue	T	3	5	2	30
Low-Cycle Fatigue	L	3	5	2	30
Low-Cycle Fatigue	T	3	5	2	30
Fatigue Crack Growth Rate	L	3	5	2	30
Fatigue Crack Growth Rate	T	3	5	2	30
Creep/Stress Rupture	L	3	5	2	30
Creep/Stress Rupture	T	3	5	2	30

L is longitudinal and T is transverse.

1.3.4.2.3 Composite thermal mechanical tests

TABLE 1.3.4.2.3 *Composite thermal mechanical tests.*

Test	Fiber Directionality	Number of Lots	Stress Levels	Replicates	Number of Tests per condition
TMF in-phase (IP)	L	2	3	2	12
TMF in-phase (IP)	T	2	3	2	12
TMF out-of-phase (OP)	L	2	3	2	12
TMF out-of-phase (OP)	T	2	3	2	12
Tensile (after thermal cycling)	L	5	-	6	30
Tensile (after thermal cycling)	T	5	-	6	30

L is longitudinal and T is transverse.

1.3.4.2.4 Composite physical properties tests

TABLE 1.3.4.2.4 *Composite physical properties tests.*

Test	Number of Lots	Samples per Lot	Number of Tests per condition
Coefficient of Thermal Expansion (a)	5	1	15 min. per dir.
Specific Heat (b)	5	1	5
Thermal Conductivity (a)	5	1	15
Electrical Conductivity (a)	5	1	15
Density (c)	5	1	5
Volume Fraction (c)	5	1	15

(a) Taken in the L (longitudinal), LT (long transverse), and WT (wide transverse) directions
(b) Property taken parallel to the fiber direction only
(c) Property is independent of fiber orientation

1.3.4.3 Intermediate forms characterization

1.3.4.3.1 Metallized fibers

1.3.4.3.2 Monotapes

1.3.4.3.3 Lamina other than monotapes

1.3.4.3.4 Specialized forms

1.3.4.4 Constituent characterization

1.3.4.4.1 Fiber properties tests

TABLE 1.3.4.4.1 *Fiber property tests.*

Test	Number of Lots	Samples per Lot	Number of Tests per condition
Tensile	5	30	150
Microstructure (with magnification)	5	3	15
Chemical Analysis	5	3	15
Axial Thermal Expansion	5	3	15
Diameter (range)	5	10	50
Density	5	1	5
Electrical Conductivity	1	1	1
Thermal Conductivity	1	1	1

1.3.4.4.2 Matrix

TABLE 1.3.4.4.2 *Matrix Property Tests.*

Test	Number of Lots	Samples per Lot	Number of Tests per condition
Tensile	5	3	15
Fatigue	5	3	15
Creep	5	3	15
Crack Growth	5	3	15
Hardness	5	3	15
Microstructure (with magnification)	5	3	15
Chemical Analysis	5	3	15
Coefficient of Thermal Expansion	5	3	15
Density	5	1	5
Electrical Conductivity	1	1	1
Thermal Conductivity	1	1	1

1.3.5 DISCONTINUOUS REINFORCED MMC & CONSTITUENT MATERIAL PROPERTIES

1.3.5.1 Composite materials characterization

1.3.5.1.1 Screening

1.3.5.1.2 Acceptance testing of composite materials

1.3.5.1.2.1 Composite static properties tests

1.3.5.1.2.2 Composite fatigue properties tests

1.3.5.1.2.3 Composite thermal mechanical tests

1.3.5.1.2.4 Composite physical properties tests

REFERENCES

1.3.2.4(a) Worthem, D.W., "Flat Tensile Specimen Design for Advanced Composites," NASA CR-185261, 1990.

1.3.2.4(b) Lerch, B.A. and Saltsman, J.F., "Tensile Deformation Damage in SiC Reinforced Ti-15V-3Cr-3Al-3Sn, NASA TM-103620, 1991.

1.4 COMPOSITE TESTING AND ANALYTICAL METHODS

1.4.1 INTRODUCTION

Section 1.4 contains test and analytical methods for characterizing metal matrix composites. The purpose of this section is to provide standardized methods and commonly used techniques to pedigree the material and to generate material property data. The test methods and techniques are representative of procedures used in the composite materials industry. Existing standards are cited when they exist and are applicable. When there are no such standards available, a test method has been proposed. The proposed test methods are ones that are widely used within industry, academia, or government. Most of these test methods are taken directly from usage on monolithic metals. However, since there are special concerns regarding the testing of MMCs due to their brittle reinforcement phase and their highly anisotropic nature, special consideration must be given when adapting such methods. Cautionary notes have been added to many of the monolithic standards in order that they can be applied to MMCs.

1.4.2 CONTINUOUS FIBER REINFORCED MMC MECHANICAL PROPERTY TEST METHODS

1.4.2.1 Tension

General: Tensile testing of MMC laminates should be conducted in accordance with ASTM Test Method D3552/D3552M Tensile Properties of Fiber Reinforced Metal Matrix Composites (Reference 1.4.2.1). The following additional points should also apply:

1. A failure location within the area of one specimen width away from the grip or the specimen tab should be considered as an "at grip" failure and these data should be "flagged" as such.

2. When preparing [0] specimens, care must be taken to ensure that the fibers are aligned parallel to the coupon axis. Likewise, when preparing specimens with off-axis or cross-ply fiber orientations, good alignment should also be maintained between the coupon axis and the desired orientation. Large deviations could result in errors in the strength and modulus values. Typically, an alignment of ±0.5° is desired. Larger deviations in alignment should be reported.

1.4.2.2 Compression

This test procedure covers the preferred manner to determine compressive mechanical properties of MMCs. At the present, there are no standardized methods for such testing however, techniques developed for metals and polymer composites have been used with success. Various test fixtures have been designed to introduce compressive loads to the test specimen while minimizing stress concentrations due to gripping and misalignment. These fixtures include the Modified Celanese Fixture, The Illinois Institute of Technology Research Institute (IITRI) Fixture, and the Sendeckyj-Rolfes Fixture. To date, the IITRI test fixture is the most commonly used.

Compression tests on MMC's should be conducted in accordance with ASTM Standard D3410-87 (the latest version is ASTM D3410/D3410M-95) "Standard Test Method for Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites" (Reference 1.4.2.2). The following additional points should also apply:

1. The IITRI compressive test fixture is the preferred test setup for continuous reinforcement metal matrix composite.

2. Strain gages should be affixed to the specimen using the manufacturer's recommended procedures. Two strain gages (one on each face of the test specimen) should be used to determine the magnitude of bending taking place during each test. The use of two gages will provide redundancy and will help pinpoint problems that arise during testing. Strain readings that diverge from the beginning of the test suggest specimen bending caused by test specimen/fixture misalign-

ments. A sudden divergence between the two readings suggests the onset of specimen buckling. A sharp discontinuity in either or both readings suggests a grip/wedge seating anomaly.

3. Fixture alignment is extremely critical when testing MMC's. The maximum allowable percent bending stress (PBS), as defined below, should not exceed five percent at failure. Bending stresses above this limit should invalidate the test. Tests with percent bending stresses between three and five percent should be flagged as such.

$$PBS = ABS((G1-G2)/(G1+G2)) \qquad 1.4.2.2$$

where $G1$ and $G2$ are the values from strain gages #1 and #2.

4. A failure location within the area of one specimen width away from the grip or specimen tab should be considered an "at grip" failure. These data should be "flagged" as such.

1.4.2.3 Shear (in-plane)

This test procedure covers the preferred manner to determine the in-plane shear properties of MMC. Shear tests on MMCs should be conducted in accordance with ASTM Standard D5379/D5379M "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method" (Reference 1.4.2.3). The following additional points should also apply:

1. Strain gages should be affixed to the specimen using the manufacturer's recommended procedures. It is strongly suggested that two strain gages (one on each face of the test specimen) be used to determine the magnitude of twisting taking place during each test. The use of two gages will provide redundancy, will allow signal averaging if required, and will help pinpoint problems that arise during testing. Strain readings that diverge from the beginning of the test suggest specimen twisting caused by test specimen/fixture misalignments.

1.4.2.4 Fatigue

1.4.2.4.1 Scope

This standard addresses isothermal fatigue testing of metal matrix composites. These tests may be performed in either load or strain control and at any constant load (or strain) ratio (R_σ or R_ε). In general, the tests should follow ASTM Test Methods E466 (Reference 1.4.2.4.1(a)) and E606 (Reference 1.4.2.4.1(b)). The following notes should also apply:

1.4.2.4.2 Specimen design

The specimen design and preparation should follow the recommendations given in Section 1.3.2.4.

1.4.2.4.3 Waveforms

Either a triangular (that is, linear ramp) or sinusoidal waveform may be used for cyclic loading. Any constant loading/unloading rate may be employed. Slower loading rates will tend to facilitate creep or stress relaxation of the constituents. Loading rates that are greater than approximately 10 Hz may cause frictional heating between the fibers and the matrix due to interfacial sliding. These loading rates should be avoided unless the material application dictates such rates.

1.4.2.4.4 Control mode

Either load or strain control modes may be used in fatigue testing. When using load control, specimen strain will typically ratchet towards the tensile direction. This is particularly true for high positive load ratios and laminates which do not contain a 0-ply.

Strain controlled tests typically show stress relaxation during the test, and in fact can lead to relaxation into the compressive field. This can lead to buckling of thin plate specimens (see Section 1.4.2.4.5). Also, the definition of failure under strain control is frequently a problem (see Section 1.4.2.4.6).

1.4.2.4.5 Compressive loading

Testing of thin plate MMCs under compressive loads can lead to unstable buckling of the test specimen. This can be caused either by the applied compressive load, or due to the fact that the load has relaxed into compression during a strain controlled test. To avoid buckling, two options exist. The first is to test thicker materials which can withstand compressive loads. This may not be an option due to the high cost of thick materials or difficulties in manufacturing thick composites. The second option is to employ buckling guides. These guides minimally constrain the lateral surfaces of the specimen to prevent buckling. They have been used successfully in the fully reversed loading of thin plate TMC specimens (References 1.4.2.4.5(a) and (b)). In addition, specimens tested with these buckling guides have been shown to have equivalent lives to thick specimens which were tested under identical conditions without buckling guides.

It should be cautioned that improperly designed buckling guides can either erroneously increase the fatigue lives by assuming too much of the axial load or erroneously decrease fatigue lives by introducing frictional wear on the contact surfaces. Therefore, the experimentalist must verify that use of buckling guides is not affecting specimen fatigue life (see Reference 1.4.2.4.5(c) for guidance).

1.4.2.4.6 Failure

Testing should continue until failure has occurred. The failure criterion which is used to define failure should be clear.

Note 1: With load controlled tests, the specimens should fail in two pieces if there is a tension load in the cycle. Therefore, two pieces is often used as a failure criterion. However, other definitions of failure, particularly for strain controlled tests, can be used (see Reference 1.4.2.4.1(b) for examples).

1.4.2.4.7 Data reporting

1. Stress-strain hysteresis loops should be recorded at periodic times during the test either digitally and/or with analog recorders.

2. The maximum and minimum loads (or strains, which ever are the non-controlled parameters) should be plotted for each specimen as a function of cycles.

3. The failure location and failure criterion should be reported as well as the reason for any anomalous crack initiation (for example, thermocouple attachment).

1.4.2.5 Fatigue crack growth rate

General: This standard allows the determination of fatigue crack growth rates in composite materials using middle-tension, M(T), or single-edge-notch, SE(T) specimens. The results of crack growth rates are expressed in terms of the cyclic range of the applied stress intensity factor, the crack length, or the cyclic range of the effective crack tip stress intensity factor using one of the fiber bridging models such as a shear lag model (References 1.4.2.5(a) through 1.4.2.5(c)), a spring model (References 1.4.2.5(d) and

(e)) or a fiber pressure model (References 1.4.2.5(e) and (f)), if a bridging zone develops during the fatigue crack growth experiment.

This standard should apply only to composite materials which promote self-similar crack extension such as [0], [90], or [0/90] fiber lay-ups. In other fiber lay-ups, complex failure modes usually develop near the machined notch causing a large network of micro-cracks, multiple cracks, delamination, and non self-similar crack extension.

The fatigue crack growth tests should be conducted in accordance with ASTM Standard E647 Standard Test Method for Measurement of Fatigue Crack Growth Rates (Reference 1.4.2.5(g)). The following notes should also apply:

Specimen Configuration:

1. The thickness of the specimen is controlled by the available composite material, since the available plate material is generally not machined to a specific thickness. All other dimensions will then be based upon this available thickness and will be determined by the equations for the specimen dimensions given in ASTM E647.

2. Direct pin-loading of a unidirectional MMC specimen is not recommended due to the likelihood of a local bearing failure in the vicinity of the machined holes. Therefore, a wedge loading fixture, similar to those described in ASTM E647, is recommended. The specimen depth in the wedge zone should be greater than 0.5W for a middle-tension M(T) specimen and W for the single-edge-notch tension SE(T) specimen. This distance is dictated primarily by frictional effects and the amount of specimen needed to be clamped by the wedge grips to prevent slippage.

3. Middle-Tension Specimen, M(T):

   Standard ASTM E647 M(T) specimens (Figure 1.4.2.5(a)) can be used for specimens which will be tested in a wedge loaded fixture. A wider and longer gripping area can be accommodated, as long as the length of the specimen between the grips is greater than or equal to 3W.

4. Single-Edge-Notch Tension Specimen, SE(T):

   The SE(T) specimen (Figure 1.4.2.5(b)) is basically a M(T) specimen which has been sliced in half longitudinally. The length of the specimen between the grips (H) should be greater than 2W. The applied stress intensity factor range, $K_{applied}$, for the SE(T) specimen is very sensitive to the loading method and special attention should be given to the gripping and data reduction when using the SE(T).

The pinned load-train transfers load through a clevis-pin arrangement as shown in Figure 1.4.2.5(c). The grip is free to rotate, creating a uniform stress boundary condition. The applied stress intensity factor range, $K_{applied}$, for the SE(T) specimen with a pinned load-train is calculated as follows:

$$\Delta K_{applied} = \Delta\sigma\sqrt{(\pi a)} \bullet F(\alpha) \qquad 1.4.2.5(a)$$

where $\Delta\sigma$ is the applied stress range and:

$$F(\alpha) = \sqrt{(2/\pi\alpha)\tan(\pi\alpha/2)} \bullet \frac{0.752 + 2.02(\alpha) + 0.37(1-\sin(\pi\alpha/2))^3}{\cos(\pi\alpha/2)} \qquad 1.4.2.5(b)$$

where $\alpha = a / W$; expression valid within ±0.5% for any α (Reference 1.4.2.5(h)).

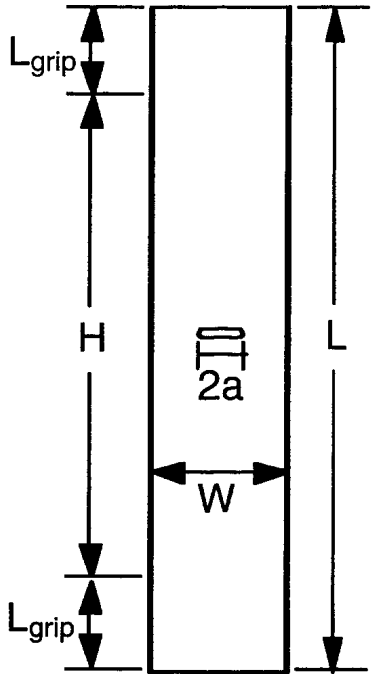


FIGURE 1.4.2.5(a) *Middle tension specimen, M (T).*

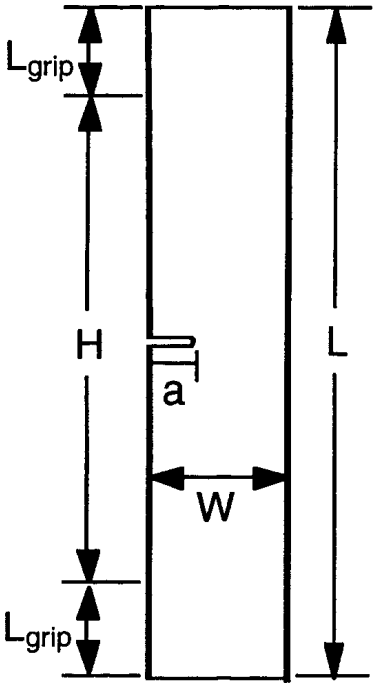


FIGURE 1.4.2.5(b) *Single-edge tension specimen, SE (T).*

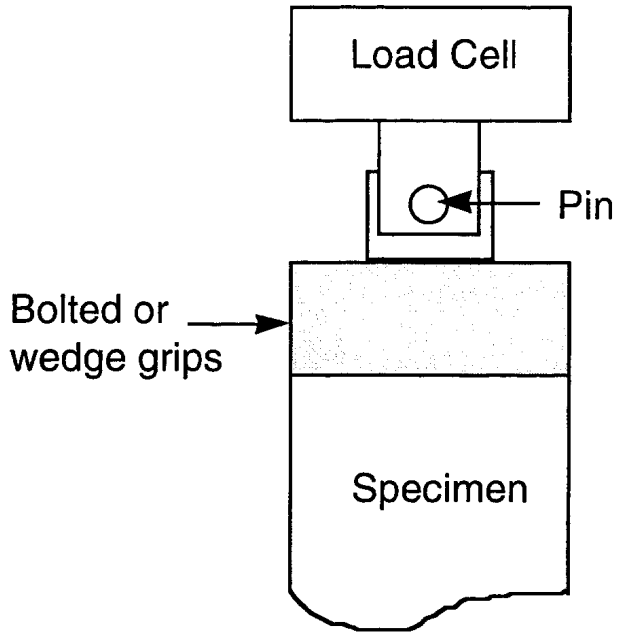


FIGURE 1.4.2.5(c) *Pin-loaded gripping arrangement.*

SE(T) with fixed load-train:

The SE(T) geometry with a fixed load-train (Figure 1.4.2.5(d)) has different boundary conditions than the pin loaded configuration. The specimen is constrained from rotation, having a uniform displacement boundary condition instead of a uniform stress boundary condition. In this configuration, the applied stress intensity factor, $K_{applied}$, is very sensitive to the ratio of specimen height, H over specimen width, W, and only approaches the pinned load-train configuration for very large values of H/W (References 1.4.2.5(h) through 1.4.2.5(k)). The appropriate $K_{applied}$ and crack mouth opening solutions for the SE(T) specimen with a fixed load-train are given in Reference 1.4.2.5(k) for H/W ranging from 2 to 10.

Compact-Tension Specimen C(T):

The C(T) geometry is not recommended for testing unidirectional composites where the reinforcement is parallel to the direction of loading. Anisotropy and the presence of large bending stresses may lead to non-self-similar crack extension (Reference 1.4.2.5(l)). The C(T) geometry can, however, be successfully used for testing relatively thick unidirectional composites in the transverse (that is, [90]) orientation (Reference 1.4.2.5(m)). Consideration should be made for the possibility of local bearing failure in the vicinity of the machined holes as mentioned above.

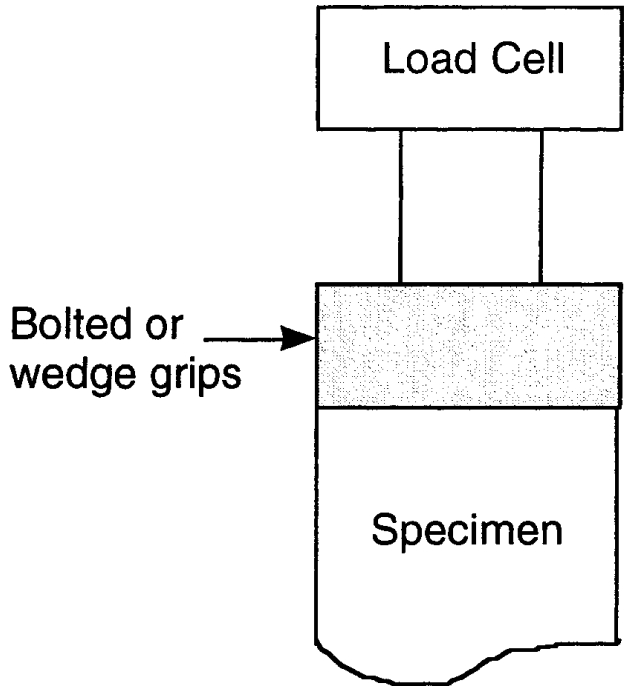


FIGURE 1.4.2.5(d) *Rigid gripping arrangement.*

Notch Configuration:

1. The machined notch detail is crucial to ensure self-similar crack extension. A narrow sawcut or EDM slot having a length less than 0.0625W and terminated by a 30 degree taper at the crack tip is recommended as described in ASTM E647. If a circular notch (hole) is used, multiple cracks will most probably initiate making the crack opening displacement monitoring more complex.

Crack Length Measurements

1. The standard method of determining the crack length using a compliance gage is not valid in the presence of a fiber-bridged crack, since the bridging fibers shield the crack tip. In addition, the direct current electric potential technique (DCEP) will not yield accurate crack length measurements due to the influence of unbroken, bridging fibers. Therefore, high resolution optical measurements must be made during crack growth testing to accurately determine the crack tip location. For automated testing, the direct current electric potential technique (DCEP) may be used to monitor crack growth according to ASTM E647 Annex 3; however, post-test correction of the DCEP crack lengths to the optical measurements is required paying special attention to fiber failures in the crack wake.

2. When bridging does not occur, errors in the crack length estimated from the compliance reading can be introduced due to material anisotropy. Therefore, an effective modulus must be used to calculate the crack length from the isotropic compliance.

Bridging Zone Measurements

Although the length of the bridging zone (if it exists) is a crucial parameter for calculating the effective crack tip driving force, an expedient method for measuring it *in-situ* is not yet available. Prior to any fiber failures, the bridging zone ($a_{bridged}$) corresponds to the difference between the current matrix crack tip (a) and the machined notch length (a_0):

$$a_{bridged} = a - a_0 \qquad 1.4.2.5(c)$$

After fibers start failing, the bridged zone decreases suddenly, causing a rapid change in the crack opening profile. Acoustic emission can be used to detect fiber failure and provide a criteria for interrupting the test to evaluate the new bridging zone. NDE techniques such as the scanning acoustic microscope can then be used to determine the length of the bridged zone.

The length of the bridged zone can also be determined during the test using a periodic comparison of the crack opening profile along the full crack length with those predicted for an unbridged crack. These measurements require special optical devices due to the small magnitude of the crack displacements in the bridged region. Differences in the crack opening profiles between the bridged and unbridged crack provide a qualitative indication of the extent of bridging and can be used in conjunction with available crack bridging models to deduce the bridged length (Reference 1.4.2.5(n)).

Effective Crack Tip Stress Intensity Factor

When bridging occurs, the crack tip is shielded from the global applied load, since some of the load is still carried through the bridging fibers. Therefore, the effective crack tip stress intensity factor is given by:

$$K_{effective} = K_{applied} - K_{bridging} \qquad 1.4.2.5(d)$$

$K_{bridging}$ corresponds to the closure stress intensity factor caused by the effect of the bridging fibers which act as a closure pressure to the matrix crack tip. If no fiber bridging occurs, then $K_{bridging} = 0$. Otherwise, $K_{bridging}$ is given by:

$$K_{bridging} = \int_{a_0}^{a} C(x) \bullet g(x) \bullet dx \qquad 1.4.2.5(e)$$

where $C(x)$ is the closure load of the bridging fibers in the bridging zone, and $g(x)$ is the weight function of the stress intensity factor for a unit point load applied at a distance x from the crack tip. The function is geometry dependent and is available in the literature for standard geometries (for example, References 1.4.2.5(h) and (k)).

If the assumed fiber pressure formulation relates the closure load to the crack opening displacement (that is, $C(x) = f(u(x))$, where $u(x)$ is the crack opening displacement), an iterative technique is required to solve for the unknown closure load and crack opening displacement. References 1.4.2.5(a) through (f) and 1.4.2.5(o) provide detailed methodologies to calculate the bridging stress intensity factor for various closure formulations.

1.4.2.6 Creep/stress rupture

1.4.2.7 Pin bearing tension

1.4.2.8 Pin bearing compression

1.4.2.9 Filled hole tension

1.4.2.10 Open hole tension/notch sensitivity

1.4.2.11 Flexure (three-point bend)

1.4.2.12 Filled hole compression

1.4.2.13 Fiber pushout tests

1.4.2.13.1 Background

Since being introduced by Marshall (Reference 1.4.2.13.1(a)), fiber indentation techniques have evolved into several variations that have become useful in determining both frictional and bonding contributions to the fiber/matrix interfacial shear strength. For small diameter fibers (<50 μm), the thick sample configuration originally used by Marshall (Reference 1.4.2.13.1(a)) is usually followed. In this fiber push-in configuration, only the top portion of the total fiber length experiences any debonding and sliding, and the resultant top-end fiber displacement is related to the compressive strain introduced along the length of debonded fiber. For large diameter fibers (>50 μm), a thin-sample fiber push-out (or push-through) configuration, initially demonstrated by Laughner et al. (References 1.4.2.13.1(b) and (c)) for CMCs and later applied towards MMCs (References 1.4.2.13.1(d) and (e)) is usually favored. In this thin-specimen configuration, the entire fiber length slides at a critical load. The fiber push-out approach applied to large-diameter fibers will be the test method described herein.

Several refinements of the fiber push-out test have improved the quality of data as well as convenience of operation. The most important advance was the change from dead-weight loading of fibers to driving the indenter with a constant-displacement-rate mechanism. This allows acquisition of continuous load vs. time or load vs. displacement curves. Bright et al. (Reference 1.4.2.13.1(f)) first demonstrated this approach using an Instron testing machine to control the indenter motion. *In-situ* video imaging and acoustic emission detection to aid identification of fiber debonding and sliding events were additional features incorporated into a desktop testing version by Eldridge (Reference 1.4.2.13.1.(g)); this apparatus used a small motorized vertical translation stage instead of an Instron as the constant-displacement-rate mechanism. Direct displacement measurements rather than crosshead speed determinations have been very useful for more reliable interpretation of the portion of the push-out curves before complete fiber debonding (References 1.4.2.13.1(h) and (i)). In some cases, direct measurements of fiber-end displacements have been made (References 1.4.2.13.1(j) and (k)), eliminating the need for any compliance corrections to the measured displacements. Another significant improvement in testing large diameter fibers has been the use of flat-bottomed tapered (Reference 1.4.2.13.1(f)) or cylindrical (Reference 1.4.2.13.1(d)) indenters. The flat-bottomed indenters apply the load more uniformly over the fiber end and allows higher applied loads without fiber damage compared to the commonly used pointed microhardness indenters (for example, Vickers). The cylindrical flat-bottomed indenters allow fiber displacements to much greater distances than tapered indenters; however, the tapered flat-bottomed indenters can sustain higher loads.

Additional capabilities such as high-temperature testing (References 1.4.2.13.1(l) through (n)) as well as SEM-based instruments (Reference 1.4.2.13.1(o)) provide significant benefits but will not be discussed here.

1.4.2.13.2 General

This method covers the basic requirements and procedures for determining interfacial properties of composites using the fiber pushout test method. The method described is recommended for composites reinforced by continuous fibers having a diameter, d_f, in the range 50mm<d_f<200mm.

Although this method has been used successfully in a wide variety of MMCs (SiC/Ti, SiC/Al, Al_2O_3/NiAl) and CMCs (SiC/SiC, SiC/SiN_3), it may not be suitable for all composite systems. The most important factor limiting the use of this method is the strength of the indenter (punch) with respect to the

strength of the interface. Fiber pushout testing may not be applicable to composite systems with a high interface strength since the punch may fail prior to interfacial debonding. In such cases, further reducing the thickness of the composite slice (test specimen) is not recommended as this may result in undesirable failure modes such as matrix cracking, fiber fragmentation, and matrix deformation.

It is not in the scope of this work to determine the criteria or provide guidelines to assess the applicability of this method for various composite systems. However, Tables A1(a) and A1(b) in Appendix A provide some useful information on the SCS-6/Ti-24-11 composite system, in addition to giving properties of tungsten carbide indenters having flute lengths 2-3 times its diameter.

1.4.2.13.3 Description of the method

In the fiber pushout test method an indenter (punch) is used to apply axial compressive loading on a fiber in order to debond the fiber and force the fiber to slide relative to the matrix. The fiber to be pushed out is typically situated over a support member with a hole or groove which will accommodate the fiber displacement. This method is shown schematically in Figure 1.4.2.13.3. The load measured at the onset of displacement of the full fiber length is used to determine the shear strength of the interface.

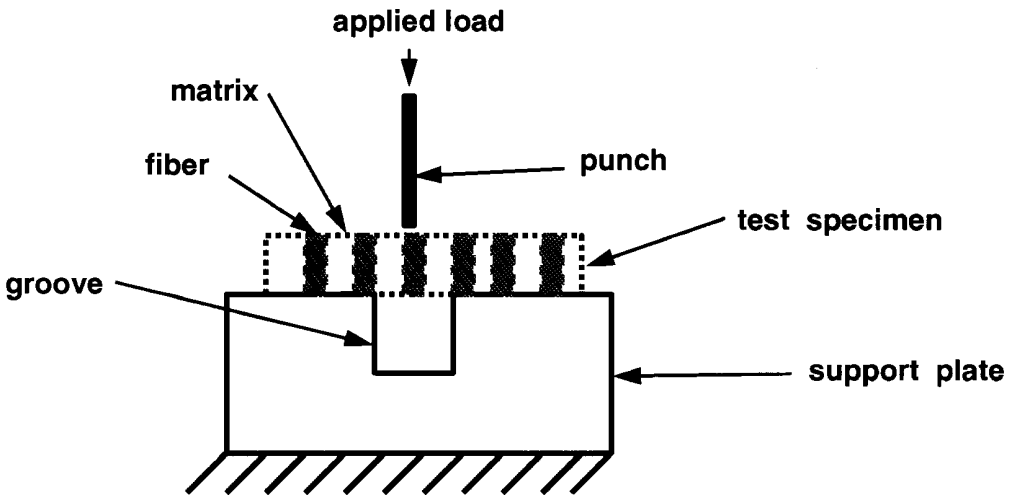


FIGURE 1.4.2.13.3 *Schematic of the fiber pushout test method.*

1.4.2.13.4 Significance and use

In general, there are many reasons that make this method attractive for determining interfacial properties of composites. Preparation of the sample is relatively easy and test specimens are small and can be taken directly from an already manufactured composite. Test samples can also be taken from specimens previously tested or subjected to various heat treatments and exposures. This insures that the residual stress states and conditions of the interface in the pushout specimen will be very similar to those found in the composite or tested specimen where they were obtained.

The interfacial shear strength values obtained by this method are particularly useful in the direct comparison of interfacial properties and failure modes of various composites. This method is also very useful in ascertaining the effects of a particular treatment or mechanical loading on the interface properties, however, the use of the values obtained through this method as an absolute physical property of the inter-

face is not recommended since the stress state present during the pushout test is not well understood. Furthermore, the stress state may vary among different composite systems.

1.4.2.13.5 Apparatus

A schematic of the apparatus needed to perform a fiber pushout test is shown in Figure 1.4.2.13.5(a). A stand-alone table top pushout test frame developed by J. Eldridge and used at NASA LeRC is shown in Figure 1.4.2.13.5(b). The size and configuration of the pushout testing apparatus is very compact. Therefore, most commercially available testing frames can be easily and temporarily modified to accommodate fiber pushout testing.

The fiber pushout test is usually performed using stroke (displacement) control. Displacement rates are generally in the 60mm/min range.

Any commercially available load cell with a load range of 25-50 lbs in compression is adequate. The load cell should be calibrated according to ASTM Standard E4 (Practices for Load Verification of Testing Machines).

An x-y stage is required for moving and aligning the sample under the punch. A fine x-y movement (micrometer type) is necessary to facilitate easy alignment of the indenter with the fiber. Any commercially available precision positioning stage is adequate for this purpose.

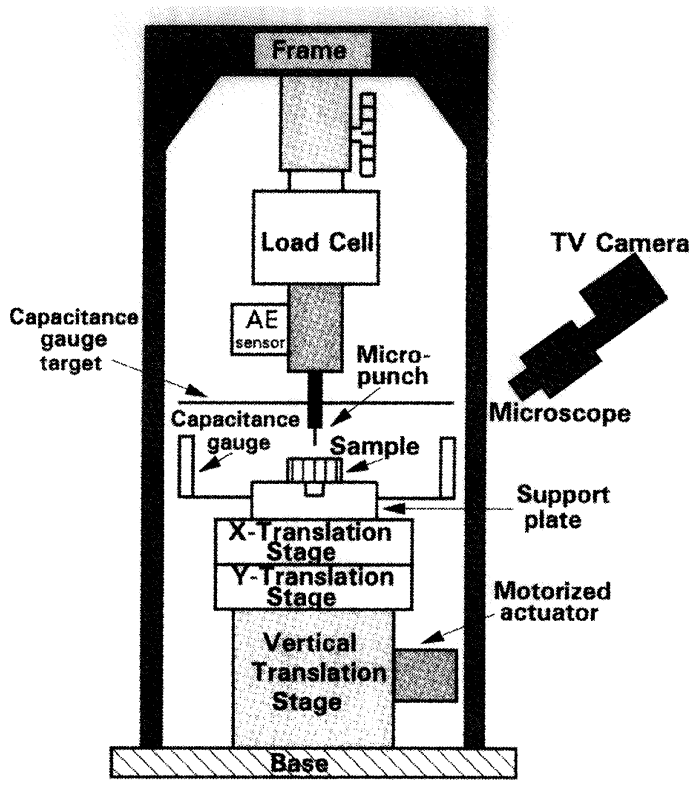


FIGURE 1.4.2.13.5(a) *Typical configuration of the pushout test.*

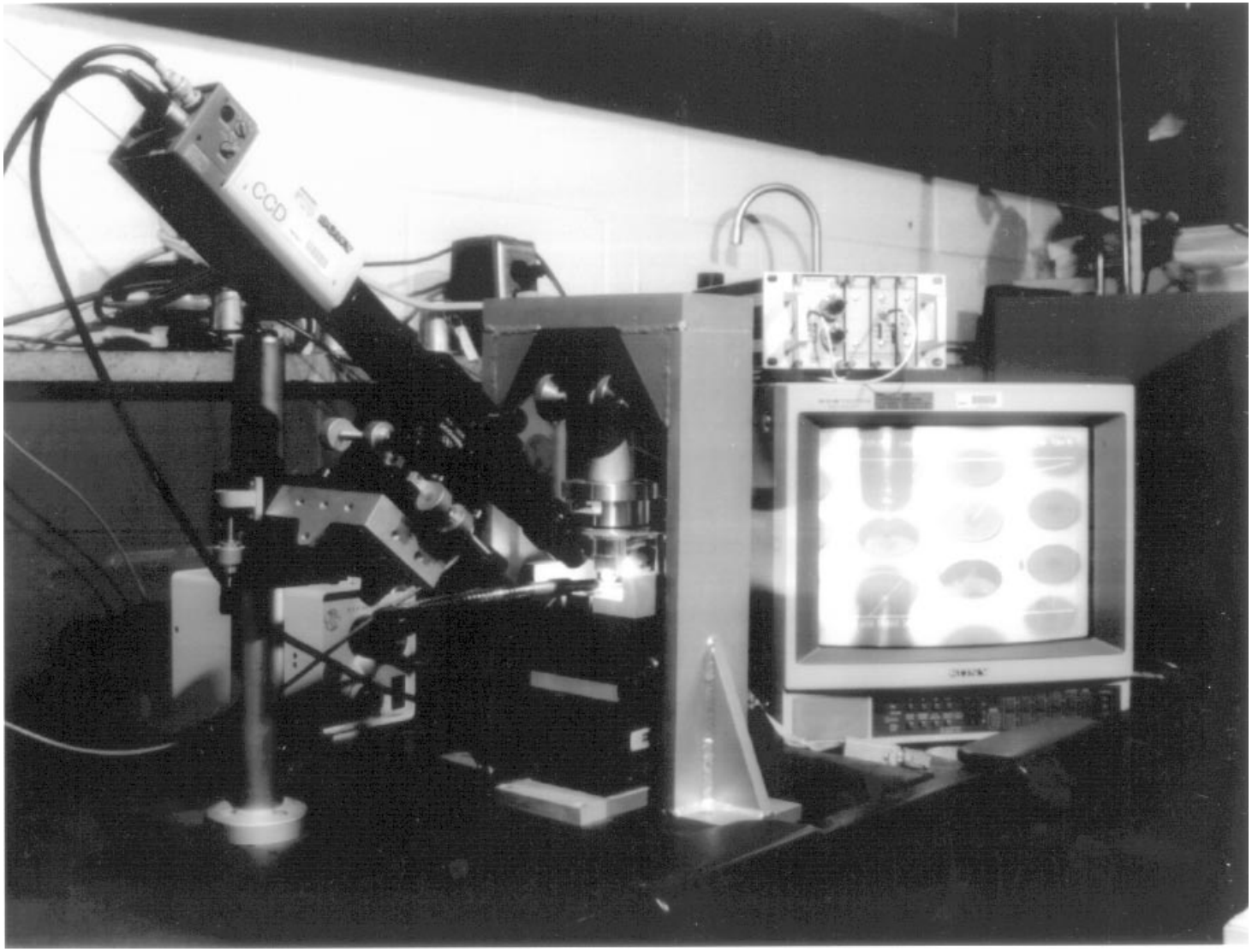


FIGURE 1.4.2.13.5(b) *Tabletop fiber pushout testing system used at NASA Lewis Research Center.*

1.4.2.13.6 Indenter

A detailed diagram of the indenter (punch) is shown in Figure 1.4.2.13.6. The bottom of the indenter should be flat and perpendicular to the axis in order to assure a uniform compression loading to the fiber, and to prevent premature failure of the punch. The diameter of the punch will depend on the diameter of the fiber tested and should typically be on the order of 0.75-0.80 times the fiber diameter, d_f.

The flute length of the punch becomes important only after the debonding event, in which case the longer the flute length the further the fiber can be pushed out. However, punches with long flute lengths are inherently weaker than those with shorter flute lengths and, therefore, it is advisable to keep the flute length to the minimum required for the desired fiber sliding distances.

Punches are usually made from WC (tungsten carbide) or SiC (silicon carbide), however, any suitable material can be used provided the punch does not plastically deform or buckle during testing. Flat-bottomed conical diamond indenters are capable of applying much higher loads than cylindrical punches, but displacements are limited to several microns and the diamond indenters are more likely to damage the fiber.

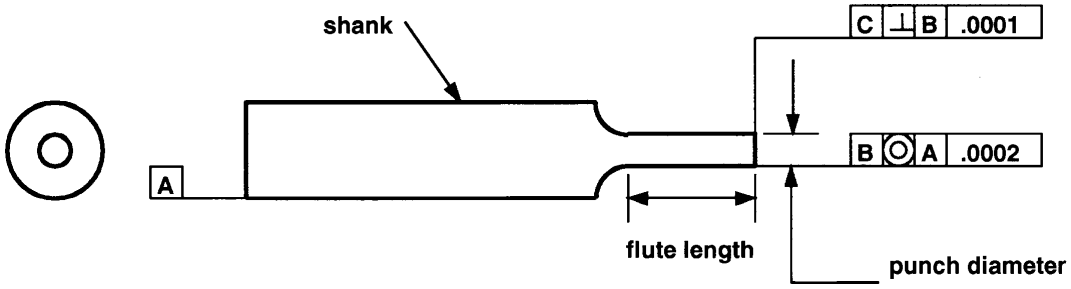


FIGURE 1.4.2.13.6 *Typical punch.*

1.4.2.13.7 Support plate

A typical support plate is shown in Figure 1.4.2.13.7. The support plate can have any configuration required to perform the test. A wide variety of grooves or holes can be incorporated on the support plate in order to accommodate a wide variety of specimen orientations. The width of the grooves will depend on the composite and test specimen geometry. In general, groove widths should be kept to the minimum required to perform the test, in order to minimize bending of the test specimen. Typically groove widths should be on the order of 2-3 d_f or approximately the thickness of the test specimen. The depth of the grooves is arbitrary, however, the depth should accommodate the desired fiber sliding distances or even the complete removal of the fiber.

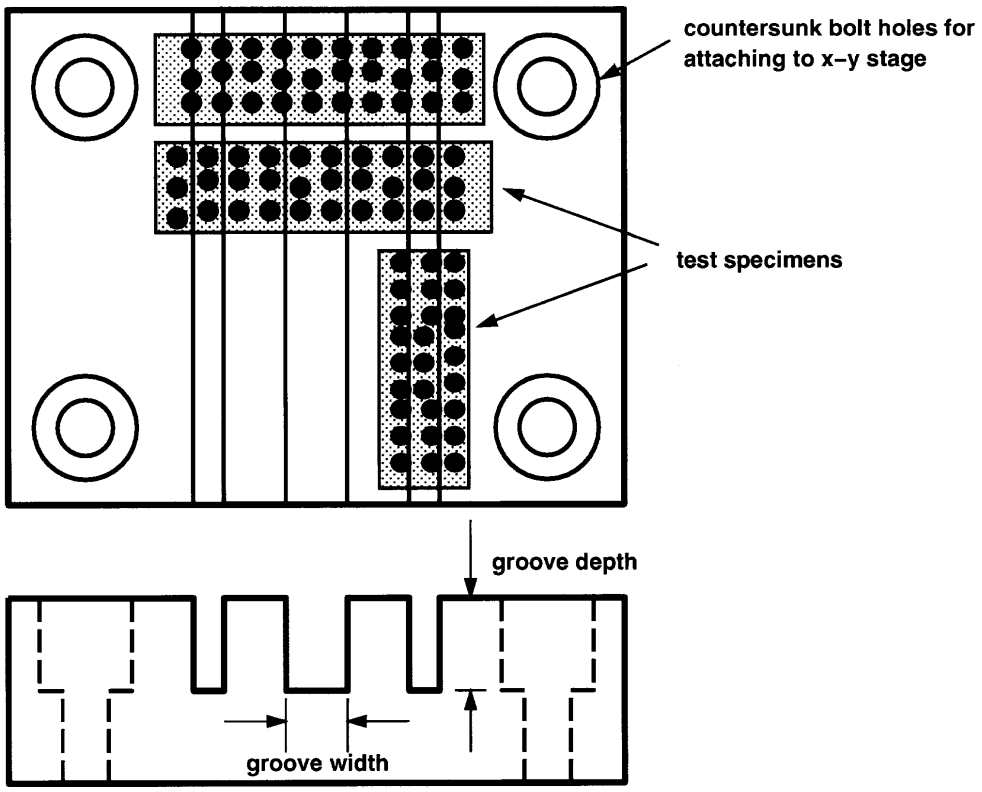


FIGURE 1.4.2.13.7 *Typical support plate.*

1.4.2.13.8 Acoustic emission sensor

An acoustic emission sensor can be placed on the punch support, specimen support block, or any other suitable location, in order to record the acoustical emissions associated with the debonding event. The use of this sensor is optional, however, it can prove to be very useful in determining the loads at the onset and completion of debonding.

1.4.2.13.9 Displacement sensor

In the fiber pushout test, the relative fiber/matrix displacements are inherently difficult to record. As a result, the pushout behavior is usually recorded as load vs. time. If displacements are required, load vs. stroke can be recorded if the test is performed on a commercially available test frame. Otherwise, an externally mounted displacement gage, such as a proximity gage, can be employed. It is advisable to mount two proximity gauges on opposite sides of the indenter (180° apart) in order to average out any errors due to slight tilting in the load train during the test. These errors tend to be most significant when the direction of travel is reversed, for example during cyclic testing. It is important to note that the displacements measured in this manner do not represent the actual fiber/matrix relative displacements, since the measured displacements still include the compliance from a portion of the load train, such as compression of the indenter.

1.4.2.13.10 Remote viewing using a microscope/camera

Due to the size of the fibers, accurate alignment under the punch usually cannot be accomplished by the naked eye. In most cases, moderate magnification in the order of 50X is required. Due to the configuration of the loading train, a microscope is usually mounted at an angle with respect to the punch, therefore requiring a focal length greater than 1.5" (3.8 cm). A microscope with a mounted camera is preferred due to the ease of operation and the additional magnification provided by the camera. The use of a camera also makes it possible to obtain a video image record of the test. Alternatively, a two-station configuration can be used. One station is the microscope viewing station where the sample is viewed at normal incidence, and the fiber to be tested is positioned at the center of the field of view. The second station is the test station where the fiber is pushed out. The alignment of the two stations is maintained so that the indenter contacts the specimen at the location corresponding to the center of the field of view observed through the viewing microscope. This two-station approach allows superior imaging of the specimen surface due to closer proximity of the microscope objective and the normal incident-viewing, but does not provide viewing during the test. This makes the two-station approach the configuration of choice for small-diameter (< 25 μm) fiber testing.

1.4.2.13.11 Test specimen preparation

A thin composite slice should be obtained from any region of interest from either the bulk composite material or a test specimen. Since thin slices are generally required for the pushout test, special care should be taken throughout the specimen preparation process to insure that interfacial damage is not introduced. This will depend primarily on the composite system and initial interface condition and may require various experimenting along the way in order to obtain a proven process.

The test slice should initially be on the order of 0.02-0.05 in. (0.6-1.30 mm) thick (Figure 1.4.2.13.11(a)). The specimen should be sliced such that the fibers are oriented axially within ±1°. A larger variation could result in errors in both the debond strength and frictional strength measurements.

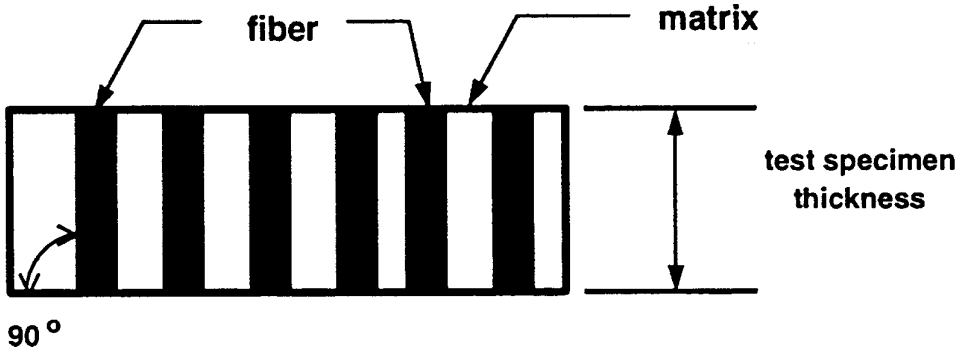


FIGURE 1.4.2.13.11(a) *Test specimen.*

The initial thickness of the slice will depend on the desired final thickness. When adjusting the position of the sample material over the saw blade, the kerf loss due to the blade thickness should be accounted for. In general, the slice should be thick enough to accommodate polishing and the removal of any damage accrued during the sectioning process. Fine polishing of the test specimen also provides the contrast required for microscopic alignment during testing and makes post failure analysis of interfacial failure possible.

The test specimen should be polished on both surfaces (by any previously approved method) to a metallographic finish (usually 1mm or better). For the usual situation with MMCs where the fibers are much harder than the matrix, diamond lapping films (polyester films coated with diamond particles) greatly reduce the surface relief and rounding observed using diamond paste and nappy polishing cloths. The two surfaces should be polished flat and parallel to within 10mm over the range of interest.

The test specimen thickness should be measured (to 1-2mm accuracy) following final polishing. Once the fibers are pushed out it may be difficult to obtain an accurate, original thickness measurement. The final thickness should be in the range of 0.01 to 0.02 in. (0.30 to 0.50 mm). This is the thickness range in which the debonding strength remains constant (Figure A1(a)). At lower thicknesses, different failure mechanisms are activated and the debonding strength becomes a function of thickness. At thicknesses greater than 0.5 mm, the debond strength is again a function of thickness. This is also the range of thicknesses where the pushout loads are high, increasing the likelihood of a punch failure.

The test specimen can now be mounted to the support plate. It is important that the fibers of interest are properly located over the grooves or holes. Once the fibers of interest are properly aligned, the test specimen should be secured to the support plate to prevent shifting of the specimen. This can be done using an adhesive (such as cyanoacrylate), or a clamping device as shown in Figure 1.4.2.13.11(b). If an adhesive is used, care must be taken to prevent the adhesive from seeping between the test specimen and the support plate, which could alter the alignment.

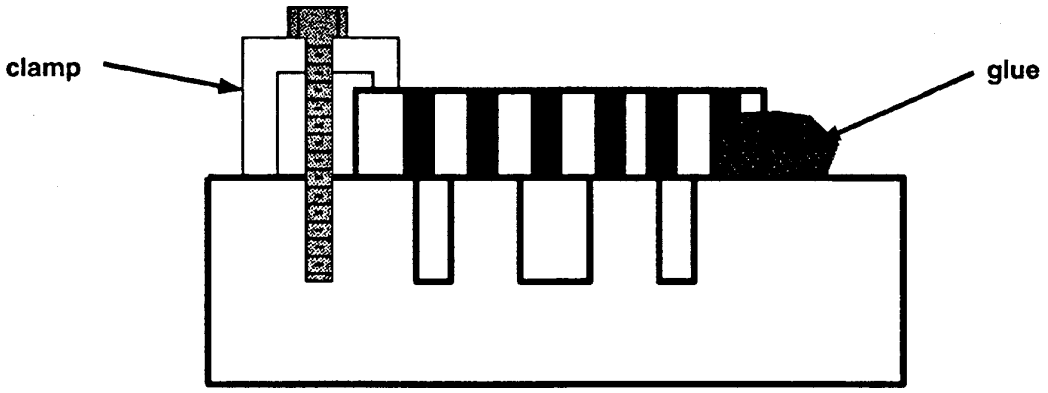


FIGURE 1.4.2.13.11(b) *Typical test specimen mountings on support plate.*

At this time, if the test specimen has more than one fiber that requires testing, a low magnification photograph of the specimen mounted on the support plate should be taken. This photograph will serve as a reference for locating the fibers of interest during and after testing.

1.4.2.13.12 Test procedure

The test procedure described does not apply universally to all composite systems, however, it can serve as a basic guideline for determining a proper test procedure. The following procedure is also based on test specimens where many fibers are available and a large fiber population is required.

The order of testing can be very important if more than one fiber per test sample needs to be tested. Neighboring fibers should be avoided, because in some cases previously tested fibers may influence the results of adjacent, untested fibers. The fibers to be tested should be chosen at random and at a safe distance from previously tested fibers. If the effects of previously tested fibers on the adjacent fibers is not known, and a large fiber population per test sample is required, then a testing sequence should be em-

ployed that reveals the influence of neighboring tests. The testing sequence will be dependent on the test specimen and fiber arrangement. A simple example of a testing sequence is shown in Figure 1.4.2.13.12. This testing order will help determine if there is an effect of neighboring fibers. For example, if the average of tests 7, 8, and 9, are statistically different from the average of 1, 2, 3, 4, 5, and 6, then previously tested fibers probably influence adjacent fiber results. Likewise, if the average of tests 1, 2, 3, 4 is statistically different from the average of tests 5, 6, 10, and 11, an edge effect may be present. It is obvious that several baseline tests are required to obtain a good understanding of the pushout behavior and the factors which affect the results.

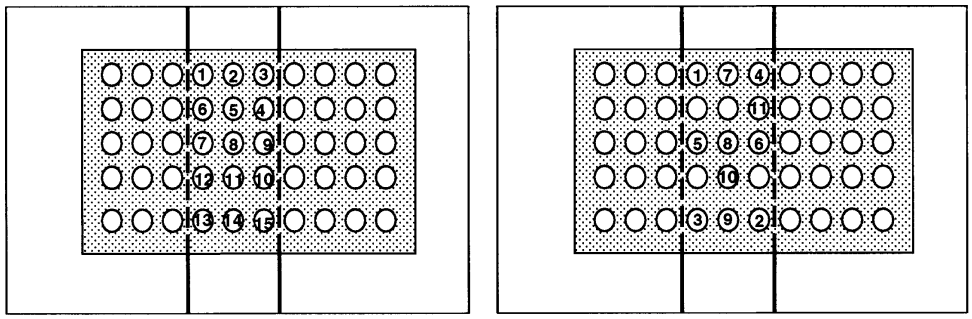


FIGURE 1.4.2.13.12 *Sample testing sequences.*

1.4.2.13.13 Effects of environment

Most fiber push-out tests are performed in room (laboratory) air without considering the effects that moisture or other constituents of air may have on the test results. Recent studies (References 1.4.2.13.1(n) and 1.4.2.13.13) have suggested that the presence of moisture and/or oxygen in the testing environment can substantially alter fiber sliding behavior in some composite materials. As an example, Figure 1.4.2.5(e) shows a set of seven push-out curves obtained in laboratory air and seven tests performed in dry nitrogen on the same SCS-6/Ti-24-11 specimen. These curves show that frictional sliding loads were consistently lower and the decrease in load after debonding much more abrupt in the tests performed in room air compared to tests performed in nitrogen. Such large differences appear to be associated with interfacial failure in a carbon-rich zone, where fiber sliding would be expected to show similar environmental sensitivity to sliding graphite surfaces, which need adsorbed moisture to maintain low friction. These results dictate that an awareness of possible environmental effects is necessary for a reliable comparison of test results, and, as a minimum, the recording of the humidity level for room air tests is recommended.

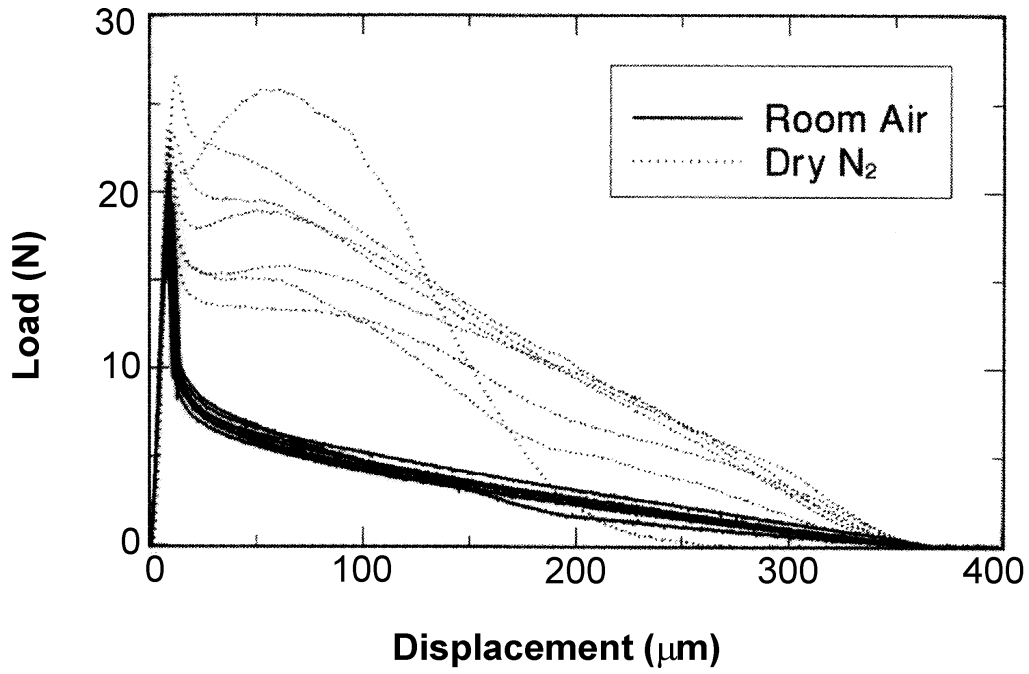


FIGURE 1.4.2.13.13 *Effect of environment on the interfacial properties of SC-6/T-24-11 at room temperature.*

1.4.2.13.14 Analysis of results

An example of a basic data sheet for recording information during testing is given in Figure A1(b) in Appendix A.

It is not in the scope of this report to distinguish between acceptable and unacceptable data results, since for the pushout test even unacceptable results can be useful for qualitative comparisons. The following section should serve only as a guideline for interpreting the results.

Figure 1.4.2.13.14 shows typical pushout behaviors as observed in various MMC and CMC systems. The behaviors shown in Figure 1.4.2.13.14, a thru d, are acceptable; behaviors in Figure 1.4.2.13.14, e and f, are difficult to interpret.

In general, the load increases linearly until the debonding occurs, which is usually associated with a load drop as the fiber is pushed out of the bottom of the specimen. This is often associated with an acoustic emissions event. The debond load, P_{debond}, is defined as the maximum load prior to the load drop. Following the debonding, the fibers slide out of the matrix, being restricted by the frictional resistance between the fiber and the matrix. The applied load generally decreases as the fiber displacement increases, since the contact area between the fiber and matrix, and hence the frictional resistance, is decreasing. The frictional load, $P_{friction}$, is usually taken at the secondary peak (if available) as shown in Figure 1.4.2.13.14, a and b, or directly following the load drop as shown in Figure 1.4.2.13.14, c and d.

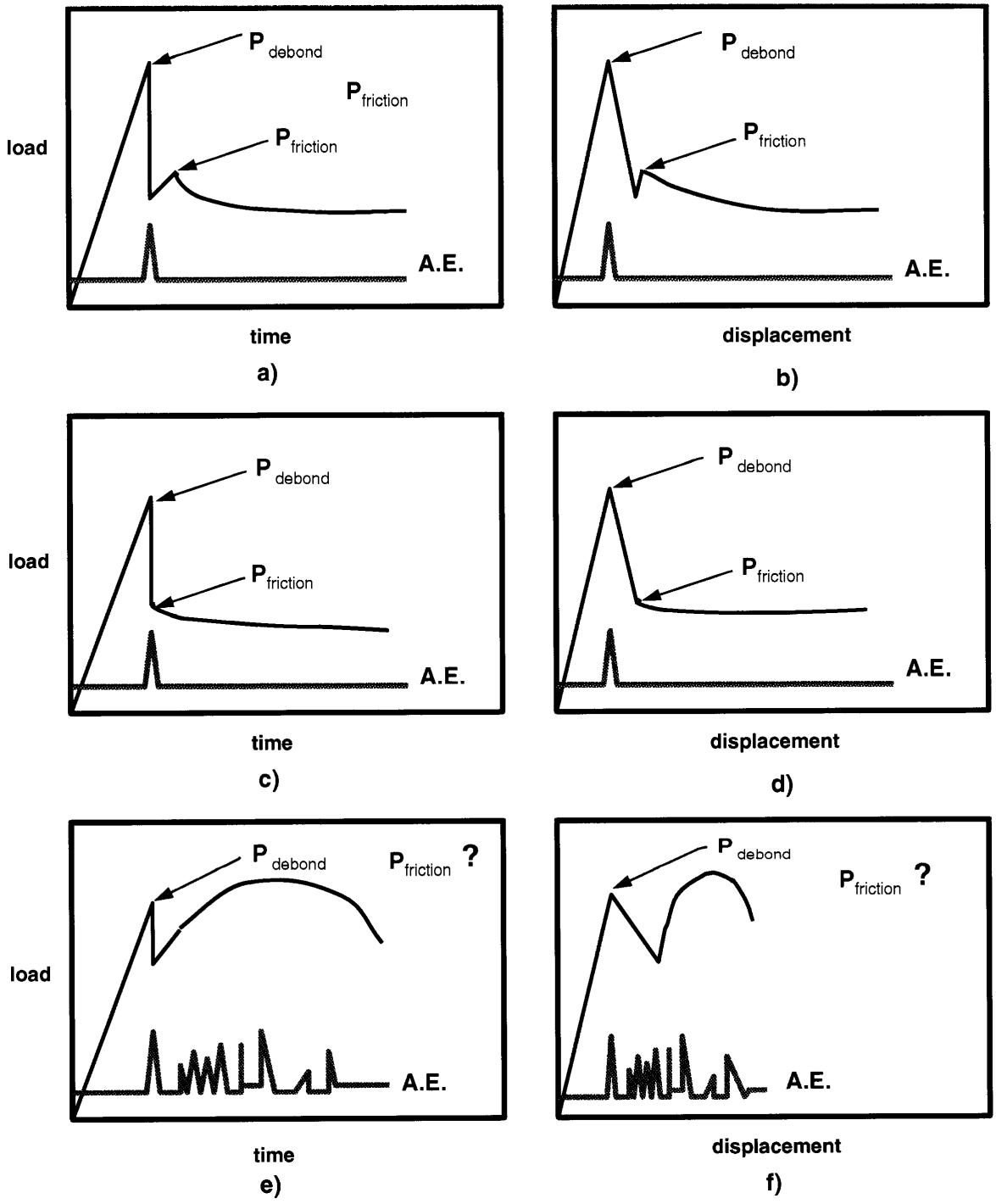


FIGURE 1.4.2.13.14 *Typical pushout behavior (A.E. represents the acoustic emissions).*

Occasionally, the load will again increase after the fiber has debonded, as shown in Figure 1.4.2.13.14, e and f. Pushout behavior such as this is more difficult to interpret, since following the debonding event the fiber does not slide freely. In such cases, extreme interface roughness or interfacial debris results in interlocking, which further resists fiber displacement. As a result the load increases and

may even surpass the initial debond load. Therefore, true frictional behavior is not present in these interfaces and the frictional load will depend on the extent of interlocking and/or the amount of interfacial debris present. In these cases, the load at the first peak may still be considered as the debond load, however, it should be realized that the degree of interlocking may also influence the debonding event. The usefulness of such results become obvious after a baseline data set has been obtained.

The average interfacial shear stress at complete fiber debonding, τ_{debond}, can be calculated from the experimentally obtained debond load using the following equation:

$$\tau_{debond} = \frac{P_{debond}}{2\pi R_f t} \qquad 1.4.2.13.14$$

where R_f is the fiber radius and t is the specimen thickness.

This stress is an average over the entire fiber length, and thus, does not reflect actual (local) shear stresses, which have been shown to vary significantly along the fiber length (References 1.4.2.13.14(a) and (b)). While useful for comparison between similar thickness specimens, τ_{debond} does not correspond directly to an easily identifiable interfacial property; it contains contributions from both the interfacial debond strength (or fracture energy) as well as frictional resistance to fiber sliding (as partial fiber debonding and sliding precedes complete debonding). More sophisticated approaches (References 1.4.2.13.14(c) and (d)) can be used that incorporate residual stresses and fiber roughness; however, care must be taken in modeling the interfacial failure sequence because thin-slice push-outs of MMCs often show interfacial failure initiation at the specimen backface, (References 1.4.2.13.14(a) and (d)), opposite the indenter, and can also show effects of matrix plasticity (Reference 1.4.2.13.14(e)). The analysis must then be tailored to allow/predict this sequence of failure (References 1.4.2.13.14(f) and (g)).

The interfacial friction strength, $\tau_{friction}$, can also be obtained using the above equation by substituting $P_{friction}$ and $\tau_{friction}$ for P_{debond} and τ_{debond}.

In contrast to the τ_{debond} calculation, the $\tau_{friction}$ calculation is a much better approximation to the actual shear stresses present, because when the entire fiber is moving, the resistance to fiber movement is purely frictional and the interfacial shear stress is near uniform along the length of the fiber. It should be pointed out that $\tau_{friction}$ is a function of fiber sliding distance rather than a single value. For some tests (Figure 1.4.2.13.14. a thru d), $\tau_{friction}$ is fairly constant with continued fiber sliding, but for others (Figure 1.4.2.13.14, e thru f), due to severe interfacial wear, $\tau_{friction}$ changes rapidly with fiber sliding distance. Therefore, it can sometimes be useful to report $\tau_{friction}$ at several sliding distances (References 1.4.2.13.13 and 1.4.2.13.14(h)).

1.4.2.14 Microhardness

General: This procedure covers the determination of the microhardness of the in-situ matrix material of a MMC. Such information may be desired for determining the state of the in-situ matrix. Microhardness readings may be related to other mechanical properties (for example, strength and modulus), which would be needed for micromechanical modeling purposes, and therefore hardness may be used as a method to estimate the in-situ matrix properties. Some reasons for measuring the microhardness are:

1. To see if the hardness has been modified by matrix and/or composite processing and/or subsequent heat treatment.

2. To study changes in the reaction zone or the matrix adjacent to the fiber/matrix interface. Fiber dissolution or intermetallic phase formation may affect these regions.

3. To measure interstitial embrittlement due to interactions with the environment.

4. To measure hardness of individual phases.

Microhardness testing should be conducted in accordance with ASTM Standard E384, “Standard Test Method for Microhardness of Materials” (Reference 1.4.2.14). The following notes should also apply:

1. If the hardness indentations are not to be affected by the fibers and interphase, the indentation should be positioned and sized appropriately. This is done by allowing the distance of approximately two indentation diagonals between the fiber and the indentations.

2. If information is desired regarding the microhardness of the intragranular regions of the in-situ matrix grains, then the indentation should be placed in the center of the grain. If possible, the indentation should be sized such that there is a distance of two indentation diagonals between the indentation and the grain boundaries. This will ensure that the grain boundary has a minimal influence on the microhardness readings.

1.4.2.15 Thermomechanical fatigue (TMF) (in-phase/out-of-phase)

1.4.2.15.1 Scope

This standard describes the procedure for conducting TMF tests on MMC coupon specimens. These tests are performed in load-control and at any constant load-ratio with any constant phasing. This standard applies to composite materials containing any fiber layup.

The tests should follow, in general, ASTM Standard E466 (Reference 1.4.2.4.1(a)). The following exceptions and notes should also apply.

1.4.2.15.2 Specimen design

Specimen design and preparation should follow the recommendations given in Section 1.3.2.4.

1.4.2.15.3 Temperature control and measurement

1. Specimen temperature should be measured using thermocouples in contact with the specimen surface, or by means of other non-contacting techniques, for example, optical pyrometry, that have been calibrated using specimens instrumented with thermocouples.

2. A sufficient number of thermocouples should be used on a dummy specimen of the same material and geometry which will be used in the tests, to accurately establish the temperature profile along the uniform gage length of the specimen. Discretion is warranted when deciding on the location and number of thermocouples on actual test specimens (subsequent to the specimen used for temperature calibration). Issues of significance include the sensitivity of the test results to surface anomalies and the ease of thermocouple attachment.

3. For all tests, the maximum allowable axial temperature gradient over the gage section at any given instant in the cycle should be ±0.015 T_{max} , where T_{max} is the nominal maximum test temperature given in °C and measured under dynamic conditions.

   Note 1: The axial temperature gradient over the gage section, ℓ_o, should be optimized under dynamic conditions and minimized at an appropriate point within the given temperature cycle (denoted as T_{opp}). This will likely allow for the gage section temperature gradients to be no greater than ±0.01 T_{opp} at the time T_{opp} is experienced in the cycle.

   Note 2: It is recommended that the parallel section of the specimen design be a minimum length of $2\ell_o$ unless otherwise restricted by specimen buckling concerns. A minimum length of $2\ell_o$ will allow all of the temperature gradient calibration thermocouples to be located along a constant ge-

ometry section of the specimen, facilitating optimization/minimization of the gage section axial temperature gradients under dynamic conditions. This condition is particularly advantageous when the method of heating is direct induction.

The temperature(s) indicated by the control thermocouple(s) should not vary by more than ±3°C from the initial value(s) at any given instant in time within the cycle, throughout the duration of the test.

The temperature(s) indicated by the non-control thermocouple(s) should not vary from the initial value(s) at any given instant in time within the cycle by more than the thermocouple's standard limits of error plus ±2°C, throughout the duration of the test. For example, the standard limits of error for K-type Chromel(+) versus Alumel(-) thermocouples are as follows:

Temperature	Standard Limits of Error
0 to 326°C	± 2°C
327 to 1310°C	± 0.75 % of T (°C)

Therefore, if the temperature indicated by a non-controlled thermocouple at, for example, $t = t_{15}$ (that is, 15 seconds into the cycle) is 800°C, (standard limits of error = ± 6°C), the temperature measurement at $t = t_{15}$ in all subsequent cycles should not exceed the range of 792 to 808°C.

1.4.2.15.4 Waveforms

1. The preferred control waveform for both the temperature and load should be a triangular waveform (that is, linear ramp). This provides for constant loading rates for both the temperature and load throughout the cycle. The use of a sine waveform is not recommended, as both the temperature and loading rates vary continuously throughout the cycle, making rate-related analyses of the data difficult.

2. Both the temperature and the load command waveforms should be of the same type (for example, sine, triangular).

3. The temperature response waveform should be measured at the center of the gage section. This may, or may not be the location of the closed-loop temperature control. This measurement should be used for the purpose of quantifying the accuracy of the temperature range (maximum and minimum limits) and load-temperature phasing.

1.4.2.15.5 Phasing

1. Out-of-phase (OP) tests should be conducted such that the load and temperature response waveforms are 180-degrees out of synchronization.

2. In-phase (IP) tests should be conducted such that the load and temperature waveforms are in synchronization with one another.

3. Any other constant phase shift between temperature and load may be used as long as it is clearly described and the other guidelines in this standard are followed.

4. Phase-shift error: The two response waveforms should be within a 2-degree phase shift of the prescribed command. For example, for a prescribed 180-degree OP test, the response phase-shift should be between 178 and 182 degrees. Phasing accuracy should be determined based on the response waveforms, not the command waveforms.

1.4.2.15.6 Pre-test measurements

1. Record the modulus, E, of the specimen as a function of temperature, T, over the range of the temperature which will be applied in the actual test (see ASTM D3039/D3039M Standard Test Method for

Tensile Properties of Polymer Matrix Composite Materials (Reference 1.4.2.15.6(a)) for definition of E). This should be done at temperature intervals no greater than 100°C. Smaller intervals are suggested if they are needed to accurately define the curve, E vs. T. These data may later be used for calculating the inelastic strains, ε_{in}, from the total mechanical strain, ε_{mech}, as given by:

$$\varepsilon_{in} = \varepsilon_{mech} - \sigma / E(T) \qquad \text{1.4.2.15.6(a)}$$

where σ is the instantaneous applied stress.

Note 1: The temperature and test system must reach equilibrium at each temperature before the modulus should be measured. If this is not done, then the modulus values can be in error.

Note 2: For the purposes of TMF testing, standard high temperature extensometers should be actively cooled to ensure thermal equilibrium of the extensometer during thermal cycling of the specimen.

Note 3: The variation in modulus for a batch of specimens seeing the same processing may be small. If this can be demonstrated, then the modulus vs. temperature curve for only one specimen needs to be performed. The pre-test modulus for all other specimens can be restricted to measurements taken only at the minimum and maximum temperature of the cycle.

2. The thermal expansion strain from R.T. to the test initiation temperature, T_{init}, should be measured for the purpose of adjusting the initial gage length, l_o, existing at T_{init}, that is:

$$l_o\,(T) = l_o\,(\text{R.T.}) + \Delta\, l_{th} \qquad \text{1.4.2.15.6(b)}$$

where Δl_{th} is the change in the gage length due to thermal expansion from RT to T_{init}.

Note 1: The difference in gage length will be at most 2%. If the actual change is smaller and is not believed to affect the results, then the process of adjusting the gage length can be eliminated.

Note 2: Subsequent to this initial calculation of l_o at T_{init}, it is not required to continually adjust l_o as a function of temperature throughout the temperature cycle for the purpose of calculating real-time strain. That is, it is sufficient to assume that l_o remains constant at its T_{init} value.

3. Thermal cycling should be performed under zero load over the range of temperatures which will be used in the actual test. Several thermal cycles should be performed to ensure thermal equilibrium of the test set-up and stabilization of the thermal strain, ε_{th} as a function of T. Having established this state of equilibrium, the thermal strain, ε_{th}, should be measured as a function of the temperature for both heating and cooling portions of the cycle. This allows the calculation of mechanical strain, ε_{mech}, during the post-test data analysis, where:

$$\varepsilon_{mech} = \varepsilon_{total} - \varepsilon_{th} \qquad \text{1.4.2.15.6(c)}$$

where ε_{th} is a function of temperature. The point of this cycling is not to document the material property (CTE), but rather to enable accurate data reduction by confidently measuring the thermal strains in each specimen over the temperature range.

Note 1: This data reduction step is a simplifying assumption which assumes that the thermal expansion behavior of the composite, as measured before the test, remains constant throughout the test (that is, the CTE of the composite material does not change during the test). This assumption has been shown to be in error; the degree of which is dependent upon specific loading conditions, laminate orientation, and damage mechanisms present (Reference 1.4.2.15.6(b)). Ideally, one would record the CTE as a function of cycles and account for the changes accordingly in the data analysis.

Note 2: An attempt should be made to ensure that the number of thermal cycles is kept to the minimum required to obtain a stable ε_{th} response. Excessive/prolonged thermal cycling may promote internal damage and/or an undesirable state of initial material oxidation (Reference 1.4.2.15.6(c)).

1.4.2.15.7 Starting the test

1. Subsequent to the measurement of the thermal compensation, thermal cycling should continue, and the load waveform should be started at the point in the thermal cycle which corresponds to zero load.

   Note 1: In a test in which the load does not go through zero (for example, a tension-tension or compression-compression load cycle), subsequent to establishing the thermal dynamic equilibrium, the load should be ramped to the minimum load desired in the test in time to properly synchronize the load and temperature cycles within the required phase-shift error.

2. The test should run until failure has occurred. The failure definition which is used should be clearly defined.

   Note 1: With load-controlled tests, the specimens should fail in two pieces if there is a tension load in the cycle. Therefore, two pieces is often used as a failure criterion. However, other definitions of failure can be used such as, a percentage change in the original maximum strain or strain range, a percentage change in the modulus at some specified temperature, or buckling of the specimen.

1.4.2.15.8 Data reporting

1. Stress-strain hysteresis loops should be recorded at periodic times during the test either digitally and/or with analog recorders.

2. The maximum and minimum mechanical strain should be plotted for each specimen as a function of cycles.

3. The mechanical strain range and the total strain range ($\Delta\varepsilon_{total} = \Delta\varepsilon_{mech} + \Delta\varepsilon_{th}$) should be plotted as a function of cycles.

4. The failure location and failure criterion should be reported as well as the reason for any anomalous crack initiation (for example, thermocouple attachment).

1.4.2.16 Residual strength and stiffness

The life of a composite component depends on its ability to withstand damage. Damage can assume many forms in the complicated structure of the composite. Some examples of damage are fiber cracks, matrix cracks, interfacial debonding, interface growth, and oxidation of one or more of the constituents. The designer must be aware of how and to what severity each form of damage affects the composite structure. This is particularly important since composites are often highly anisotropic and damage may only manifest itself in one particular direction. In an attempt to define how much damage has been accrued due to some prior loading scheme, residual strength and stiffness tests are often performed. These tests involve subjecting the composite test coupon to some loading sequence such as fatigue loading to various life fractions (that is, $N/N_f < 1$), or thermal cycling to address damage from the CTE mismatch between the fiber and the matrix. Subsequently, a tensile test is conducted and the stiffness and ultimate strength are measured. The tensile test should be conducted per the instructions found in Section 1.4.2.1 and can be performed at any temperature and strain rate which befits the service conditions. Residual strength and stiffness are then defined as the ratios between those properties in the damaged composite

and those in the initial, undamaged state. To completely characterize damage, tensile tests should be run in several directions with respect to the fiber layup to account for any anisotropy in the damage state.

1.4.2.17 Bearing fatigue

1.4.2.18 Open hole fatigue

1.4.2.19 Filled hole fatigue

1.4.2.20 Corrosion fatigue

1.4.2.21 Stress corrosion cracking

1.4.2.22 Wear

1.4.2.23 Impact

1.4.2.24 Damping

1.4.3 DISCONTINUOUS REINFORCED MMC MECHANICAL PROPERTY TEST METHODS

1.4.3.1 Tension

1.4.3.2 Compression

1.4.3.3 Shear (in-plane)

1.4.3.4 Fracture toughness

1.4.3.5 Fatigue

1.4.3.6 Fatigue crack growth

1.4.3.7 Creep/stress rupture

1.4.3.8 Corrosion fatigue

1.4.3.9 Stress corrosion cracking

1.4.3.10 Wear

1.4.3.11 Impact

1.4.3.12 Damping

1.4.4 PHYSICAL PROPERTY TEST METHODS

1.4.4.1 Density

Density of the composite should be measured using the Archimedes method described in ASTM D792, “Standard Test Method for Density and Specific Gravity (Relative Density) of Plastics by Displacement” (Reference 1.4.4.1).

1.4.4.2 Fiber volume fraction

The fiber volume fraction of composites may be obtained by one of two methods. The first is by metallographic analysis by which the total fiber area is divided by the total specimen area examined (see Section 1.4.5.1 for details). This method requires a well-polished metallographic sample which has been cut and polished at a right angle to the fiber axis. This method can be simplified by using commercially available image analysis equipment.

The second method consists of dissolving the matrix and weighing the remaining, clean fibers. This method can be found in ASTM D3553, “Standard Test Method for Fiber Content by Digestion of Reinforced Metal Matrix Composites” (Reference 1.4.4.2).

1.4.5 MICROSTRUCTURAL ANALYSIS TECHNIQUES

1.4.5.1 Titanium matrix composites

Microstructural details provide important information in characterizing the composite material. Information such as grain size, phase analysis and distribution, fiber distribution and volume fraction, the status of the fiber/matrix interface, is necessary to pedigree the composite. This section provides methods of performing microstructural analysis for continuous reinforced titanium alloys. Some general metallographic practices can be found in References 1.4.5.1(a) through (c).

Metallographic preparation of the composite is much more difficult than preparation of monolithic metals. This is due to the fact that the reinforcement is usually a ceramic, which polishes at a different rate from the matrix. This can lead to rounding of the fiber/matrix interface during polishing, obscuring important details of this area. Additionally, parts of the fiber can break-off, scratching the surrounding, soft matrix material. Damage, such as fiber and interface cracking, can also be induced during metallographic preparation. Therefore, great care must be taken when preparing composite samples to get optically flat, damage-free surfaces.

SiC reinforced titanium alloys are best prepared using a fixed grit abrasive, followed by a rolling diamond abrasive to remove material. The rolling abrasive is accomplished with a ridged lapping disc to produce the rolling abrasive action for high material removal rates with limited grinding-induced deformation. A common practice method is given below:

1. Diamond grind using successive 181, 68 and 20 micron fixed diamond grits.

2. Grind using successive 6 and 3 micron polycrystalline diamond suspensions using the rolling abrasive technique.

3. Polish using successive 3 and 1 micron polycrystalline diamond suspensions applied to a hard synthetic silk polishing cloth.

4. Polish using the above mentioned attack polishing procedure to remove deformation induced from the diamond polishing steps.

5. Final polish using a vibratory polisher with 0.5 micron diamond with a synthetic high nap polishing cloth.

Etching of most titanium alloys both in the fiberless forms and in the composite can generally be accomplished by immersion in Kroll's reagent:

1-3 ml hydrofluoric acid
3-6 ml nitric acid
100 ml water

Gamma TiAl requires a swab etchant referred to as 30-15-5:

30 ml lactic acid
15 ml nitric acid
5 ml water

Microstructural details of the fiber are sometimes desired and are easily acquired from polished sections of the composite. To best reveal fiber microstructure in the composite, two methods may be used. The first is an interference layering technique. In this technique, a thin layer of PtO_2 or PbO_2 is deposited on the polished sample by sputter-coating. The oxide layer changes the samples reflection coefficient. Since each phase has a different reflection coefficient, this gives rise to various colors and enhanced contrast. More details on this process can be found in (References 1.4.5.1(d) and (e)).

The second technique is plasma etching, in which a reactive gas is used as an etchant. This technique has the advantage over more aggressive techniques in that the sample remains cool during the process. This technique is especially useful for etching SiC (Reference 1.4.5.1(f)). More details on this method can be found in (References 1.4.5.1(g) and (h)).

The distribution of the fibers in the composite is of interest to monitor the quality of the manufacturing process. Excessive fiber swimming and touching fibers can be detrimental to the composite properties. Fiber distribution also affects the mechanical properties as is described in Reference 1.4.5.1(i) and fiber distribution should therefore be controlled (when possible) and documented.

Fiber distribution can be documented by standard metallographic techniques. Measurements such as center-to-center distance, distance between fibers and plies, and fiber packing array (for example, square, rectangular, and hexagonal) are some of the commonly used measurements. An automated image analysis system (References 1.4.5.1(j) and (k)) can aid in the determination of these values.

Image analysis systems can also be invaluable in determining fiber volume fraction of the material. In continuously reinforced materials, fiber volume fraction, V_f, can be calculated by measuring the area fraction of fibers on a metallographic section taken perpendicular to the long axis of the fibers. Fiber volume fraction is then given by:

V_f = (cross-sectional area of fiber) x (number of fibers) / (cross-sectional area of the composite)

Although this is a seemingly simple calculation, various values of fiber volume fraction can be calculated depending upon whether or not the outer-most layer of matrix (that is, the face sheets) are included in the cross-sectional area of the composite. This is especially true if the composite material has a cladding of matrix material on the outside of the composite. Composite structures often employ a composite core imbedded in a matrix component. In this case, there is the question whether the cross-sectional area is that of the entire part, or only the section which contains fibers. Depending on which cross-sectional area is use, different fiber volume fractions will result. An accurate stress or fatigue life analysis depends on a clear understanding of the fiber volume fraction and therefore, the method of calculating fiber volume fraction should be clearly described.

Another source of error in fiber volume fraction measurements occurs when portions of fibers and/or missing fibers exist on the cut edges of the composite sample. Typically, these errors are small and can generally be ignored, as long as the method of calculating the fiber volume fraction has been thoroughly described.

The interface is the region between the fiber and the matrix. This region often consists of any coating or sizing which remains on the fiber after consolidation, as well as any reaction zone which may form as a result of the chemical interaction between the matrix and either the fiber or its coating. The interface is important in determining the properties of the composite. This is especially true if off-axis loads are applied to the material, because the interface is critical to the transfer of loads from the matrix to the fiber.

The interface is generally very small (for example, <10μm thick) and composite mechanical properties typically decline with increasing thickness of the interface region[1]. The thickness of the interface can be increased during consolidation if the temperature is too high or the time during consolidation is too long. Additionally, if the composite material is used at elevated temperatures, the interface can grow with time by stress-assisted diffusion mechanisms, thus degrading the composite properties. Therefore, monitoring the thickness of this region is important.

If a sample of the composite is properly prepared by, for instance, the metallographic techniques mentioned above, the thickness of the interface can be measured on an optical micrograph. Likewise, on a well-polished sample, the interface can be inspected for cracking, debonding, oxidation, or change in grain morphology or grain size. Due to the small size of the interface, examination of the polished samples within an SEM is often required due to the enhanced resolution capabilities of the SEM. Detailed chemical information within the interface can sometimes be obtained from an electron microprobe or a chemical analysis in the SEM. However, if an accurate analysis is required, TEM must be used to definitively identify chemistry, phases, and phase morphology in the interface.

1.4.6 CHEMICAL ANALYSIS TECHNIQUES

1.4.6.1 Analysis of carbon and sulfur

Test method ASTM E1587 analyzes interstitial carbon and sulfur in composite materials as well and its constituents (Reference 1.4.6.1). To perform this test, a small amount of the subject material is abraded to remove any surface contamination, cut into small pieces (if it is not already in powdered form), degreased in ether, and placed in an alundum crucible. Accelerators are added to the crucible to ensure and speed up combustion. Runs are then made of the empty alundum crucible, followed by NIST or Leco standards to generate a linear calibration curve.

The sample is combusted in a stream of oxygen at temperatures exceeding 2700°F (1500°C) in an induction furnace. Carbon and sulfur in the sample are released and converted to carbon dioxide and sulfur dioxide, respectively. The sample gases are carried by the oxygen through two infrared detection cells where they absorb energy and produce a spectrum. The energy then passes through a wavelength filter that inhibits all wavelengths except CO_2 or SO_2, respectively. The detector responds to changes in energy between the carrier gas (oxygen) and the measured gases to determine the concentration of CO_2 and SO_2. Detector output is converted from an analog to a digital signal which is corrected and adjusted for calibration, specimen container, and weight compensation. Carbon and sulfur values are then displayed and printed out in weight percent.

Qualitatively, this combustion method can be used to identify the presence of carbon and sulfur. It cannot, however, distinguish between the various forms of carbon or sulfur. It is useful for samples containing either high or low levels of carbon and/or sulfur, since the instrument contains dual-range cells for both elements. The versatility of the dual-range cells enables the accurate measurement of very low levels of sulfur and carbon.

Quantitatively, the detection range of the instrument for a one gram sample is 0.6 parts per million (ppm) to 5 weight percent (wt%) carbon, and 0.3 ppm to 0.35 wt% sulfur. By reducing the sample weight, the maximum amount of each element that can be detected increases. For more accurate readings at lower concentrations, a larger sample size can be used.

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[1]The exception to this rule is where an interfacial layer is "engineered" to compensate for the mismatch in properties, for example, thermal expansion, between the fiber and the matrix. A compensating or compliant layer may be designed to be thick to better alleviate the high stresses created at the interface, thus improving the overall properties of the composite. The effects of compensating layers are described in detail in References 1.4.5.1(l) through (n).

This method is useful for all metals, alloys, ceramics, and composites. It can also be used for the analysis of sand and for graphite fibers.

1.4.6.2 Analysis for oxygen and nitrogen by inert gas fusion

This method is for analyzing interstitial nitrogen and oxygen in composite materials. It can also be used for the neat matrix or reinforcement material (Reference 1.4.2.4.5(a)). To perform this test, a small amount of the subject material is abraded to remove any surface contamination, cut into small pieces (if it is not already in powdered form), and degreased in ether. Samples are then placed into nickel baskets. Powdered samples are first placed in tin capsules and tightly crimped to exclude air before placing them in nickel baskets. The instrument is calibrated with NIST or Leco standards to generate a linear calibration curve. Runs are then made with only the nickel basket (or time capsule and nickel basket) to eliminate elements coming from the containers themselves.

The sample is analyzed by sealing a graphite crucible between two electrodes in a furnace and purging it of atmospheric gases. A high current is passed through the crucible to outgas it (remove gases trapped in the graphite). Helium is used as the carrier gas. The sample is then dropped into the crucible and a slightly lower current is passed through the crucible to drive off the sample gases. The oxygen released from the sample combines with the carbon from the crucible to form carbon monoxide. The carbon monoxide passes through a heated copper oxide and is converted to carbon dioxide. Sample gases then move through an infrared cell where they absorb energy and pass through a wavelength filter that inhibits all wavelengths but CO_2. The detector responds to changes in energy between the carrier gas (helium) and the measured gases to determine the concentration of CO_2. The detector output is converted from an analog to a digital signal which is corrected and adjusted for calibration, specimen container, and weight compensation. The oxygen value is then displayed and printed out in weight percent.

The remaining gases move on to the thermal conductivity cell which consists of a Wheatstone bridge that detects nitrogen by becoming unbalanced due to the difference in thermal conductivity of nitrogen compared to that of helium. The output is converted, integrated, adjusted, and the weight percent nitrogen is displayed and printed out.

Qualitatively, this fusion method can be used to identify the presence of nitrogen and oxygen. In certain sample types, it can differentiate between different forms of oxygen and nitrogen by temperature ramping. It is useful for either high or low levels of nitrogen, since the instrument contains dual-range cells for nitrogen. The low range nitrogen cell enables the accurate measurement of very low levels of nitrogen.

Quantitatively, the detection range of the instrument for a one gram sample is 0.1 ppm to 0.1 weight percent (wt%) oxygen, and 0.1 ppm to 0.5 wt% nitrogen. By reducing the sample weight, the maximum amount of each element that can be detected increases. For more accurate readings at lower concentrations, a larger sample size can be used.

This method is useful for all metals, alloys, ceramics, and composites, except those containing Al_2O_3 fibers. It can also be used to determine high amounts of oxygen (up to approximately 10 wt%) in samples such as Si_3N_4.

1.4.7 NON-DESTRUCTIVE EVALUATION TEST METHODS

A variety of non-destructive testing (NDT) techniques are available for detecting both surface and interior flaws in composites. Visual inspection and liquid penetrant methods can be used for identifying surface defects, while more sophisticated techniques are required for detecting internal flaws (that is, voids, inclusions, debonds, fiber non-uniformity). These techniques include ultrasonics, radiography, thermography, acoustic emission, X-ray, and eddy-current testing. The basic principles and procedures for these methods are covered in the MIL-HDBK-728 series, while more specific information on the theory and interpretation of data can be found in the following:

MIL-HDBK-731 Thermography
MIL-HDBK-732 Acoustic Emission
MIL-HDBK-733 Radiography
MIL-HDBK-787 Ultrasonic

These documents do not discuss the recent advances in NDT techniques, which are currently an active field of research and development.

1.4.8 ENVIRONMENTAL EFFECTS TEST METHODS

1.4.9 INTERPHASES AND INTERFACES TEST METHODS

REFERENCES

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1.5 INTERMEDIATE FORMS TESTING AND ANALYTICAL METHODS

1.5.1 INTRODUCTION

1.5.2 MECHANICAL PROPERTY TEST METHODS

1.5.3 PHYSICAL PROPERTY TEST METHODS

1.5.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES

1.5.5 CHEMICAL ANALYSIS TECHNIQUES

1.5.6 NON-DESTRUCTIVE EVALUATION TEST METHODS

1.6 FIBER TESTING AND ANALYTICAL METHODS

1.6.1 INTRODUCTION

Composites require strong, stiff fibers with adequate high temperature properties. At many of the projected use temperatures, the matrix material is overextended and is used at temperatures higher than the matrix would normally be used in its monolithic state. Therefore, the fibers must be able to handle the added loads and provide strength in the material. Consequently, fiber development is a crucial part of continued composite improvement. Test methods must be available to determine the properties of the fibers, not only to provide relative properties for fiber development, but also to provide data for micromechanical composite analyses.

Testing fibers is a difficult task since the fibers are very fine (< 150 μm diameter) with some as small as a few microns in diameter. They are consequently difficult to handle and grip in any test rig. Additionally, the fibers are generally ceramic and their fracture strength is dependent upon surface and volumetric flaws. Hence, the fiber strength becomes dependent upon the amount of material tested (that is, the length of the gage is important). Such brittle behavior lends a probabilistic nature to fiber fracture and data from many tests have to be statistically analyzed. The test methods in this section describe the proper procedures for dealing with the reinforcing fibers.

1.6.2 MECHANICAL PROPERTY TEST METHODS

1.6.2.1 Tensile tests

The recommended procedure for testing single filaments in tension is ASTM D3379 (Reference 1.6.2.1).

1.6.2.2 Creep and creep rupture

Since the properties of high temperature composites are strongly influenced by the properties of the reinforcing fibers, the fibers must contain adequate strength at elevated temperatures. Additionally, long term applications require the fibers to have good creep resistance. For the development of high temperature composites and the prediction of long term properties using micromechanics analyses, the creep properties of the fiber must be well-documented.

For the evaluation of the creep and creep rupture strength of the fibers, the conventional test procedure is to apply a constant tensile load to the fiber at a constant temperature (References 1.6.2.2(a) and (b)). This is typically performed in a dead weight test set-up as described in Reference 1.6.2.2(c). A length of fiber is gripped vertically in cold grips to avoid the possibility of interaction between the grips, fiber, and environment if hot grips were employed. A resistance furnace is used to maintain a constant temperature over a specified gage length (typically 1 inch or 25 mm). Elongation and fracture strain are measured using any one of a variety of non-contacting displacement devices. The creep tests can be run in air or in a protective environment by using a suitable chamber surrounding the fiber and heating elements.

The creep rupture strength, time, and strain to failure will display a large amount of scatter. This is because fracture of the brittle fiber is probabilistic in nature and the flaw size and distribution can increase with time at load and temperature. For these reasons, many fibers have to be tested and statistically analyzed to gain a good understanding of the rupture properties.

1.6.2.3 Bend stress relaxation

This procedure provides a simple method to measure the creep and specifically the stress relaxation behavior of fibers. The bend stress relaxation (BSR) method consists of tying the fiber into a loop and then subjecting it in a furnace to a specific time at temperature. After exposure, the fiber loop is returned to room temperature and the diameter is measured. The applied strain is then removed by breaking the loop at one point and any effects due to the exposure are measured in terms of residual loop radius. Details of the test method and data on selected fibers are given in References 1.6.2.3(a) and (b).

The BSR method has many advantages over the typical tensile creep tests (Section 1.6.2.2), which include the ability to simultaneously study many fibers of small diameter and short length under the same set of conditions (time, temperature, atmosphere). Also, the BSR test gives insight into the ability of the fibers to be creep-formed into woven structures or tight radii.

1.6.3 PHYSICAL PROPERTY TEST METHODS

1.6.3.1 Density

The density of a fiber should be measured using one of three techniques found in ASTM D3800, “Standard Test Method for Density of High-Modulus Fibers” (Reference 1.6.3.1).

1.6.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES

1.6.5 CHEMICAL ANALYSIS TECHNIQUES

1.6.6 ENVIRONMENTAL EFFECTS TEST METHODS

REFERENCES

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1.7 FIBER SIZING TESTING AND ANALYTICAL METHODS

1.7.1 INTRODUCTION

1.7.2 PHYSICAL PROPERTY TEST METHODS

1.7.3 CHEMICAL ANALYSIS TECHNIQUES

1.8 FIBER COATINGS, INTERFACES AND INTERPHASES TESTING AND ANALYTICAL METHODS

1.8.1 INTRODUCTION

1.8.2 MECHANICAL PROPERTY TEST METHODS

1.8.3 PHYSICAL PROPERTY TEST METHODS

1.8.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES

1.8.5 CHEMICAL ANALYSIS TECHNIQUES

1.9 MATRIX TESTING AND ANALYTICAL METHODS

1.9.1 INTRODUCTION

The matrix is the major constituent in the MMC. Its job is to bind the fibers in place and protect them from mechanical and environmental damage. The matrix also acts to transfer load to the fibers. In addition, it imparts its own properties to the composite, which are characteristic to metals, such as ductility, electrical and thermal conductivity.

As the major constituent, the properties of the matrix are influential in dictating the behavior of the composite. Therefore, the matrix should be thoroughly understood and characterized. The following sections give testing techniques for the documentation of matrix properties. This knowledge can be used in both quality control, as well as micromechanics analyses.

In general, the testing techniques for the matrix are similar to those used with conventional monolithic materials. However, there are a few additional notes added to account for the idiosyncrasies associated with the non-conventional manufacturing forms of these materials.

1.9.2 MECHANICAL TEST METHODS

This section gives test methods for characterizing the mechanical properties of the neat matrix. These properties may be used for input into micromechanics models when analyzing the behavior of the composite. This is particularly useful when no composite data exist and some idea of how the composite will behave is necessary.

The matrix materials analyzed under this section are manufactured in a method which is similar to the processing of the composite, including both consolidation and heat treatment. This ensures that the properties of the neat matrix are truly representative of those in the composite.

1.9.2.1 Tension

Tensile testing of metallic matrices should be conducted in accordance with ASTM Test Method E8 (Reference 1.9.2.1(a)) for room temperature tests and E 21 (Reference 1.9.2.1(b)) for tests at elevated temperatures.

Note: Due to the non-conventional processing of these matrix materials, they may be anisotropic. Therefore, if a detailed characterization of these materials is desired, specimens should be taken from various directions with respect to the geometry of the supplied material. Additionally, transverse strain should be measured on selected tensile coupons.

1.9.2.2 Creep

Creep testing of the matrix material should be conducted in accordance with ASTM Test Method E139 (Reference 1.9.2.2).

1.9.2.3 Stress relaxation

Stress relaxation is similar to creep testing with the exception that at the maximum load, the strain is held constant and the stress is allowed to relax until a saturation point is finally reached, at which time the test can be terminated. With this exception, all other testing conditions should be conducted in accordance with ASTM Test Method E139 (Reference 1.9.2.3). In addition, the relaxation stress versus time data should be reported.

1.9.2.4 Fatigue

Fatigue testing may be done on the neat matrix in order to predict the fatigue life of the composite using some micromechanical approach. Dependent upon the ultimate goals of the testing and the model used, either load or strain controlled tests can be conducted. This should be done in accordance with ASTM Test Method E466 (Reference 1.9.2.4(a)) for load controlled and E606 (Reference 1.9.2.4(b)) for strain controlled tests.

1.9.3 PHYSICAL TEST METHOD

1.9.3.1 Density

The density of the matrix should be measured using the Archimedes method found in ASTM D792, "Standard Test Method for Density and Specific Gravity (Relative Density) of Plastics by Displacement" (Reference 1.9.3.1).

1.9.4 MICROSTRUCTURAL ANALYSIS TECHNIQUES

Metallography on the matrix material is performed using standard methods as have been applied to metallic monolithic materials. Some typical procedures can be found in References 1.9.4(a) through (c). Below is a common practice for metallographically preparing titanium alloys:

Monolithic titanium is relatively easy to prepare with semi-automatic polishing equipment and using 150 rpm and a pressure of 5 pounds per sample. Grinding is performed on successive SiC papers of 320, 400, 600, 800, and 1200 grit sizes.

Final preparation is best accomplished by the use of attack polishing during the final polishing step. This process removes material by chemical and mechanical action to produce scratch- and deformation-free microstructures. Typically, a chemotextile polishing cloth is used with a 50 nm colloidal silica suspension as follows:

150 ml water
150 ml 50 nm colloidal silica
30 ml hydrogen peroxide
1 ml nitric acid
1 ml hydrofluoric acid

1.9.4.1 Microstructural analysis techniques titanium

1.9.4.2 Microstructural analysis techniques aluminum

1.9.5 CHEMICAL ANALYSIS TECHNIQUES

1.9.6 ENVIRONMENTAL EFFECTS TEST METHODS

REFERENCES

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1.9.4(b) Samuels, L.E., *Metallographic Polishing by Mechanical Methods*, ASM, Materials Park, OH, 1982.

1.9.4(c) Bousfield, B., *Surface Preparation and Microscopy of Materials*, John Wiley and Sons, NY, 1992.

1.10 STRUCTURE SENSITIVE PROPERTIES CHARACTERIZATION

1.10.1 INTRODUCTION

1.10.2 MECHANICALLY-FASTENED JOINTS

1.10.3 BONDED, BRAZED, AND WELDED JOINTS

1.10.4 CURVED SHAPES

1.10.5 STRUCTURAL DESIGN DETAILS

1.10.6 TRANSITION AND OTHER SPECIAL REGIONS

1.10.7 SIZE EFFECTS

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1.11 ANALYSIS OF DATA

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1.11.2 PROCEDURES OF CALCULATION OF STATISTICALLY-BASED MATERIAL PROPERTIES

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2.1.2 PURPOSE, SCOPE, AND ORGANIZATION OF SECTION 2

2.2 USE OF DATA

2.3 STRUCTURAL DESIGN AND ANALYSIS

2.3.1 INTRODUCTION

2.3.2 GENERAL DESIGN GUIDELINES

2.3.3 DESIGN GUIDELINES – CONTINUOUS FIBER REINFORCED MMC

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2.3.5 PROCESS RELATED DESIGN CONCEPTS

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2.3.5.2 Wrought MMC

2.3.5.2.1 Sheet and plate products

2.3.5.2.2 Extruded products

2.3.5.2.3 Forged products

2.4 DESIGN GUIDELINES - JOINING

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2.4.2 DISCONTINUOUS REINFORCED MMC

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3.1 GENERAL INFORMATION

3.1.1 INTRODUCTION

3.1.2 PURPOSE, SCOPE, AND ORGANIZATION OF SECTION

3.1.3 DATA PRESENTATION FORMAT AND ORGANIZATION

3.1.3.1 Manuals

3.1.3.2 Electronic

3.2 REINFORCEMENT PROPERTIES

3.2.1 INTRODUCTION

The following information pertains to the mechanical properties of various fiber reinforcements. These properties are based on material of varying maturity and should be considered experimental in nature. “Typical” values are listed for approximate rule-of-mixtures calculations, but should not be used for final design purposes. These “typical” values are based on as-received properties and some change in properties should be anticipated as a result of the composite manufacturing process.

3.2.2 ALUMINA FIBERS

3.2.3 BORON FIBERS

3.2.4 BORON CARBIDE FIBERS

3.2.5 CARBON AND GRAPHITE FIBERS

3.2.6 SILICON CARBIDE FIBERS

3.2.7 STEEL FIBERS

3.2.8 TUNGSTEN FIBERS

3.2.9 OTHER FIBERS

3.2.10 OTHER REINFORCEMENTS

3.3 PROPERTIES OF MATRIX MATERIALS

3.3.1 INTRODUCTION

Section 3.3 contains data for the properties of the neat matrix materials. These monolithic metals are not manufactured by conventional techniques such as standard forging, rolling, and casting operations (whose properties would be found in Mil-Handbook 5), but rather are uniquely processed to mimic the processing operation which is used when making the composite. Common processing techniques for the neat matrix are hipped foil and hipped sheet. With these types of processing techniques, the properties of the neat matrix should be as close as possible to those of the *in-situ* matrix in the composite. Note, however, that the reinforcement may affect the *in-situ* properties of the matrix due to either residual stresses

and/or reaction of the reinforcement and matrix and corresponding diffusion/depletion of the elements in either constituent.

Property data taken from the neat matrix material (Section 3.3) and reinforcement (Section 3.2) can be used with micromechanical analyses to aid in composite design. This is especially helpful to predict composite properties for cross-ply laminates, for which limited information is currently given in this Handbook. Additionally, there are many types of composite properties for which limited or no data are available. In such cases, composite properties can be estimated from the constituent properties using analytical relationships. Note that matrix properties taken from conventionally processed alloys will be different from those taken from the neat matrix, and, therefore, any estimation of composite properties based on conventionally processed materials rather than those of the neat matrix should be done with caution.

3.3.2 ALUMINUMS

3.3.3 COPPERS

3.3.4 MAGNESIUMS

3.3.5 TITANIUMS

3.3.5.1 Ti-15V-3Cr-3Al-3Sn (NASA-LeRC)

The material was manufactured by Textron through consolidation of sheets or foils to yield plates approximately 0.4” thick. The plates were cut into specimens and heat treated in vacuum for 24 h at 1292°F (700°C). Tensile tests were conducted according to test methods in Section 1.9.2.1. Direct induction heating was used for testing at elevated temperatures. Test were generally performed in air. Some tests were performed at Marshall Space Flight Center to assess the effects (and very little were observed) of high pressure hydrogen on this material. These tests were either run in 5 ksi helium or 5 ksi hydrogen.

The majority of the Ti-15-3 tests were conducted to characterize various viscoplastic models. Therefore, the failure of the specimen was not required and these tests were unloaded after a given amount of strain. Hence, many of the failure strains in the raw data table in Appendix B have a “>” sign preceding the strain at which unloading occurred. For the same reason, many of the UTS values are missing. For interrupted tests, only those UTS values are given where the specimen had already reached a maximum stress and subsequently softened until the specimen was unloaded.

The table of average tensile properties for room temperature tests is shown in Tables 3.3.5.1(a) and (d). Since strain rate does not play a significant role at room temperature for this material, and neither did testing in high pressure hydrogen or helium, all of these data were combined to give the room temperature information in this table. The term “lot” in this table refers to one plate of material.

The UTS is given in Figure 3.3.5.1(a) as a function of temperature and strain rate. There is approximately a factor of two decrease in the UTS between 75°F (24°C) and 1000°F (538°C). At 1000°F (538°C) the UTS is very dependent upon the strain rate.

The elastic modulus is plotted as a function of temperature and strain rate in Figure 3.3.5.1(b). The data points in this figure are not means but are values from individual tests. The Figure shows that the modulus generally decreases 13% between room temperature and 1000°F (538°C). Up to 800°F (427°C) there is little effect of strain rate on modulus. Above 800°F (427°C), the modulus rapidly decreases with increasing temperature for specimens tested at the slower strain rate. This is not depicted in this figure, but can be ascertained by examining the raw data in Appendix B.

The proportional limit, 0.02% and 0.2% yield strengths are plotted in Figures 3.3.5.1(c) – (e) as a function of temperature and strain rate. There is approximately a factor of two decrease in the yield strengths between 75°F (24°C) and 1000°F (538°C). At temperatures greater than or equal to 600°F

(316°C), the yield strengths become highly strain rate sensitive. The slower the strain rate, the lower is the yield strength and the lower is the temperature at which a rapid drop-off in the yield strength occurs with increasing temperature.

Tensile curves are plotted as a function of strain rate for three different temperatures: 400°F (204°C) (Figure 3.3.5.1(f)), 800°F (427°C) (Figure 3.3.5.1(g)), and 1000°F (538°C) (Figure 3.3.5.1(h)). At 400°F (204°C) there is minimal strain rate sensitivity. However, at 800°F (427°C), strain rate has a large effect on the tensile behavior. At a temperature of 800°F (427°C), a strain rate of $1x10^{-5}$ s^{-1} is slow enough to induce softening after the attainment of the UTS. At still slower strain rates, dynamic strain aging is active, which leads to hardening as the tests progress.

At 1000°F (538°C) the temperature is high enough to induce softening after attaining the UTS. At a strain rate of $1x10^{-6}$ s^{-1}, the material exhibits dynamic strain aging, but not to the extent of that observed at 800°F (427°C). Dynamic strain aging results in the hardening effect observed in the initial part of the stress-strain curve.

Figures 3.3.5.1(i) and (j) show the effect of temperature on the tensile behavior at two different strain rates: $1x10^{-4}$ and $1x10^{-6}$ s^{-1}. The maximum stress in each curve decreases with increasing temperature. Additionally, dynamic strain aging results in some anomalous behavior in some of the curves (see, for example, the curves at 800°F (427°C) and 1000°F (538°C) at a strain rate of $1x10^{-6}$ s^{-1}).

3.3.5.1 Ti-15V-3Cr-3Al-3Sn HIP sheet/foil*

MATERIAL:	Ti-15V-3Cr-3Al-3Sn HIP sheet/foil		**Ti Ti-15-3 Summary**
MATRIX:	Ti-15V-3Cr-3Al-3Sn	MANUFACTURER: Textron	
PROCESS SEQUENCE:	Hipped Sheet or Foil		
PROCESSING:		SOURCE: NASA LeRC	

Date of matrix manufacture		Date of data submittal	6/98
Date of testing	5/96-7/97	Date of analysis	8/98

MATRIX PROPERTY SUMMARY

Temperature	75°F		400°F	600°F	800°F	900°F	1000°F	
Environment	Air(1)		Air	Air	Air	Air	Air	
Tension	SS-SSSS		-S--SSS	-S--SSS	-S--SSS	SS--SSS	SS--SSS	

(1) Some testing at 5 ksi Helium and 5 ksi Hydrogen, results pooled.

Classes of data: F - Fully approved, S - Screening in order: Strength/Modulus/Poisson's Ratio/Strain-to-failure/Proportional Limit/0.02-offset-strength/0.2-offset-strength.

* Raw data tables are presented in Appendix B.

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Table 3.3.5.1(a)
Ti HIP sheet/foil
Ti-15-3
Tension
75, 400, 600
Air
Screening

Temperature (°F)		75	400	600			
Environment		Air (1)	Air	Air			
Strain Rate (1/s)		(3)	(3)	$1 \cdot 10^{-4}$			
	Mean	124					
	Minimum	120					
	Maximum	127					
	C.V.(%)	1.83					
	B-value	(2)					
F^{tu}	Distribution	ANOVA					
(ksi)	C_1	2.89					
	C_2	12.9					
	No. Specimens	7					
	No. Lots	2					
	Approval Class	Screening					
	Mean	12.4	12.3	11.4			
	Minimum	11.9	12.0				
	Maximum	13.0	12.6				
E^{t}	C.V.(%)	3.39					
(Msi)	No. Specimens	8	3	1			
	No. Lots	3	2	1			
	Approval Class	Screening	Screening	Screening			
	Mean						
ν^{m}	No. Specimens						
	No. Lots						
	Approval Class						
	Mean	19.3					
	Minimum	16.8					
	Maximum	22.1					
	C.V.(%)	10.7					
	B-value	(2)					
ε^{tu}	Distribution	Normal					
(%)	C_1	19.3					
	C_2	2.06					
	No. Specimens	7					
	No. Lots	2					
	Approval Class	Screening					

(1) Some testing at 5 ksi Helium and 5 ksi Hydrogen, results pooled.
(2) B-basis values appear for fully-approved data only.
(3) Strain rates pooled (1/s): $1 \cdot 10^{-6}$, $8.3 \cdot 10^{-5}$, $1 \cdot 10^{-4}$, $2 \cdot 10^{-3}$.

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

Table 3.3.5.1(b)
Ti HIP sheet/foil
Ti-15-3
Tension
800
Air
Screening

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Temperature (°F)		800	800	800	800		
Environment		Air	Air	Air	Air		
Strain Rate (1/s)		$1 \cdot 10^{-8}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$		
	Mean						
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
F^{tu}	Distribution						
(ksi)	C_1						
	C_2						
	No. Specimens						
	No. Lots						
	Approval Class						
	Mean	17	10.8	10.8	11.3		
	Minimum						
	Maximum						
E^{t}	C.V.(%)						
(Msi)	No. Specimens	1	1	1	1		
	No. Lots	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
	Mean						
ν^{m}	No. Specimens						
	No. Lots						
	Approval Class						
	Mean						
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
ε^{tu}	Distribution						
(%)	C_1						
	C_2						
	No. Specimens						
	No. Lots						
	Approval Class						

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Table 3.3.5.1(c)
Ti HIP sheet/foil
Ti-15-3
Tension
900, 1000
Air
Screening

Temperature (°F)		900	1000	1000	1000		
Environment		Air	Air	Air	Air		
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-3}$		
	Mean	75	24	43	67		
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
F^{tu}	Distribution						
(ksi)	C_1						
	C_2						
	No. Specimens	1	1	1	1		
	No. Lots	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
	Mean	10.8	5.3	10.5	11		
	Minimum	10.7					
	Maximum	10.9					
E^{t}	C.V.(%)						
(Msi)	No. Specimens	2	1	1	1		
	No. Lots	2	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
	Mean						
ν^{m}	No. Specimens						
	No. Lots						
	Approval Class						
	Mean						
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
ε^{tu}	Distribution						
(%)	C_1						
	C_2						
	No. Specimens						
	No. Lots						
	Approval Class						

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Table 3.3.5.1(d)
Ti HIP sheet/foil
Ti-15-3
Tension
75, 400, 600
Air
Screening

Temperature (°F)		75	400	600			
Environment		Air (1)	Air	Air			
Strain Rate (1/s)		(3)	(3)	$1 \cdot 10^{-4}$			
	Mean	103	75.3	69			
	Minimum	94	65				
	Maximum	111	81				
	C.V.(%)						
	B-value						
F^{pl} (ksi)	Distribution						
	C_1						
	C_2						
	No. Specimens	2	3	1			
	No. Lots	2	2	1			
	Approval Class	Screening	Screening	Screening			
	Mean	113	85.3	78			
	Minimum	108	84				
	Maximum	117	87				
	C.V.(%)						
	B-value						
$F^{ty0.02}$ (ksi)	Distribution						
	C_1						
	C_2						
	No. Specimens	2	3	1			
	No. Lots	2	2	1			
	Approval Class	Screening	Screening	Screening			
	Mean	115	95.7	87			
	Minimum	110	95				
	Maximum	124	96				
	C.V.(%)	3.64					
	B-value	(2)					
$F^{ty0.2}$ (ksi)	Distribution	ANOVA					
	C_1	5.74					
	C_2	5.75					
	No. Specimens	8	3	1			
	No. Lots	3	2	1			
	Approval Class	Screening	Screening	Screening			

(1) Some testing at 5 ksi Helium and 5 ksi Hydrogen, results pooled.
(2) B-basis values appear for fully-approved data only.
(3) Strain rates pooled (1/s): $1 \cdot 10^{-6}$, $8.3 \cdot 10^{-5}$, $1 \cdot 10^{-4}$, $2 \cdot 10^{-3}$.

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Table 3.3.5.1(e)
Ti HIP sheet/foil
Ti-15-3
Tension
800
Air
Screening

Temperature (°F)		800	800	800	800		
Environment		Air	Air	Air	Air		
Strain Rate (1/s)		$1 \cdot 10^{-8}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$		
F^{pl} (ksi)	Mean	5.2	20	56	59		
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens	1	1	1	1		
	No. Lots	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
$F^{ty0.02}$ (ksi)	Mean	40	29	69	73		
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens	1	1	1	1		
	No. Lots	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
$F^{ty0.2}$ (ksi)	Mean		43	83	84		
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens		1	1	1		
	No. Lots		1	1	1		
	Approval Class		Screening	Screening	Screening		

MATERIAL: Ti-15V-3Cr-3Al-3Sn HIP sheet/foil

TEST METHOD: Sec. 1.9.2.1 MODULUS CALCULATION: Least squares analysis up to proportional limit

PRE-TEST EXPOSURE: Vacuum 1292°F, 24 hr SOURCE: NASA LeRC

NORMALIZED BY: N/A

Table 3.3.5.1(f)
Ti HIP sheet/foil
Ti-15-3
Tension
900, 1000
Air
Screening

Temperature (°F)		900	1000	1000	1000		
Environment		Air	Air	Air	Air		
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-3}$		
F^{pl} (ksi)	Mean	54	6	23	50		
	Minimum	50					
	Maximum	57					
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens	2	1	1	1		
	No. Lots	2	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
$F^{ty0.02}$ (ksi)	Mean	65	6	33	60		
	Minimum						
	Maximum						
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens	2	1	1	1		
	No. Lots	2	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		
$F^{ty0.2}$ (ksi)	Mean	74.5	8	42	67		
	Minimum	74					
	Maximum	75					
	C.V.(%)						
	B-value						
	Distribution						
	C_1						
	C_2						
	No. Specimens	2	1	1	1		
	No. Lots	2	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening		

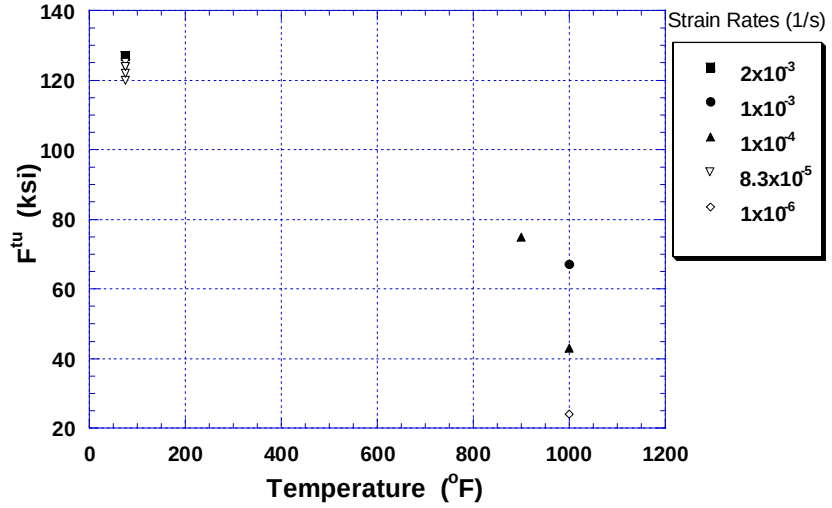

FIGURE 3.3.5.1(a) *Ultimate tensile strength as a function of temperature and strain rate.*

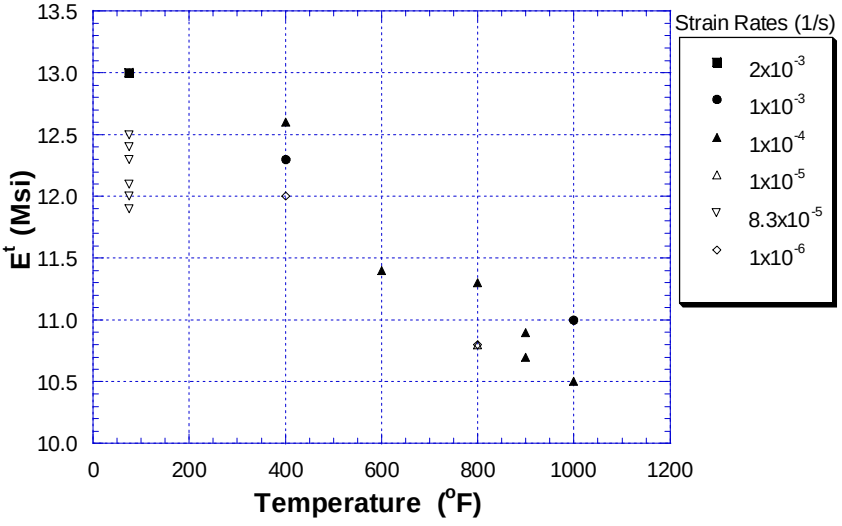

FIGURE 3.3.5.1(b) *Tensile modulus as a function of temperature and strain rate.*

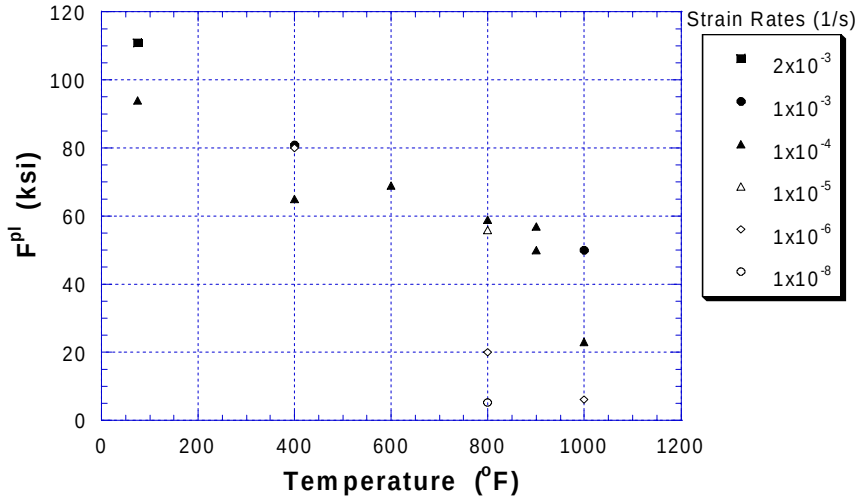

FIGURE 3.3.5.1(c) *Proportional limit as a function of temperature and strain rate.*

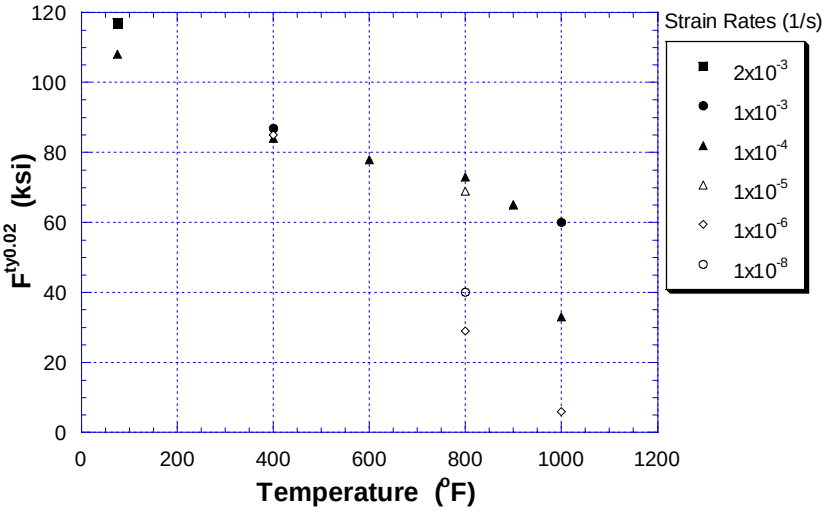

FIGURE 3.3.5.1(d) *0.02-offset-yield-strength as a function of temperature and strain rate*

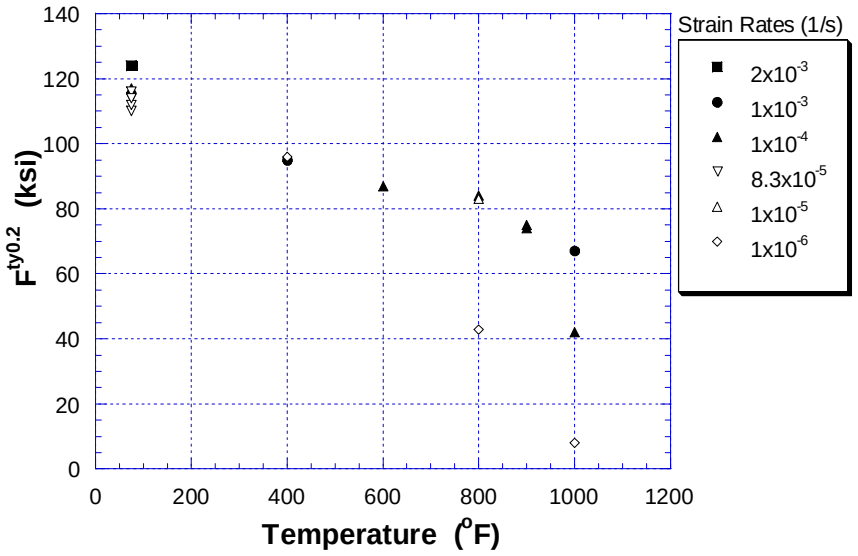

FIGURE 3.3.5.1(e) *0.2-offset-yield-strength as a function of temperature and strain rate.*

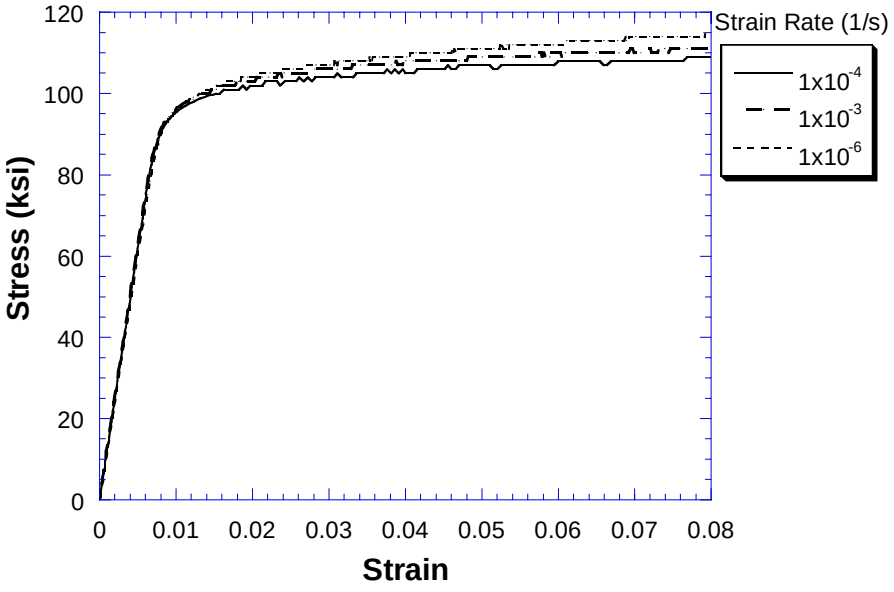

FIGURE 3.3.5.1(f) *Tensile curves at 400°F (204°C) as a function of strain rate.*

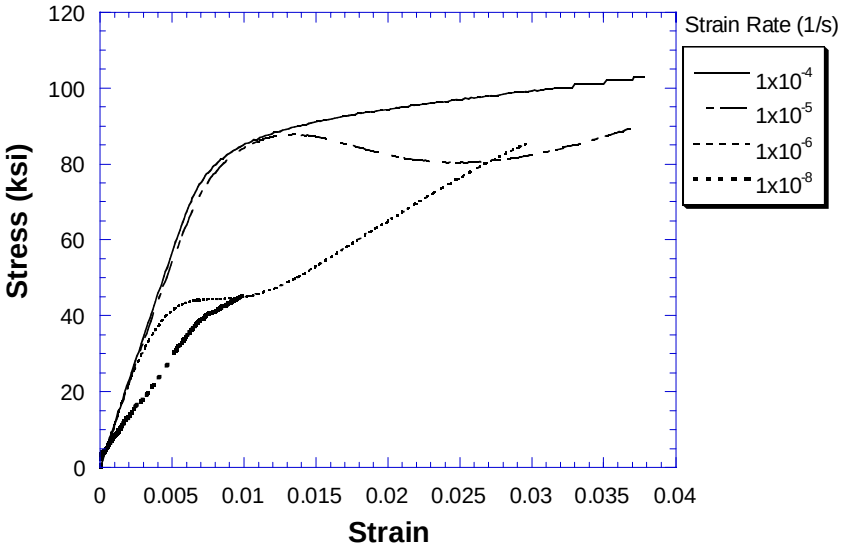

FIGURE 3.3.5.1(g) *Tensile curves at 800°F (427°C) as a function of strain rate.*

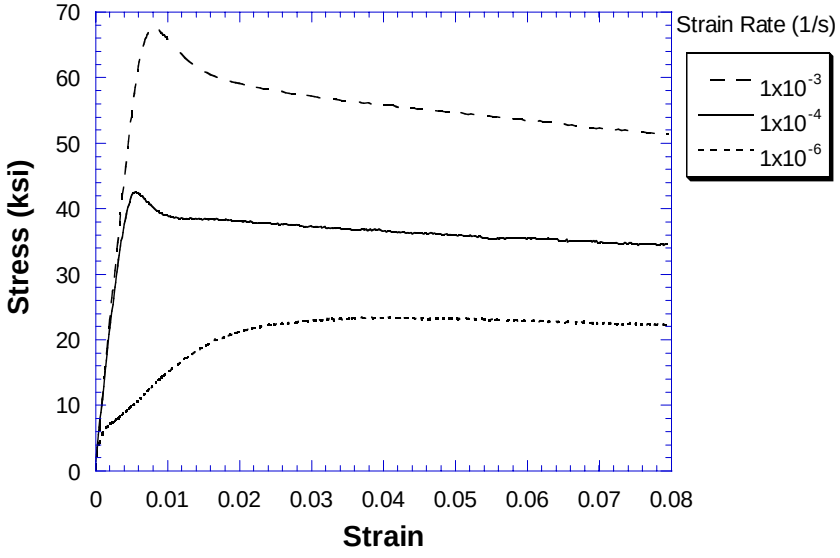

FIGURE 3.3.5.1(h) *Tensile curves at 1000°F (538°C) as a function of strain rate.*

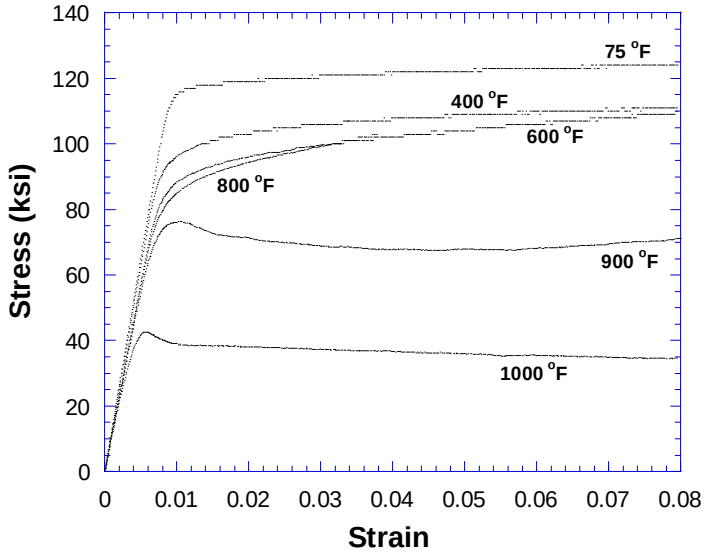

FIGURE 3.3.5.1(i) *Tensile curves at a strain rate of $10^{-4}s^{-1}$ as a function of temperature.*

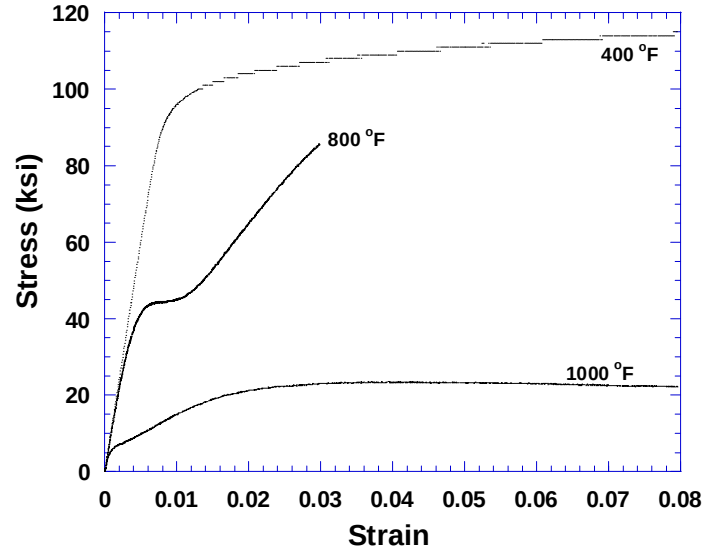

FIGURE 3.3.5.1(j) *Tensile curves at a strain rate of $10^{-6}s^{-1}$ as a function of temperature.*

3.3.6 OTHERS

3.4 FIBER COATING PROPERTIES

3.4.1 INTRODUCTION

3.4.2 CARBON

3.4.3 TITANIUM DIBORIDE

3.4.4 YTTRIA

3.4.5 OTHERS

3.5 ALUMINUM MATRIX COMPOSITE PROPERTIES

3.5.1 INTRODUCTION

3.5.2 ALUMINA/ALUMINUM

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3.5.4 BORON CARBIDE/ALUMINUM

3.5.5 GRAPHITE/ALUMINUM

3.5.6 SILICON CARBIDE/ALUMINUM

3.5.7 STEEL/ALUMINUM

3.5.8 TUNGSTEN/ALUMINUM

3.5.9 OTHERS/ALUMINUM

3.6 COPPER MATRIX COMPOSITE PROPERTIES

3.6.1 INTRODUCTION

3.6.2 GRAPHITE/COPPER

3.6.3 OTHERS/COPPER

3.7 MAGNESIUM MATRIX COMPOSITE PROPERTIES

3.7.1 INTRODUCTION

3.7.2 GRAPHITE/MAGNESIUM

3.7.3 ALUMINA/MAGNESIUM

3.7.4 OTHER/MAGNESIUM

3.8 TITANIUM MATRIX COMPOSITE PROPERTIES

3.8.1 INTRODUCTION

At the time of this edition, only data for SiC-reinforced titanium alloys are presented in this section. They have all been produced by foil-fiber-foil compactions (see Section 1.2.6.2.2). The SiC fiber used in all cases is the SCS-6 monofilament. This fiber has a nominal UTS of 500 ksi, with a 50-60 Msi modulus. Due to these high values, the fiber properties dominate in directions parallel to the fiber axis in the composited form.

The SCS-6 monofilament is coated with a double-pass, carbon-rich layer. This coating protects the surface of the fiber from handling damage. Additionally, it acts as a diffusion barrier to prevent reaction of the titanium matrices with the SiC fiber during consolidation. The coating forms a weak interface which leads to fiber/matrix debonding and low transverse properties. Thus, the properties of the materials listed in this section are extremely anisotropic.

3.8.2 SILICON CARBIDE/TITANIUM

3.8.2.1 SiC/Ti-15-3

Composite plates were consolidated by Textron using the foil-fiber-foil method. The matrix foils were of the alloy Ti-15V-3Cr-3Al-3Sn (Ti-15-3) and the reinforcement was the SCS-6 fibers. Plates were either 8 or 32-ply thick and had dimensions of 10” x 14”. All fiber mats used in these plates were woven with metallic ribbons. The type of ribbon used (Ti, Mo, or Ti-Nb) depended upon the manufacturing year.

Tensile specimens were cut from the plates and prepared according to Section 1.3.2.4. All specimens were heat treated in vacuum for 24 h at 1292°F (700°C). Tensile tests were conducted in air according to the test methods in Section 1.4.2.1. Direct induction heating was used for testing at elevated temperatures.

Effects of Fiber Volume Fraction

Tables of average tensile properties for the [0] orientation are given in Tables 3.8.2.1(a) through (d) for materials with various fiber volume fractions. In these and all subsequent tables, the term “lot” refers to one plate of material. Tensile properties and pedigree information for each specimen are presented in the Raw Data Table in Appendix C.

Average tensile properties for the [90] orientation are given in Tables 3.8.2.1(e) and (f) for three fiber volume fractions. Average tensile properties for cross-ply laminates with various fiber lay-ups are presented in Table 3.8.2.1(g) through (n). The tensile properties and pedigree information for these tests are given in the Raw Data Table in Appendix C. There are three tests in the Raw Data Tables which have a “>” sign preceding the values for the failure strains. These tests were interrupted and unloaded at the strain value listed and, therefore, the real value for the failure strain is larger that those indicated in the table.

The ultimate tensile strength (UTS) is plotted in Figure 3.8.2.1(a) as a function of fiber volume percent and temperature for [0] and [90] laminates. The UTS increases with increasing fiber volume percent for the [0] laminate. There is little difference in the UTS between 75°F (24°C) and 800°F (427°C) for fiber volume percents greater than 25%. However, at a fiber volume percent of 15 there is a stronger dependence of the UTS on temperature, indicating the stronger influence of the matrix properties. In contrast to the [0] laminates, the UTS of the [90] laminates at 75°F (24°C) decreases with increasing fiber volume fraction.

The elastic modulus is plotted in Figure 3.8.2.1(b) as a function of temperature and fiber volume percent for [0] and [90] laminates. The modulus increases for the [0] laminates as fiber volume percent increases. There is no significant difference between the modulus at 75°F (24°C) and 800°F (427°C) for the [0] laminates. The modulus for the [90] laminates is independent of fiber volume percent.

The proportional limits is given in Figure 3.8.2.1(c) as a function of temperature and volume fraction for [0] and [90] laminates. For the limited amount of data present, there is no change in proportional limit as a function of either volume fraction nor temperature. This is in part due to the large variation in these values and the subjective manner in which these values are determined.

The 0.02% yield strength is given in Figure 3.8.2.1(d) as a function of volume fraction and temperature for [0] and [90] laminates. There is a slight increase in the [0] yield strength as a function of fiber volume fraction, but no significant difference as a function of temperature. The yield strength of the [90] laminate is independent of both parameters.

Selected tensile curves at 75°F (24°C) (Figure 3.8.2.1(e)) and 800°F (427°C) (Figure 3.8.2.1(f)) are plotted as a function of fiber volume percent. The material becomes increasingly stiffer and stronger with increasing fiber volume percent. At a fiber volume fraction of 15%, there is significantly more inelasticity, as indicated by the curvature in the stress-strain behavior, than for the materials with higher fiber volume percents. Note also that the failure strain is independent of fiber volume percent, particularly at 800°F (427°C).

Figure 3.8.2.1(g) shows the stress-transverse width strain curves at 800°F (427°C) as a function of fiber volume percent. Again, the curves are stiffer and stronger at higher fiber volume percents.

Effects of Fiber Orientation for a Fiber Volume Percent of 35%

The average elastic modulus is plotted in Figure 3.8.2.1(h) as a function of fiber layup for both the 75°F (24°C) and 800°F (427°C) test temperatures. The modulus decreases for fiber lay-ups moving from the left to the right in this figure, which represents a trend towards less influence from the fiber and more influence from the matrix properties. Given the paucity of tests, no significant difference between the modulus at 75°F (24°C) and 800°F (427°C) could be observed.

The average UTS is shown in Figure 3.8.2.1(i) as a function of fiber layup for test temperatures of 75°F (24°C) and 800°F (427°C). The UTS decreases from a value of approximately 200 ksi for the strongest orientation (that is, [0]), to a value of approximately 60 ksi for the weakest orientation (that is, [90]). The strength of the cross-ply laminates lie somewhere in between and depend on the amount of contribution from a near-zero ply. There is no significant difference in the UTS values between the two temperatures.

Tensile curves at 75°F (24°C) for various laminate orientations are given in Figure 3.8.2.1(j). The initial portion of the tensile curve for the unreinforced matrix is also given for comparison (the arrows indicate that those curves continue to higher strains). All of the composite laminates are stiffer than the unreinforced matrix material. However, only three of the composite laminates ([0], [90/0] and [+/-30]) are stronger than the unreinforced matrix. Also, all of the composite laminates have far less ductility than the unreinforced matrix.

3.8.2.1 SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil*

MATERIAL:	SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil			**SiC/Ti SCS-6/Ti-15-3 Summary**
FIBER	SCS-6, continuous, 145 μm	MATRIX:	Ti-15V-3Cr-3Sn-3Al	
MANUFACTURER:	Textron			
PROCESS SEQUENCE:	Hipped Foil/Fiber/Foil Preforms			
PROCESSING:		SOURCE:	NASA LeRC	

Date of fiber manufacture		Date of testing	6/98-10/96
Date of matrix manufacture		Date of data submittal	5/98
Date of composite manufacture		Date of analysis	9/98

LAMINA PROPERTY SUMMARY

Temperature	75°F			800°F			
Environment	Air			Air			
Fiber v/o	15	35	41	15	25	35	41
[0] Tension, 1-axis	SS-SSSS	SSSSSS-	SS-SSS-	SSSS-S-	SSSS-S-	SS-SSS-	SSSS---
[90] Tension, 2-axis	SS-SSSS	SSSSSSS	SS-S---			SS-SSSS	

Classes of data: F - Fully approved, S - Screening in order: Strength/Modulus/Poisson's Ratio/Strain-to-failure/Proportional Limit/0.02-offset-strength/0.2-offset-strength.

* Raw data tables in Appendix C.

		Nominal	As Submitted	Test Method
Fiber Density	(g/cm^3)	3.0	3.0	
Foil Matrix Density	(g/cm^3)	4.8		
Composite Density	(g/cm^3)			
Ply Thickness*	(in)			

* Fiber center to fiber center

LAMINATE PROPERTY SUMMARY

Temperature	75°F		800°F				
Environment	Air		Air				
Fiber v/o	35		35				
[+/- 30] Tension, x-axis	SS-SSSS		SS-SSSS				
[+/- 45] Tension, x-axis	SS-SSSS		SS-SSSS				
[+/-60] Tension, x-axis	SS-SSSS		SS-SSSS				
[0/90] Tension, x-axis	SSSSSSS						

Classes of data: F - Fully approved, S - Screening in order: Strength/Modulus/Poisson's Ratio/Strain-to-failure/Proportional Limit/0.02-offset-strength/0.2-offset-strength.

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.06-0.12 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Table 3.8.2.1(a)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 1-axis
$[0]_8$
75
Screening

Temperature (°F)		75	75	75				
Environment		Air	Air	Air				
Fiber Volume (%)		15	35	41				
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$				
	Mean	185	200	227				
	Minimum		168	201				
	Maximum		217	252				
	C.V.(%)		7.16					
	B-value		(2)					
F_1^{tu}	Distribution		Normal					
(ksi)	C_1		200					
	C_2		14.3					
	No. Specimens	1	9	2				
	No. Lots	1	2	1				
	Approval Class	Screening	Screening	Screening				
	Mean	20	26.6	31				
	Minimum		25.0	31				
	Maximum		29.0	31				
E_1^t	C.V.(%)		5.66					
(Msi)	No. Specimens	1	8	2				
	No. Lots	1	2	1				
	Approval Class	Screening	Screening	Screening				
	Mean		0.28					
ν_{12}^t	No. Specimens		1					
	No. Lots		1					
	Approval Class		Screening					
	Mean	1.21	0.84	0.82				
	Minimum		0.66	0.73				
	Maximum		1	0.9				
	C.V.(%)		14					
	B-value		(1)					
ε_1^{tu}	Distribution		Normal					
(%)	C_1		0.84					
	C_2		0.12					
	No. Specimens	1	9	2				
	No. Lots	1	2	1				
	Approval Class	Screening	Screening	Screening				

(1) B-basis values appear for fully-approved data only.

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM/water jet/diamond grind FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: in. MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs. SOURCE: NASA LeRC
NORMALIZED BY: Not normalized

Table 3.8.2.1(b)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 1-axis
$[0]_8$ (1)
800
Screening

Temperature (°F)		800	800	800	800	800	800	
Environment		Air	Air	Air	Air	Air	Air	
Fiber Volume (%)		15	25	35	35	35	41	
Strain Rate (1/s)		$1\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-5}$	$1\cdot10^{-4}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$	
	Mean	137	195	198	200	226	248	
	Minimum	136	192			201	245	
	Maximum	138	197			252	251	
	C.V.(%)							
	B-value							
F_1^{tu}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	2	2	1	1	4	2	
	No. Lots	1	1	1	1	1	1	
	Approval Class	Screening	Screening	Screening	Screening	Screening	Screening	
	Mean	19	24	29	32	27	31	
	Minimum	19	24			26	30	
	Maximum	19	24			29	32	
E_1^t	C.V.(%)							
(Msi)	No. Specimens	2	2	1	1	4	2	
	No. Lots	1	1	1	1	1	1	
	Approval Class	Screening	Screening	Screening	Screening	Screening	Screening	
	Mean	0.38	0.32				0.3	
ν_{12}^t	No. Specimens	2	2				2	
	No. Lots	1	1				1	
	Approval Class	Screening	Screening				Screening	
	Mean	0.81	0.90	0.82	0.77	0.95	0.84	
	Minimum	0.75	0.88			0.84	0.83	
	Maximum	0.86	0.91			1.06	0.84	
	C.V.(%)							
	B-value							
ε_1^{tu}	Distribution							
(%)	C_1							
	C_2							
	No. Specimens	2	2	1	1	4	2	
	No. Lots	1	1	1	1	1	1	
	Approval Class	Screening	Screening	Screening	Screening	Screening	Screening	

(1) Also contains data from 32-ply material.
(2) B-basis values appear for fully-approved data only.

Table 3.8.2.1(c)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 1-axis
$[0]_8$
75
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.06-0.12 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	75	75				
Environment		Air	Air	Air				
Fiber Volume (%)		15	35	41				
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$				
	Mean	123	116	140				
	Minimum		33	128				
	Maximum		150	151				
	C.V.(%)		31.9					
	B-value		(1)					
F_1^{pl}	Distribution		ANOVA					
(ksi)	C_1		36.6					
	C_2		2.45					
	No. Specimens	1	9	2				
	No. Lots	1	2	1				
	Approval Class	Screening	Screening	Screening				
	Mean	141	145	176				
	Minimum		82	160				
	Maximum		186	192				
	C.V.(%)		25.8					
	B-value		(1)					
$F_1^{ty0.02}$	Distribution		ANOVA					
(ksi)	C_1		40.6					
	C_2		6.35					
	No. Specimens	1	9	2				
	No. Lots	1	2	1				
	Approval Class	Screening	Screening	Screening				
	Mean	172						
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_1^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1						
	No. Lots	1						
	Approval Class	Screening						

(1) B-basis values appear for fully-approved data only.

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM/water jet/diamond grind FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: in. MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs. SOURCE: NASA LeRC
NORMALIZED BY: Not normalized

Table 3.8.2.1(d)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 1-axis
$[0]_8$ (1)
800
Screening

Temperature (°F)		800	800	800	800	800	800	
Environment		Air	Air	Air	Air	Air	Air	
Fiber Volume (%)		15	25	35	35	35	41	
Strain Rate (1/s)		$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	
	Mean			24	17	91		
	Minimum					31		
	Maximum					151		
	C.V.(%)							
	B-value							
F_1^{pl}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens			1	1	2		
	No. Lots			1	1	1		
	Approval Class			Screening	Screening	Screening		
	Mean	116	158	90	42	175	200	
	Minimum	115	151			147	187	
	Maximum	116	164			187	212	
	C.V.(%)							
	B-value							
$F_1^{ty0.02}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	2	2	1	1	4	2	
	No. Lots	1	1	1	1	1	1	
	Approval Class	Screening	Screening	Screening	Screening	Screening	Screening	
	Mean							
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_1^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens							
	No. Lots							
	Approval Class							

(1) Also contains data from 32-ply material.

Table 3.8.2.1(e)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 2-axis
$[90]_8$
75, 800
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.06-0.12 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	75	75	800	800		
Environment		Air	Air	Air	Air	Air		
Fiber Volume (%)		15	35	41	35	35		
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$		
	Mean	96	61	28	41	42		
	Minimum		59	23				
	Maximum		62	33				
	C.V.(%)							
	B-value							
F_2^{tu}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	2	2	1	1		
	No. Lots	1	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening	Screening		
	Mean	18	18	18	17	17		
	Minimum		17	18				
	Maximum		19	18				
E_2^t	C.V.(%)							
(Msi)	No. Specimens	1	2	2	1	1		
	No. Lots	1	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening	Screening		
	Mean		0.18					
ν_{21}^t	No. Specimens		2					
	No. Lots		1					
	Approval Class		Screening					
	Mean	1.91	1.41	0.16	0.99	0.71		
	Minimum		1.38	0.12				
	Maximum		1.43	0.19				
	C.V.(%)							
	B-value							
ε_2^{tu}	Distribution							
(%)	C_1							
	C_2							
	No. Specimens	1	2	2	1	1		
	No. Lots	1	1	1	1	1		
	Approval Class	Screening	Screening	Screening	Screening	Screening		

Table 3.8.2.1(f)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, 2-axis
$[90]_8$
75, 800
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 15-41 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.06-0.12 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	75	75	800	800		
Environment		Air	Air	Air	Air	Air		
Fiber Volume (%)		15	35	41	35	35		
Strain Rate (1/s)		$1\cdot10^{-4}$	$1\cdot10^{-4}$	$1\cdot10^{-4}$	$1\cdot10^{-5}$	$1\cdot10^{-4}$		
	Mean	42	16		15	16		
	Minimum		15					
	Maximum		17					
	C.V.(%)							
	B-value							
F_1^{pl}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	2	2		1	1		
	No. Lots	1	1		1	1		
	Approval Class	Screening	Screening		Screening	Screening		
	Mean	44	39		22	25		
	Minimum		38					
	Maximum		40					
	C.V.(%)							
	B-value							
$F_2^{ty0.02}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	2		1	1		
	No. Lots	1	1		1	1		
	Approval Class	Screening	Screening		Screening	Screening		
	Mean	75	49.5		30	34		
	Minimum		49					
	Maximum		50					
	C.V.(%)							
	B-value							
$F_2^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	2		1	1		
	No. Lots	1	1		1	1		
	Approval Class	Screening	Screening		Screening	Screening		

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM/diamond grind

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Table 3.8.2.1(g)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-30]_{2s}$ (1)
75, 800
Screening

Temperature (°F)		75	800					
Environment		Air	Air					
Fiber Volume (%)		35	35					
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-3}$					
	Mean	148	134					
	Minimum	133						
	Maximum	179						
	C.V.(%)	8.16						
	B-value	(2)						
F_x^{tu}	Distribution	ANOVA						
(ksi)	C_1	24.6						
	C_2	19.8						
	No. Specimens	10	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					
	Mean	22.2	20					
	Minimum	20.0						
	Maximum	24.0						
E_x^t	C.V.(%)	5.64						
(Msi)	No. Specimens	11	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					
	Mean							
ν_{xy}^t	No. Specimens							
	No. Lots							
	Approval Class							
	Mean	1.24	1.52					
	Minimum	0.99						
	Maximum	1.66						
	C.V.(%)	17.0						
	B-value	(2)						
ε_x^{tu}	Distribution	ANOVA						
(%)	C_1	0.35						
	C_2	17.6						
	No. Specimens	9	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					

(1) Also contains data from 32-ply material.
(2) B-basis values appear for fully-approved data only.

Table 3.8.2.1(h)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-30]_{2s}$ (1)
75, 800
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM/diamond grind

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	800					
Environment		Air	Air					
Fiber Volume (%)		35	35					
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-3}$					
	Mean	55.3	40					
	Minimum	33						
	Maximum	67						
	C.V.(%)	19.1						
	B-value	(2)						
F_1^{pl}	Distribution	Weibull						
(ksi)	C_1	59.3						
	C_2	7.3						
	No. Specimens	11	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					
	Mean	69.1	50					
	Minimum	26						
	Maximum	97						
	C.V.(%)	25.7						
	B-value	(2)						
$F_x^{ty0.02}$	Distribution	Weibull						
(ksi)	C_1	75.1						
	C_2	5.0						
	No. Specimens	11	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					
	Mean	112	86					
	Minimum	91						
	Maximum	146						
	C.V.(%)	12.8						
	B-value	(2)						
$F_x^{ty0.2}$	Distribution	Normal						
(ksi)	C_1	112						
	C_2	14.3						
	No. Specimens	11	1					
	No. Lots	2	1					
	Approval Class	Screening	Screening					

(1) Also contains data from 32-ply material.
(2) B-basis values appear for fully-approved data only.

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Table 3.8.2.1(i)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-45]_{2s}$
75, 800
Screening

Temperature (°F)		75	800	800				
Environment		Air	Air	Air				
Fiber Volume (%)		35	35	35				
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$				
	Mean	77	64	68				
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
F_x^{tu}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				
	Mean	17	17	13				
	Minimum							
	Maximum							
E_x^t	C.V.(%)							
(Msi)	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				
	Mean							
ν_{xy}^t	No. Specimens							
	No. Lots							
	Approval Class							
	Mean	>4	>4.6	7.29				
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
ε_x^{tu}	Distribution							
(%)	C_1							
	C_2							
	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				

Table 3.8.2.1(j)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-45]_{2s}$
75, 800
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	800	800				
Environment		Air	Air	Air				
Fiber Volume (%)		35	35	35				
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-4}$				
	Mean	30	28	21				
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
F_1^{pl}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				
	Mean	40	30	35				
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_x^{ty0.02}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				
	Mean	52	29	47				
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_x^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1	1				
	No. Lots	1	1	1				
	Approval Class	Screening	Screening	Screening				

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Table 3.8.2.1(k)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-60]_{2s}$
75, 800
Screening

Temperature (°F)		75	800					
Environment		Air	Air					
Fiber Volume (%)		35	35					
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$					
	Mean	57	48					
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
F_x^{tu}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					
	Mean	17	14					
	Minimum							
	Maximum							
E_x^t	C.V.(%)							
(Msi)	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					
	Mean							
ν_{xy}^t	No. Specimens							
	No. Lots							
	Approval Class							
	Mean	1.8	2.95					
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
ε_x^{tu}	Distribution							
(%)	C_1							
	C_2							
	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					

Table 3.8.2.1(l)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
$[+/-60]_{2s}$
75, 800
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75	800					
Environment		Air	Air					
Fiber Volume (%)		35	35					
Strain Rate (1/s)		$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$					
	Mean	36	26					
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
F_1^{pl}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					
	Mean	41	28					
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_x^{ty0.02}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					
	Mean	50	35					
	Minimum							
	Maximum							
	C.V.(%)							
	B-value							
$F_x^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	1	1					
	No. Lots	1	1					
	Approval Class	Screening	Screening					

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Table 3.8.2.1(m)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
[0/90]$_{s}$[(1)]
75
Screening

Temperature (°F)		75						
Environment		Air						
Fiber Volume (%)		35						
Strain Rate (1/s)		$1 \cdot 10^{-4}$						
	Mean	148						
	Minimum	143						
	Maximum	154						
	C.V.(%)							
	B-value							
F_x^{tu}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						
	Mean	21						
	Minimum	15						
	Maximum	25						
E_x^t	C.V.(%)							
(Msi)	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						
	Mean	0.18						
ν_{xy}^t	No. Specimens	2						
	No. Lots	1						
	Approval Class	Screening						
	Mean	1.09						
	Minimum	1						
	Maximum	1.21						
	C.V.(%)							
	B-value							
ε_x^{tu}	Distribution							
(%)	C_1							
	C_2							
	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						

(1) Combined data from $[0/90]_{2s}$ and $[90/0]_{2s}$.

Table 3.8.2.1(n)
SiC/Ti Foil/fiber/foil
SCS-6/Ti-15-3
Tension, x-axis
[0/90](1)
75
Screening

MATERIAL: SCS-6/Ti-15V-3Cr-3Al-3Sn foil/fiber/foil

MACHINING: EDM

FIBER VOLUME: 35 %
FIBER SPACING: --

SPECIMEN THICKNESS: 0.08 in.

MODULUS CALCULATION: Least squares analysis up to proportional limit

TEST METHOD: Sec. 1.4.2.1

PRE-TEST EXPOSURE: Vac. 1292°F, 24 hrs.

SOURCE: NASA LeRC

NORMALIZED BY: Not normalized

Temperature (°F)		75						
Environment		Air						
Fiber Volume (%)		35						
Strain Rate (1/s)		$1 \cdot 10^{-4}$						
	Mean	33						
	Minimum	23						
	Maximum	47						
	C.V.(%)							
	B-value							
F_1^{pl}	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						
	Mean	58.8						
	Minimum	37						
	Maximum	80						
	C.V.(%)							
	B-value							
$F_x^{ty0.02}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						
	Mean	126						
	Minimum	115						
	Maximum	136						
	C.V.(%)							
	B-value							
$F_x^{ty0.2}$	Distribution							
(ksi)	C_1							
	C_2							
	No. Specimens	4						
	No. Lots	1						
	Approval Class	Screening						

(1) Combined data from $[0/90]_{2s}$ and $[90/0]_{2s}$.

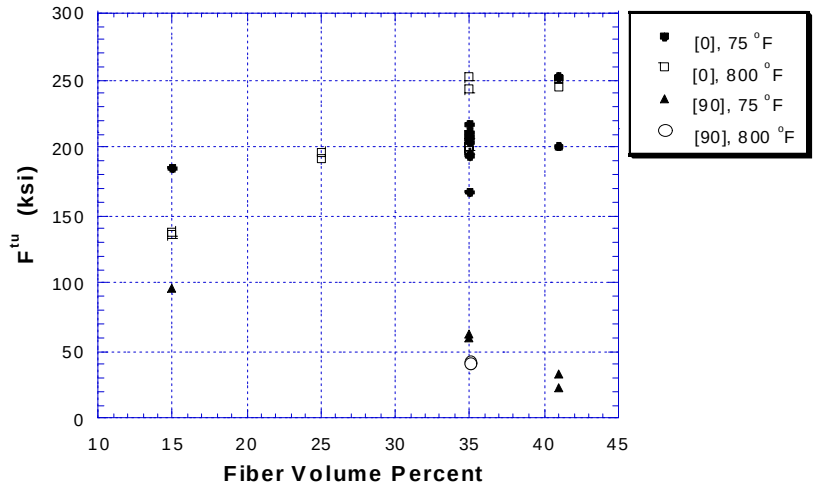

FIGURE 3.8.2.1(a) *Ultimate tensile strength as a function of fiber volume and temperature.*

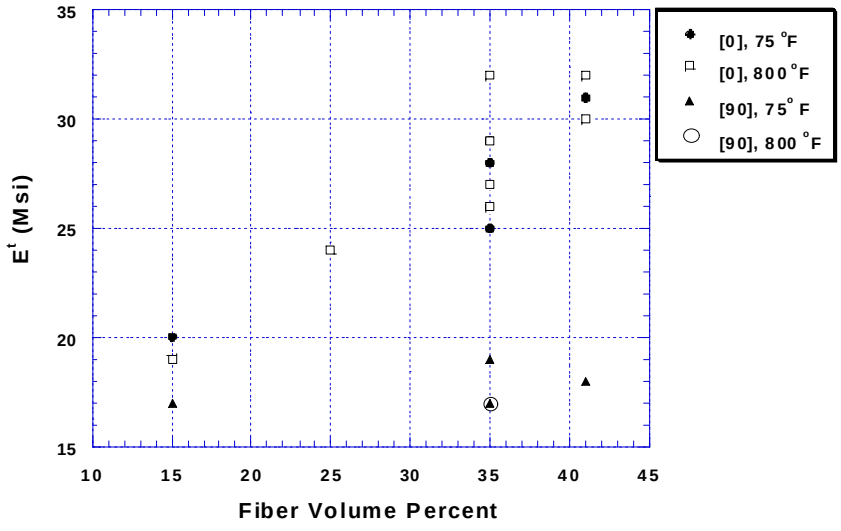

FIGURE 3.8.2.1(b) *Tensile modulus as a function of fiber volume and temperature.*

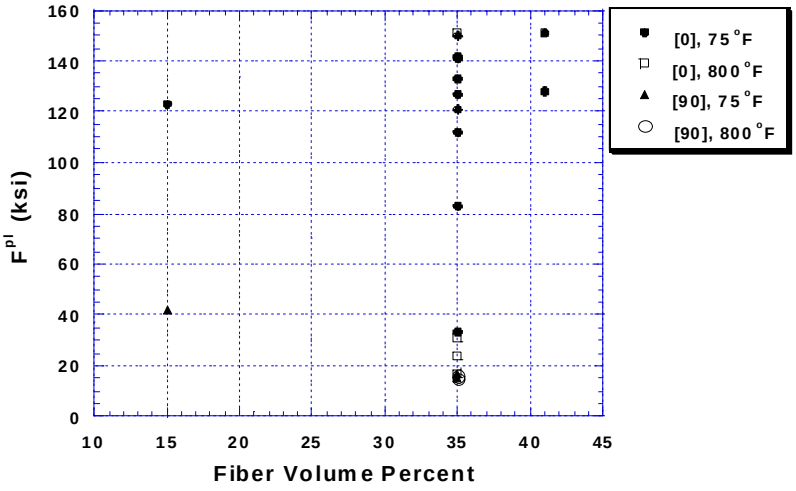

FIGURE 3.8.2.1(c) *Proportional limit as a function of fiber volume and temperature.*

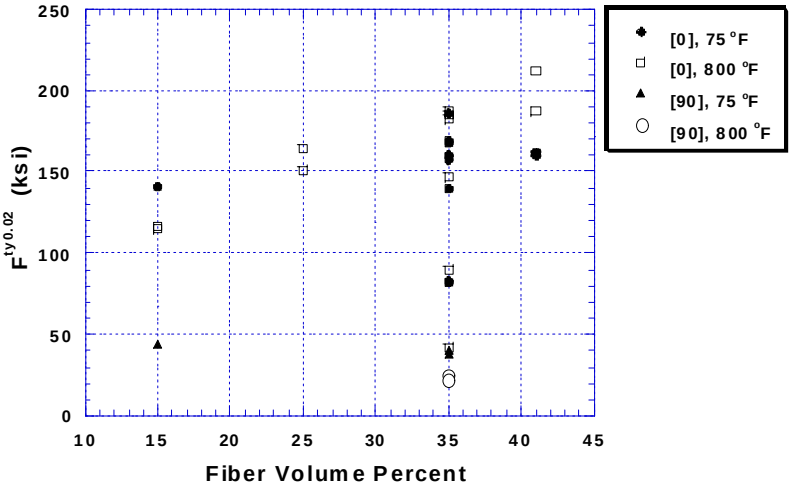

FIGURE 3.8.2.1(d) *0.02-offset-strength as a function of fiber volume and temperature.*

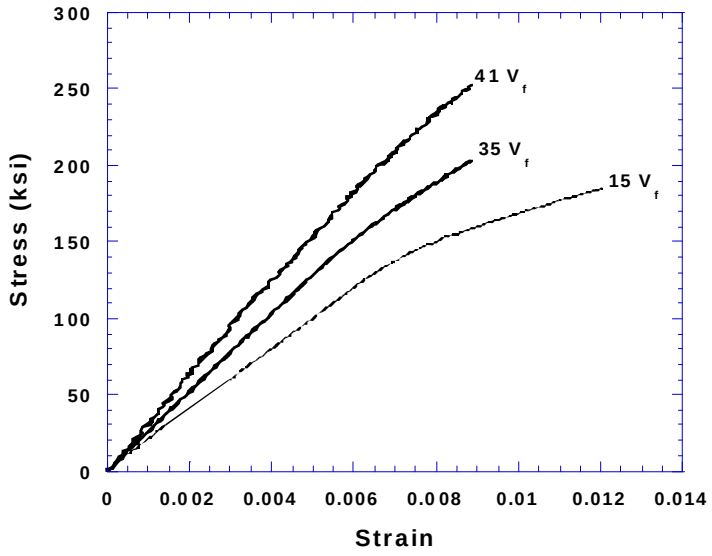

FIGURE 3.8.2.1(e) *Typical tensile behavior of $[0]_8$ laminae at 75°F (24°C) as a function of fiber volume percent (V_f) at a strain rate of $1*10^{-4}s^{-1}$.*

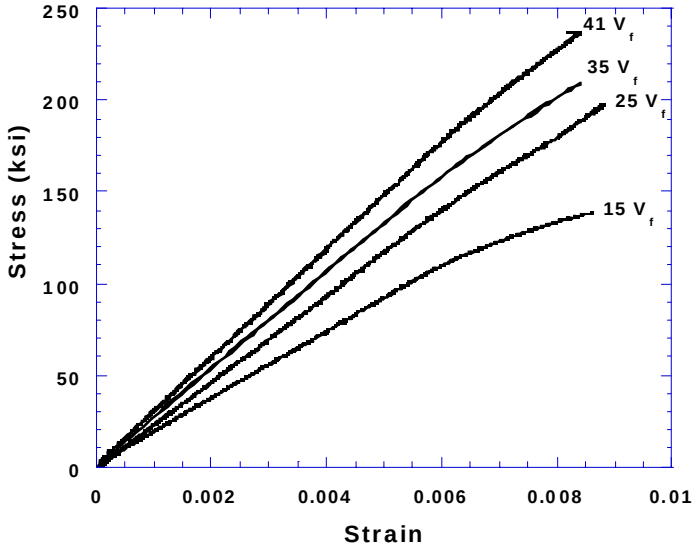

FIGURE 3.8.2.1(f) *Typical tensile behavior of $[0]_8$ laminae at 800°F (427°C) as a function of fiber volume percent (V_f) at a strain rate of $1*10^{-3}s^{-1}$.*

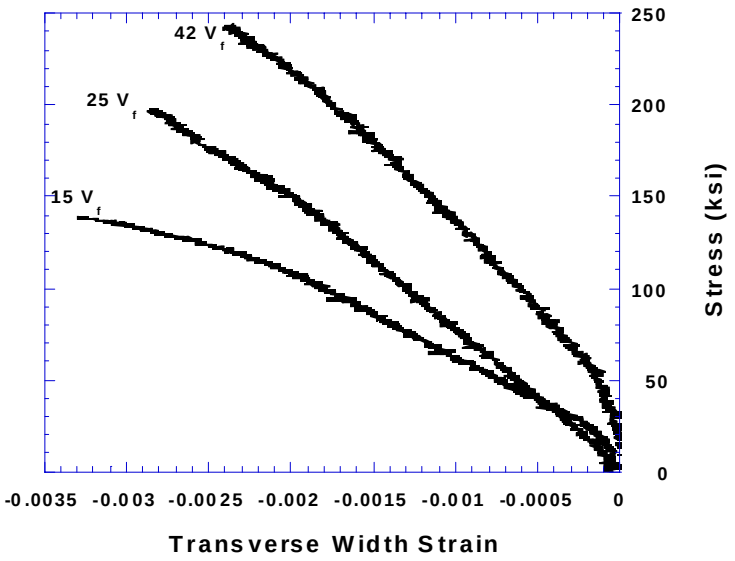

FIGURE 3.8.2.1(g) *Typical tensile behavior of $[0]_8$ laminae at 800°F (427°C) as a function of fiber volume percent (V_f) at a strain rate of $1*10^{-3}s^{-1}$.*

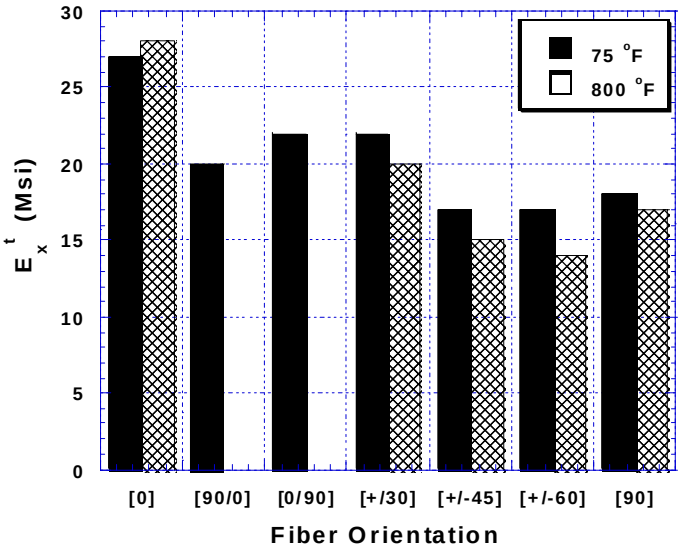

FIGURE 3.8.2.1(h) *Average tensile modulus as a function of fiber orientation and temperature tested at strain rates of $1*10^{-3}$ and $1*10^{-4}$ s^{-1}.*

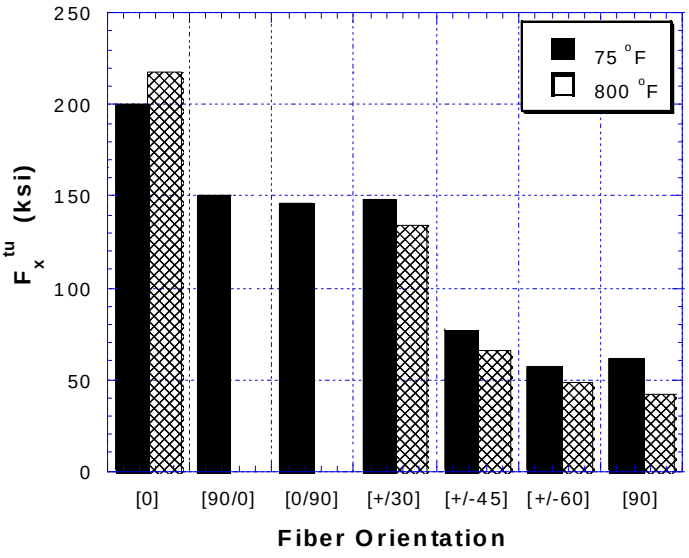

FIGURE 3.8.2.1(i) *Average tensile strength as a function of fiber orientation and temperature tested at strain rates of $1*10^{-3}$ and $1*10^{-4}$ s^{-1}.*

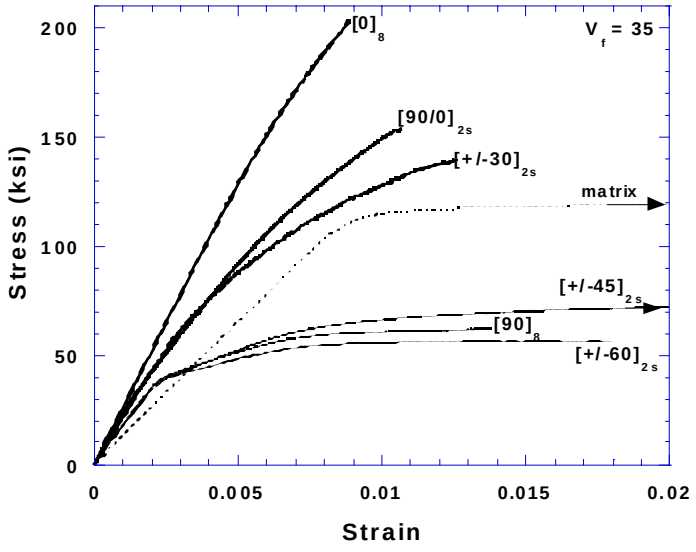

FIGURE 3.8.2.1(j) *Typical tensile behavior of SiC/Ti-15-3 at 75°F (24°C) as a function of fiber orientation (V_f = 35) at a strain rate of $1*10^{-4}$ s^{-1}.*

3.8.3 ALUMINA/TITANIUM

3.8.4 OTHER/TITANIUM

3.9 OTHER MATRIX COMPOSITES

APPENDIX A

TYPICAL PUSHOUT TEST DATA

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A1. Fiber pushout..... 152

A1. FIBER PUSHOUT

TABLE A1(a) *Debond load vs. specimen thickness for SCS-6/Ti-24-11 (Section 1.4.2.13.1).*

Specimen thickness (mm)	Debond load (N)
.149	4.56
.211	6.06
.312	15.6
.322	14.3
.343	15.8
.382	19.6
.414	18.8
.452	21.8
.483	26.8
.534	31.8
.569	45.3

TABLE A1(b) *Typical failure loads for various diameter WC punches (Section 1.4.2.13.1).*

Punch Dia. (mm)	Failure Load (N)
25	2
50	5
75	20
100	40
115	50-55
127	60-70

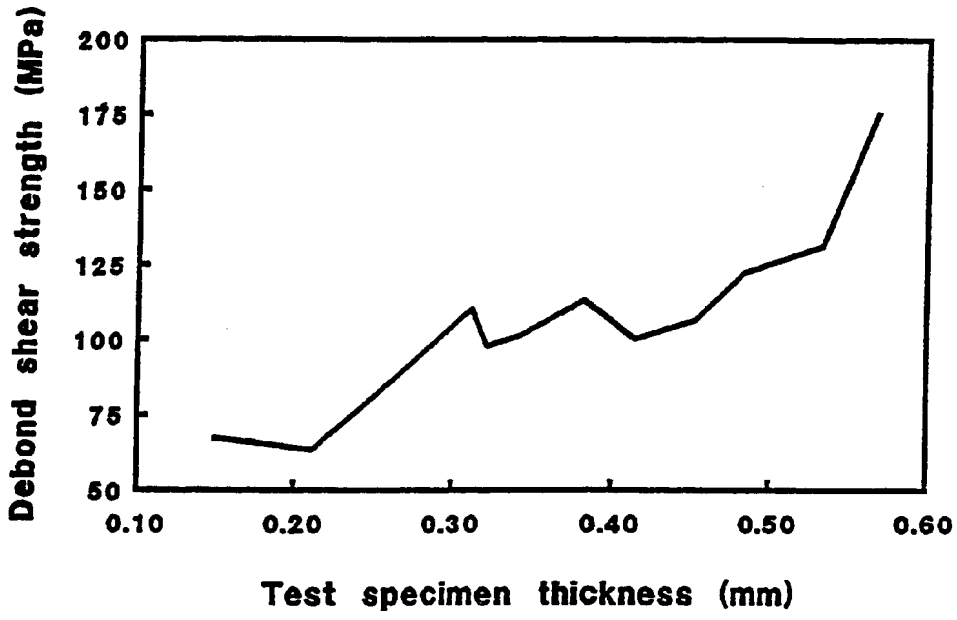

FIGURE A1(a) *The effect of specimen thickness on the observed debond strength of SCS-6/Ti24-11 composite system (Section 1.4.2.13.11).*

PUSHOUT TEST DATA SHEET

SAMPLE ID:

MATERIAL:

SPECIMEN THICKNESS:

COMMENTS:

FIBER NUMBER	DEBOND LOAD	FRICTION LOAD	A.E.

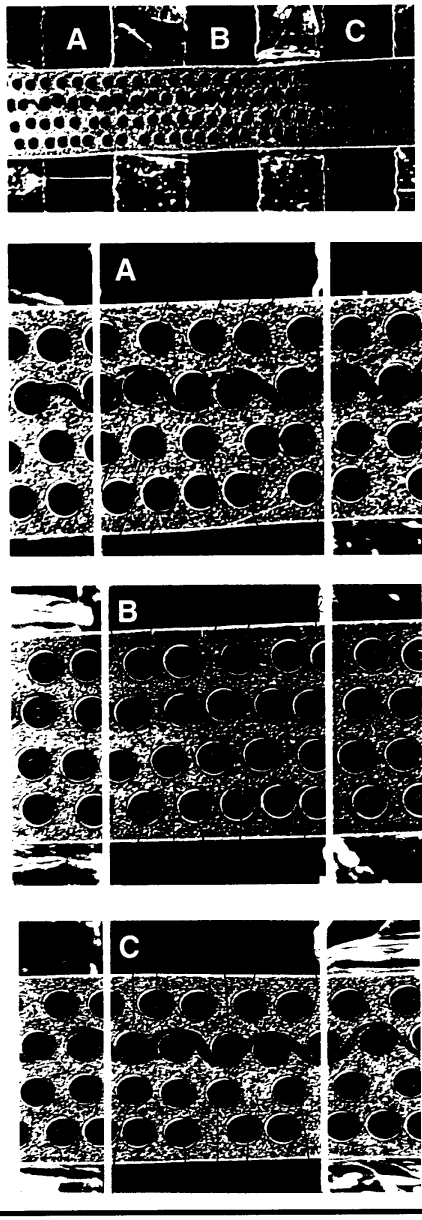

FIGURE A1(b) *Pushout test data sheet (Section 1.4.2.13.14).*

APPENDIX B

RAW DATA TABLES FOR MATRIX MATERIALS

PARAGRAPH PAGE

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B3. MAGNESIUMS 156

B4. TITANIUMS 156

B4.1 TI 15V 3CR 3AL-3SN (SECTION 3.3.5.1) 157

APPENDIX B

B1.ALUMINUMS

B2.COPPERS

B3.MAGNESIUMS

B4.TITANIUMS

B4.1 TI 15V 3CR 3AL-3SN (SECTION 3.3.5.1)

MATERIAL: Ti-15-3

NEAT MATRIX: Ti-15V-3Cr-3Al-3Sn
HEAT TREATMENT: 1292°F/24h (vac.)
TEST METHOD: Section 1.9.2.1

Table B4.1(a)
Ti-15-3
Tension
NASA LeRC
Raw Data

Specimen No.	Lot I.D. (Plate)	Test Temp	Strain Rate	E^t (1)	F^{pl}	$F^{ty0.02}$	$F^{ty0.2}$	F^{tu}	ε^{tu}	RA	Product Form	Test Environment	ν^m
		(°F)	(1/s)	(Msi)	(ksi)	(ksi)	(ksi)	(ksi)	(%)	(%)			
T36	B934021	800	1x10-6	10.8	20	29	43	-	>3	-	HIP Sheet	air	-
T42	B934021	800	1x10-4	11.3	59	73	84	-	>3.8	-	HIP Sheet	air	-
T33	B934021	800	1x10-8	17	5.2	40	-	-	>1	-	HIP Sheet	air	-
T27	B934021	900	1x10-4	10.9	50	65	75	-	>8	-	HIP Sheet	air	-
T45	B934021	600	1x10-4	11.4	69	78	87	-	>8	-	HIP Sheet	air	-
T40	B934021	400	1x10-4	12.6	65	84	96	-	>8	-	HIP Sheet	air	-
T37	B934021	75	1x10-4	13	94	108	117	-	>8	-	HIP Sheet	air	-
7_1	B934027	1000	1x10-4	10.5	23	33	42	43	>8	-	HIP Sheet	air	-
7_22	B934027	900	1x10-4	10.7	57	65	74	75	>8	-	HIP Sheet	air	-
7_15	B934027	1000	1x10-6	5.3	6	6	8	24	>8	-	HIP Sheet	air	-
7_ex	B934027	400	1x10-6	12	80	85	96	-	>8	-	HIP Sheet	air	-
7_6	B934027	400	1x10-3	12.3	81	87	95	-	>8	-	HIP Sheet	air	-
7_18	B934027	1000	1x10-3	11	50	60	67	67	>8	-	HIP Sheet	air	-
B8	B934027	800	1x10-5	10.8	56	69	83	-	>4	-	HIP Sheet	air	-
V700-1	87H?	75	2x10-3	13	111	117	124	127	20.2	-	HIP Foil	air	-
16211_B	B934027	75	8.3x10-5	12.4	-	-	114	124	20.7	37.8	HIP Sheet	5 ksi Helium	-
16210_A	B934027	75	8.3x10-5	11.9	-	-	110	120	20.3	40.3	HIP Sheet	5 ksi Helium	-
16215_F	B934027	75	8.3x10-5	12.1	-	-	112	122	22.1	39.5	HIP Sheet	5 ksi Helium	-
16212_C	B934027	75	8.3x10-5	12	-	-	116	125	16.8	22	HIP Sheet	5 ksi Hydrogen	-
16213_D	B934027	75	8.3x10-5	12.5	-	-	114	125	17.2	27.1	HIP Sheet	5 ksi Hydrogen	-
16214_E	B934027	75	8.3x10-5	12.3	-	-	114	124	17.5	27.6	HIP Sheet	5 ksi Hydrogen	-

1) Modulus was determined by least squares analysis up to the proportional limit

MATERIAL: Ti-15-3

NEAT MATRIX: Ti-15V-3Cr-3Al-3Sn
HEAT TREATMENT: 1292°F/24h (vac.)
TEST METHOD: Section 1.9.2.1

Table B4.1(a) (cont.)
Ti-15-3
Tension
NASA LeRC
Raw Data

Specimen No.	Machining Method	Specimen Geometry	Specimen Dimensions	Surface Condition	Test Date	Failure Location	Failure Mode
T36	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	5/2/96	interrupted	-
T42	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	5/3/96	interrupted	-
T33	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	5/6/96	interrupted	-
T27	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	11/13/96	interrupted	-
T45	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	11/14/96	interrupted	-
T40	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	11/14/96	interrupted	-
T37	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	11/14/96	interrupted	-
7_1	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	2/6/97	interrupted	-
7_22	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	2/6/97	interrupted	-
7_15	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	3/22/97	interrupted	-
7_ex	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	3/23/97	interrupted	-
7_6	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	4/11/97	interrupted	-
7_18	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	4/11/97	interrupted	-
B8	turned and ground	Dogbone	.25" dia. x .5" gage	as-ground	7/31/97	interrupted	-
V700-1	turned and ground	Dogbone	.125" dia. x .815" gage	as-ground	3/5/88	gage	ductile failure
16211_B	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/2/97	gage	ductile failure
16210_A	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/2/97	gage	ductile failure
16215_F	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/3/97	gage	ductile failure
16212_C	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/3/97	gage	ductile failure
16213_D	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/3/97	gage	ductile failure
16214_E	turned and ground	Dogbone	.188" dia. x .75" gage	as-ground	7/3/97	gage	ductile failure

APPENDIX C

RAW DATA TABLES FOR TITANIUM MATRIX COMPOSITES

PARAGRAPH PAGE

C1. SiC/Ti-15-3 (SECTION 3.8.2.1) 160

C1. SIC/TI-15-3 (SECTION 3.8.2.1)

MATERIAL: SiC/Ti-15-3

FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air
PRODUCT DIMENSIONS:	10” x 14”		
LAY-UP:	Unidirectional		
PLY COUNT:	8-ply		

Table C1(a)
SiC/Ti-15-3
Tension
[0]
NASA LeRC
Raw Data

Fiber v/o	Specimen No	Lot I.D. (Plate)	Test Temp. (°F)	Strain Rate (1/s)	E_1^t (Msi)	F_1^{pl} (ksi)	$F_1^{ty0.02}$ (ksi)	$F_1^{ty0.2}$ (ksi)	F_1^{tu} (ksi)	ε_1^{tu} (%)	ν_{12}^t	Comments
15	L1_15	F914005	75	1x10-4	20	123	141	172	185	1.21	-	Mo-weave
15	15_1	F914007	800	1x10-3	19	-	116	-	138	0.86	0.39	Mo-weave
15	15-2	F914007	800	1x10-3	19	-	115	-	136	0.75	0.37	Mo-weave
25	25-1	B934026	800	1x10-3	24	-	164	-	197	0.88	0.32	Ti-Nb weave
25	25-2	B934026	800	1x10-3	24	-	151	-	192	0.91	0.31	Ti-Nb weave
35	29	87H153	800	1x10-4	32	17	42	-	200	0.77	-	Ti-weave
35	30	87H153	800	1x10-3	26	31	147	-	201	0.89	-	Ti-weave
35	4	87H153	75	1x10-4	25	121	160	-	196	0.84	-	Ti-weave (1)
35	2	87H153	75	1x10-4	26	133	168	-	168	0.66	-	Ti-weave (1)
35	5	87H153	75	1x10-4	37	142	140	-	194	0.67	-	Ti-weave
35	6	87H153	75	1x10-4	28	33	82	-	194	0.85	-	Ti-weave
35	7	87H153	75	1x10-4	26	83	83	-	206	1	-	Ti-weave
35	8	87H153	75	1x10-4	26	127	157	-	204	0.89	-	Ti-weave
35	9	87H153	75	1x10-4	28	112	160	-	217	0.88	-	Ti-weave
35	33	87H153	800	1x10-5	29	24	90	-	198	0.82	-	Ti-weave
35	27	87H153	75	1x10-4	25	141	169	-	208	0.96	0.28	Ti-weave
35	53	D890054	75	1x10-4	29	150	186	-	211	0.77	-	Mo-weave
35	5_36	J890505	800	1x10-3	27	151	185	-	209	0.84	-	Mo-weave (2)
35	35-8	B934025	800	1x10-3	29	-	187	-	252	1	-	Ti-Nb weave
35	35-10	B934025	800	1x10-3	26	-	182	-	243	1.06	-	Ti-Nb weave
41	L1-45	D910518	75	1x10-4	31	151	160	-	201	0.73	-	Mo-weave
41	L4	D910518	75	1x10-4	31	128	192	-	252	0.9	-	Mo-weave
41	42-1	D910519	800	1x10-3	30	-	212	-	245	0.84	0.31	Mo-weave
41	42-2	D910519	800	1x10-3	32	-	187	-	251	0.83	0.28	Mo-weave

(1) Straight sided specimen
(2) 32 ply material

MATERIAL: SiC/Ti-15-3

Table C1(a) (cont.)
SiC/Ti-15-3
Tension
[0]
NASA LeRC
Raw Data

FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air
PRODUCT DIMENSIONS:	10” x 14”		
LAY-UP:	Unidirectional		
PLY COUNT:	8-ply		

Specimen No.	Machining Method	Specimen Geometry	Specimen Dimensions	Surface Condition	Test Date	Failure Location	Failure Mode
L1_15	EDM	Dogbone	0.5x6.0x0.12"	as-machined	9/25/92	Radius	-
15_1	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.12"	as-machined	10/2/96	Outside gage	-
15-2	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.10"	as-machined	10/2/96	mid-gage	-
25-1	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.10"	as-machined	10/2/96	mid-gage	-
25-2	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.10"	as-machined	8/21/89	gage	-
29	EDM	Dogbone	0.5x5.5x0.08"	as-machined	8/21/89	gage	-
30	EDM	Dogbone	0.5x5.5x0.08"	as-machined	8/9/88	mid-gage	-
4	EDM	Rectangular	0.5x4.0x0.08"	as-machined	6/29/88	mid-gage	-
2	EDM	Rectangular	0.5x4.0x0.08"	as-machined	6/29/88	grips	-
5	EDM	Dogbone	0.5x4.0x0.08"	as-machined	11/16/88	radius	-
6	EDM	Dogbone	0.5x4.0x0.08"	as-machined	7/8/88	radius	-
7	EDM	Dogbone	0.5x4.0x0.08"	as-machined	8/22/88	radius	-
8	EDM	Dogbone	0.5x4.0x0.08"	as-machined	6/30/88	gage	-
9	EDM	Dogbone	0.5x4.0x0.08"	as-machined	7/7/88	mid-gage	-
33	EDM	Dogbone	0.5x5.5x0.08"	as-machined	8/21/89	gage	-
27	EDM	Dogbone	0.5x5.5x0.08"	as-machined	10/17/89	gage	-
53	EDM	Dogbone	0.5x5.5x0.07"	as-machined	9/10/90	radius	-
5_36	EDM + Diamond Grind	Dogbone	0.5x6.0x0.3"	as-machined	5/23/95	radius	-
35-8	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.07"	as-machined	5/21/96	radius	-
35-10	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.07"	as-machined	7/2/96	radius	-
L1-45	EDM	Dogbone	0.5x6.0x0.06"	as-machined	9/25/92	outside gage	-
L4	EDM	Dogbone	0.5x6.0x0.06"	as-machined	10/14/92	mid-gage	-
42-1	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.06"	as-machined	10/2/96	radius	-
42-2	Water Jet + Diamond Grind	Dogbone	0.5x6.0x0.06"	as-machined	10/2/96	gage	-

MATERIAL: SiC/Ti-15-3				Table C1(b) SiC/Ti-15-3 Tension [90] NASA LeRC Raw Data
FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension	
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)	
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air	
PRODUCT DIMENSIONS:	10” x 14”			
LAY-UP:	Unidirectional			
PLY COUNT:	8-ply			

Fiber v/o	Specimen No	Lot I.D. (Plate)	Test Temp.	Strain Rate	E_2^t	F_2^{pl}	$F_2^{ty0.02}$	$F_2^{ty0.2}$	F_2^{tu}	ε_2^{tu}	ν_{21}^t	Comments
			(°F)	(1/s)	(Msi)	(ksi)	(ksi)	(ksi)	(ksi)	(%)		
15	T2_15	F914005	75	1x10-4	17	42	44	75	96	1.91	-	Mo-weave
35	41	87H153	75	1x10-4	19	17	38	49	59	1.43	0.17	Ti-weave
35	42	87H153	75	1x10-4	17	15	40	50	62	1.38	0.18	Ti-weave
35	43	87H153	800	1x10-4	17	16	25	34	42	0.71	-	Ti-weave
35	44	87H153	800	1x10-5	17	15	22	30	41	0.99	-	Ti-weave
41	T1_45	D910518	75	1x10-4	18	-	-	-	23	0.12	-	Mo-weave (1)
41	T2_45	D910518	75	1x10-4	18	-	-	-	33	0.19	-	Mo-weave

(1) Broke in elastic regime

MATERIAL: SiC/Ti-15-3

Table C1(b) (cont.)
SiC/Ti-15-3
Tension
[90]
NASA LeRC
Raw Data

FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air
PRODUCT DIMENSIONS:	10” x 14”		
LAY-UP:	Unidirectional		
PLY COUNT:	8-ply		

Specimen No.	Machining Method	Specimen Geometry	Specimen Dimensions	Surface Condition	Test Date	Failure Location	Failure Mode
T2_15	EDM	Dogbone	0.5x6.0x0.12"	as-machined	9/25/92	outside gage	-
41	EDM	Dogbone	0.5x5.5x0.08"	as-machined	10/19/89	gage	-
42	EDM	Dogbone	0.5x5.5x0.08"	as-machined	10/27/89	gage	-
43	EDM	Dogbone	0.5x5.5x0.08"	as-machined	8/22/89	gage	-
44	EDM	Dogbone	0.5x5.5x0.08"	as-machined	8/23/89	gage	-
T1_45	EDM	Dogbone	0.5x5.5x0.06"	as-machined	9/25/92	gage	-
T2_45	EDM	Dogbone	0.5x5.5x0.06"	as-machined	9/25/92	radius	-

MATERIAL: SiC/Ti-15-3

Table C1(c)
SiC/Ti-15-3
Tension
Laminates
NASA LeRC
Raw Data

FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air
PRODUCT DIMENSIONS:	10” x 14”		
LAY-UP:	Cross-ply laminates		
PLY COUNT:	8-ply		
FIBER VOLUME PERCENT:	35		

Fiber v/o	Specimen No	Lot I.D. (Plate)	Test Temp.	Strain Rate	E_x^t	F_x^{pl}	$F_x^{ty0.02}$	$F_x^{ty0.2}$	F_x^{tu}	ε_x^{tu}	ν_{xy}^t	Comments
			(°F)	(1/s)	(Msi)	(ksi)	(ksi)	(ksi)	(ksi)	(%)		
+/- 30	H3	D890053	75	1x10-4	23	44	60	105	-	-	-	Mo-weave (1)
+/- 30	H16	D890053	75	1x10-4	23	48	60	108	179	1.66	-	Mo-weave
+/- 30	26	87H149	75	1x10-4	24	58	74	114	148	1.14	-	Ti-weave
+/- 30	25	87H149	75	1x10-4	21	62	73	114	145	1.11	-	Ti-weave
+/- 30	24	87H149	75	1x10-4	22	67	75	112	144	>1.5	-	Ti-weave (2)
+/- 30	23	87H149	75	1x10-4	24	48	71	115	145	0.99	-	Ti-weave
+/- 30	22	87H149	75	1x10-4	20	65	97	146	147	1.04	-	Ti-weave
+/- 30	19	87H149	75	1x10-4	22	61	79	121	153	1.2	-	Ti-weave
+/- 30	18	87H149	75	1x10-4	21	33	26	95	133	1.44	-	Ti-weave (3)
+/- 30	12	87H149	75	1x10-4	22	59	64	91	146	1.32	-	Ti-weave
+/- 30	11	87H149	75	1x10-4	22	63	81	113	140	1.26	-	Ti-weave
+/- 30	9_23	J890509	800	1x10-3	20	40	50	86	134	1.52	-	Mo-weave (4)
+/- 45	A11	87H148	75	1x10-4	17	30	40	52	77	>4.0	-	Ti-weave (2)
+/- 45	A6	87H148	800	1x10-4	13	21	35	47	68	7.29	-	Ti-weave
+/- 45	A13	87H148	800	1x10-5	17	28	30	29	64	>4.6	-	Ti-weave (2)
+/- 60	F1	87H149	75	1x10-4	17	36	41	50	57	1.8	-	Ti-weave
+/- 60	F4	87H149	800	1x10-4	14	26	28	35	48	2.95	-	Ti-weave
0/90	B2	87H150	75	1x10-4	21	23	37	115	143	1	-	Ti-weave
0/90	B4	87H150	75	1x10-4	23	47	72	136	149	1.08	-	Ti-weave
90/0	C5	87H150	75	1x10-4	15	40	80	135	145	1.21	0.15	Ti-weave
90/0	C4	87H150	75	1x10-4	25	23	46	118	154	1.07	0.21	Ti-weave

(1) Slipped in grips
(2) Test interrupted
(3) Stress discontinuity at yield point
(4) 32 ply material

MATERIAL: SiC/Ti-15-3

Table C1(c) (cont.)
SiC/Ti-15-3
Tension
Laminates
NASA LeRC
Raw Data

FIBER:	SCS-6	TEST METHOD:	Sec. 1.4.2.1 Tension
MATRIX:	Ti-15V-3Cr-3Al-3Sn	PRE-TEST EXPOSURE:	1292°F/24 hrs. (vac.)
PRODUCT FORM:	Foil/fiber/foil	TEST ATMOSPHERE:	Air
PRODUCT DIMENSIONS:	10” x 14”		
LAY-UP:	Cross-ply laminates		
PLY COUNT:	8-ply		
FIBER VOLUME PERCENT:	35		

Specimen No.	Machining Method	Specimen Geometry	Specimen Dimensions	Surface Condition	Test Date	Failure Location	Failure Mode
H3	EDM	Dogbone	0.5x6.0x0.07"	as-machined	9/6/90	-	
H16	EDM	Dogbone	0.5x6.0x0.07"	as-machined	9/7/90	gage	
26	EDM	Rectangular	0.75x6.0x0.08"	as-machined	6/13/89	gage	
25	EDM	Rectangular	0.75x6.0x0.08"	as-machined	6/13/89	gage	
24	EDM	Rectangular	1.0x6.0x0.08"	as-machined	6/13/89	mid-gage	
23	EDM	Rectangular	1.0x6.0x0.08"	as-machined	6/13/89	gage	
22	EDM	Dogbone	0.5x6.0x0.08"	as-machined	12/1/88	gage	
19	EDM	Dogbone	0.5x6.0x0.08"	as-machined	12/1/88	radius	
18	EDM	Dogbone	0.5x4.0x0.08"	as-machined	7/13/88	radius	
12	EDM	Dogbone	0.5x4.0x0.08"	as-machined	8/9/88	grips	
11	EDM	Dogbone	0.5x4.0x0.08"	as-machined	11/15/88	gage	
9_23	EDM + Diamond Grind	Dogbone	0.5x6.0x0.3"	as-machined	11/24/92	mid-gage	
A11	EDM	Dogbone	0.5x6.0x0.08"	as-machined	1/24/90	-	
A6	EDM	Dogbone	0.5x6.0x0.08"	as-machined	3/3/89	radius	
A13	EDM	Dogbone	0.5x6.0x0.08"	as-machined	2/1/90	-	
F1	EDM	Dogbone	0.5x6.0x0.08"	as-machined	1/24/90	gage	
F4	EDM	Dogbone	0.5x6.0x0.08"	as-machined	2/1/90	radius	
B2	EDM	Dogbone	0.5x6.0x0.08"	as-machined	6/7/89	gage	
B4	EDM	Dogbone	0.5x6.0x0.08"	as-machined	4/4/89	gage	
C5	EDM	Dogbone	0.5x6.0x0.08"	as-machined	10/27/89	gage	
C4	EDM	Dogbone	0.5x6.0x0.08"	as-machined	10/19/89	gage	

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