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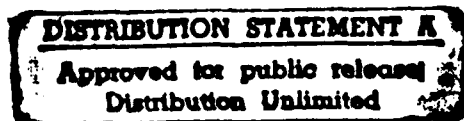
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APPENDIX: MATERIAL PROPERTIES
DATA REVIEW

FINAL REPORT

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This document describes the status and requirements of advanced composite materials which are being considered for Engineering structural applications to U.S. Army Strategic Defense Command (USASDC) advanced material systems. The material examined covers the period from 1975 to mid-1984. In addition to raw material cost projection analysis, the document also presents data on the mechanical, thermal and physical properties of general interest advanced metal matrix and polymer matrix systems. <i>Advanced metal matrix and polymer matrix systems</i>									
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FOREWORD

This two volume document describes the status and requirements of the available and near-term advanced composite materials which are being considered for engineering structural application to the U.S. Army Strategic Defense Command (USASDC) advanced material systems. The scope of the technical material goals examined is restricted to advancements in composite materials with metals and polymer matrices. The cost analysis herein is limited to an estimation of the expected raw material costs in a five-year time period. The material examined covers the period from 1975 to mid-1984. The document also presents data on the mechanical, thermal, and physical properties of general interest advanced metal matrix and polymer matrix composites.

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CHAPTER 1
INTRODUCTION

1.1 Purpose and Scope of Document. This document is Volume II of a two-volume report describing the status and requirements of the advanced composite materials for the U.S. Army Strategic Command (USASDC). It has been prepared to provide material property information for the selection of advanced composite material systems. The information contained in this volume is the result of a thorough search of the Defense Technical Information Center (DTIC) literature, contractor reports, the Metal Matrix Composites Information Analysis Center (MMCIAC), and open literature. This search covers the years 1975 to mid-1984. The objective of Volume II is to present data on the mechanical, thermal, and physical properties of general interest advanced metal matrix and plastic (polymer) systems. Because advanced composite materials are in a state of evolution in terms of property improvements, it is not possible to provide final property values in the same sense as those now available for conventional metal alloys. Thus, this volume is intended to inform the reader in general terms rather than to serve as a standard sourcebook for the advanced composite systems.

1.2 Advanced Composite Material Overview. Composite materials generally consist of a bulk material, called the matrix, and a filler or reinforcement material such as fibers, whiskers, or metal wires. The composite materials are usually divided into three broad groups identified by their matrix materials: metal, plastic (polymer), or ceramic. The reinforcement materials or agents consist of high-strength materials in continuous fibers, whiskers, particulates, or fabric form. These reinforcement materials usually carry the major stresses and loads, while the matrix material holds the reinforcement materials together. Figure 1.2-1 shows schematically how a composite material is selected and created. Because of the superior mechanical and physical properties of composite materials, they are attractive for advanced structural and nonstructural applications.

Metal matrix composite (MMC) technology began in the late 1950's and is still in the early stages of development. Many different combinations

of matrices and reinforcements have been investigated and more seem imminent. There are four major categories of composite reinforcements: continuous fibers, whiskers, particulates, and wires or fabric. Table 1.2-1 presents the variety and complexity of different types of reinforcement materials.

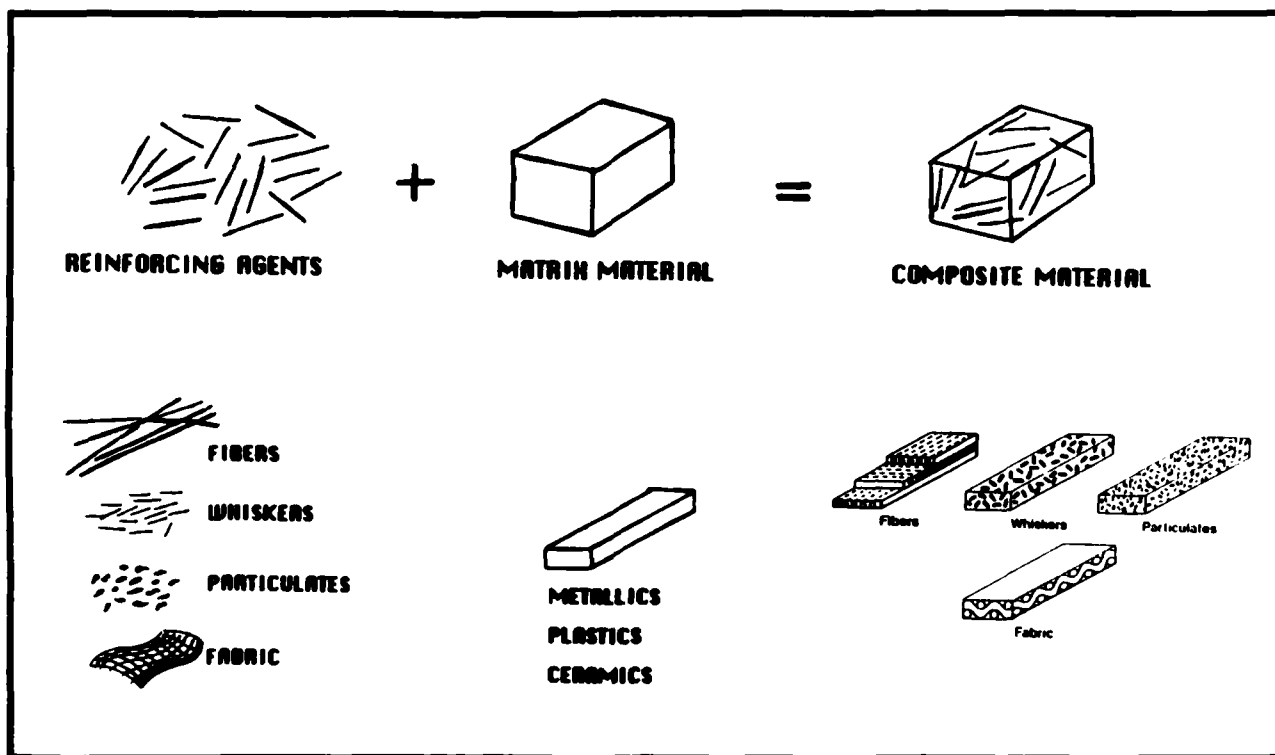


Figure 1.2-1 Composite Material Overview

TABLE 1.2-1. Variety of and Complexity of Different
Types of Reinforcement Materials for
Composite Materials

REINFORCING AGENTS	
<u>CONTINUOUS FIBERS</u> BORON (B) GRAPHITE (C) ALUMINA (Al_2O_3) SILICON CARBIDE (SiC) BORON CARBIDE (B_4C) BORON NITRIDE (BN) SILICA (SiO_2) TITANIUM DIBORIDE (TiB_2) ALUMINA-BORIA-SILICA ("NEXTEL") <u>WHISKERS</u> OVER 100 MATERIALS PRODUCED METAL REINFORCEMENTS IRON (Fe) NICKEL (Ni) COPPER (Cu) NICKEL ALUMINIDE ($NiAl_3$) ALUMINUM OXIDE-ALUMINA- SAPPHIRE (Al_2O_3) SILICON CARBIDE (SiC) GRAPHITE (C) SILICON NITRIDE (Si_3N_4)	<u>PARTICULATES</u> (including flakes) TUNGSTEN (W) MOLYBDENUM (Mo) CHROMIUM (Cr) SILICON CARBIDE (SiC) BORON CARBIDE (B_4C) TITANIUM CARBIDE (TiC) ALUMINUM DODECABORIDE (AlB_{12}) TUNGSTEN CARBIDE (WC) CHROMIUM CARBIDE (Cr_3C_2) SILICA (SiO_3) ALUMINA (Al_2O_3) MOLYBDENUM DISILICIDE ($MoSi_2$) <u>METAL WIRES</u> TUNGSTEN (W) TITANIUM (Ti) MOLYBDENUM (Mo) BERYLLIUM (Be) STAINLESS STEEL NIOBIUM-TIN ($NbSn$) - SUPERCONDUCTOR NIOBIUM-TITANIUM ($NbTi$) - SUPERCONDUCTOR

6027-2

Common continuous fibers include boron, graphite, alumina, and silicon carbide. Boron fibers are manufactured by chemical vapor deposition (CVD) onto a tungsten or carbon core. In many applications, a coating of silicon carbide is placed on the boron fibers to avoid reactions with the matrix. Silicon carbide fibers are made in a CVC process similar to that of boron. Continuous alumina fibers have properties that vary significantly from manufacturer to manufacturer. There are two types of graphite fibers, one made from pitch, the other from polyacrylonitrile (PAN). Graphite fibers are available in a wide variety of strengths and moduli.

Metal matrix composites have been tested with many metals, but the most important are aluminum, titanium, magnesium, and copper alloys. Aluminum matrix composites are reinforced with continuous fibers such as boron, silicon carbide, alumina, and graphite; discontinuous fibers such as alumina and alumina-silica; silicon carbide whiskers; or particulates of silicon carbide and boron carbide. Magnesium matrices are reinforced with graphite or alumina fibers, silicon carbide whiskers, and silicon carbide or boron carbide particulates. Titanium systems include reinforcements by coated boron fibers, silicon carbide fibers, and titanium carbide particulates. Copper matrix composites may be reinforced with graphite or silicon carbide fibers; niobium-titanium or niobium-tin wires; or silicon carbide, boron carbide, or titanium carbide particulates.

Table 1.2-2 shows the variety of types of matrix materials for composite materials. Several other composite systems have received lesser interest to date, and research in these systems is proceeding at a slower pace.

This report will review metal matrix and polymer matrix composite systems. The emphasis will be on composite systems that have been tested for structural applications, rather than on composites tested solely for behavior patterns.

TABLE 1.2-2. Variety of Different Types of Matrix Materials
for Composite Materials

MATRIX MATERIALS	
<u>METALLICS</u>	
ALUMINUM	SILVER
MAGNESIUM	ZINC
TITANIUM	BRONZE
COPPER	COBALT
NICKEL	IRON
LEAD	ALL ALLOYS OF ABOVE
<u>PLASTICS</u>	<u>CERAMICS</u>
EPOXIES	ALUMINUM OXIDE
POLYIMIDES	PORCELAIN
POLYSULFONES	PLASTER
POLYSTYRENES	CARBON
DIALLYL PHTHALATE	SILICON NITRIDE
PHENOLICS	
ARAMIDS	
POLYESTERS	
POLYCARBONATE	

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Figure 1.2-2 shows the advanced material selection recommended for the USASDC material program study. Graphite, boron, Kevlar, silicon carbide, and fiberglass are the principal reinforcement materials considered in this document. Although not truly an advanced reinforcement, fiberglass is included because of its broad, extensive use in military and commercial systems and products. For metal matrix composites, aluminum, magnesium, and titanium are selected to be the most important metal matrices for USASDC material systems. For polymer matrix composites, epoxy, phenolic, and polyimide are selected to be the most important polymer matrices.

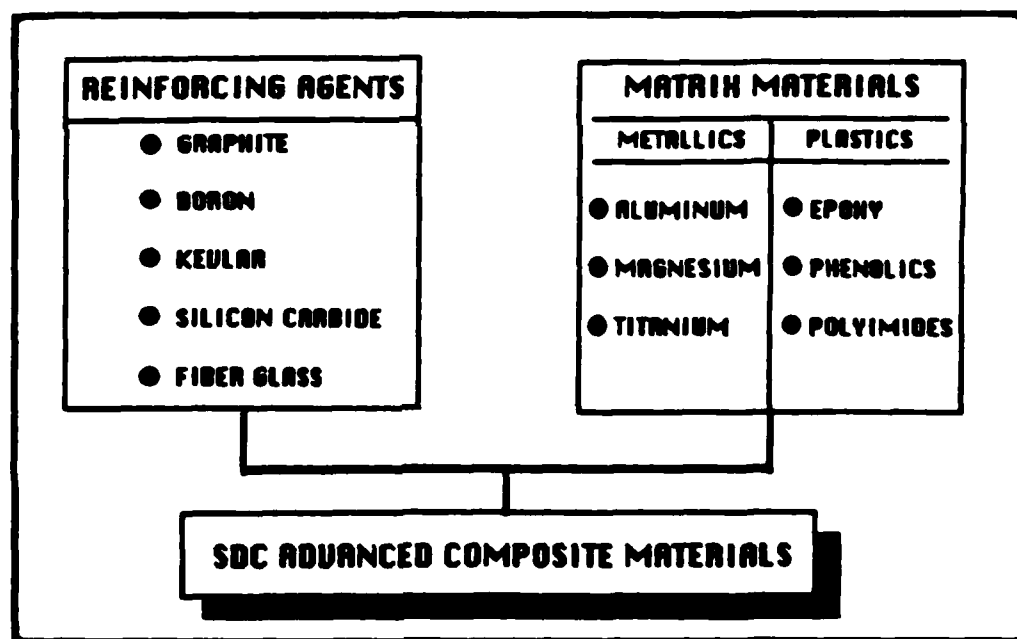


Figure 1.2-2. Advanced Materials Selection for USASDC Program Study

1.3 Metal Versus Plastic Composite Materials. Metal matrix composites (MMCs) have advantages over monolithic metals which include better fatigue resistance, better wear resistance, better elevated temperature properties, higher strength-to-density ratios, higher stiffness-to-density ratios, and lower coefficients of thermal expansion. MMCs also have advantages when compared to polymer matrix composites, including higher functional temperatures, higher transverse strength and stiffness, no moisture absorption, better conductiveness, and better radiation resistance. MMCs also have disadvantages including high costs, newer technologies, complex fabrication methods, and limited service experience.

Polymer matrix composites are highly anisotropic. Strength and stiffness are high parallel to the fibers, but low perpendicular to the fibers. PMCs have stress-strain curves that are generally linear to failure. Polymer matrix materials result in composites that have higher specific tensile strength and stiffness properties. Plastic composites are more advanced in the fabrication technology and are lower in raw material cost and fabrication cost.

Both metal and polymer matrix properties are affected by reinforcement properties, form, and arrangement; reinforcement volume; matrix properties; and reinforcement - matrix interface properties. They may also be affected by residual stress and degradation because of high temperatures and mechanical damage.

CHAPTER 2

REINFORCEMENT MATERIALS AND FABRICATION METHODS

2.1 Introduction. Advanced composite materials are composed of metal, plastic, or ceramic matrix composite materials reinforced with high-strength, high-modulus fibers. This reinforcement may be continuous in the form of fibers or filaments, or discontinuous in the form of chopped fibers or whiskers. The main focus of this discussion will be on continuous reinforcement fiber materials. Advanced reinforcement materials include high-strength, high-modulus graphite, boron, glass, silicon carbide, and aramid fibers. Fiberglass is included, although it is not a true advanced reinforcement, because of its widespread use in military and commercial applications.

Fiber reinforcement is available in a wide range of sizes. Diameters vary from a few microns to several mils, lengths from long continuous fibers to short whiskers; the composite material may contain only a few fibers, or its fiber content may be as much as 80 percent. Figure 2.1-1 shows a comparison of various fiber dimensions. This wide variety in fiber reinforcement makes many different handling techniques necessary. Other unique properties may be found in Tables 2.1-1 and 2.1-2 and in Figures 2.1-2 and 2.1-3.

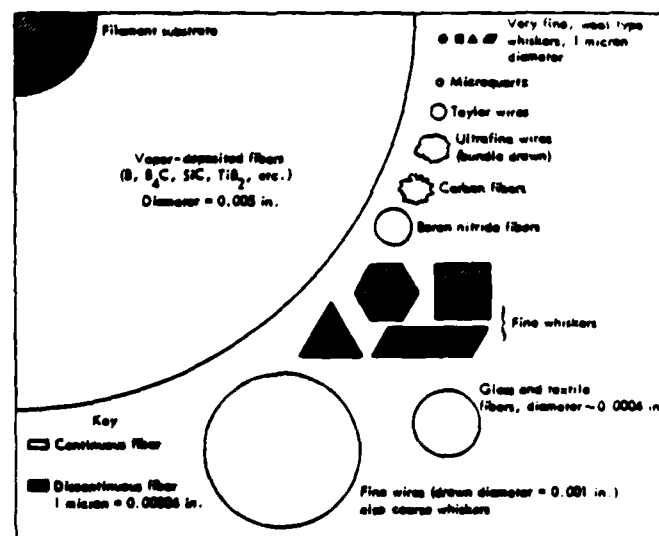


Figure 2.1-1. Relative Cross-Sectional Areas and Shapes of Several Fibrous Reinforcements (Reference 2-1)

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TABLE 2.1-1. Properties of Fibers and Conventional Bulk Materials
(Reference 2-2)

Material	Tensile Modulus (E) (GN/m ²)	Tensile Strength (σ_u) (GN/m ²)	Density (ρ) (g/cm ³)	Specific Modulus (E/ ρ)	Specific Strength (σ_u/ρ)
Fibers					
E-Glass	72.4	3.5 ^a	2.54	28.5	1.38
S-Glass	85.5	4.6 ^a	2.48	34.5	1.85
Graphite (high modulus)	390.0	2.1	1.90	205.0	1.1
Graphite (high tensile strength)	240.0	2.5	1.90	126.0	1.3
Boron	385.0	2.8	2.63	146.0	1.1
Silica	72.4	5.8	2.19	33.0	2.65
Tungsten	414.0	4.2	19.30	21.0	0.22
Beryllium	240.0	1.3	1.83	131.0	0.71
Kevlar-49 (aramid polymer)	130.0	2.8	1.50	87.0	1.87
Conventional materials					
Steel	210.0	0.34-2.1	7.8	26.9	0.043-0.27
Aluminum alloys	70.0	0.14-0.62	2.7	25.9	0.052-0.23
Glass	70.0	0.7-2.1	2.5	28.0	0.28-0.84
Tungsten	350.0	1.1-4.1	19.30	18.1	0.057-0.21
Beryllium	300.0	0.7	1.83	164.0	0.38

^aVirgin strength values. Actual strength values prior to incorporation into composite are approximately 2.1 GN/m².

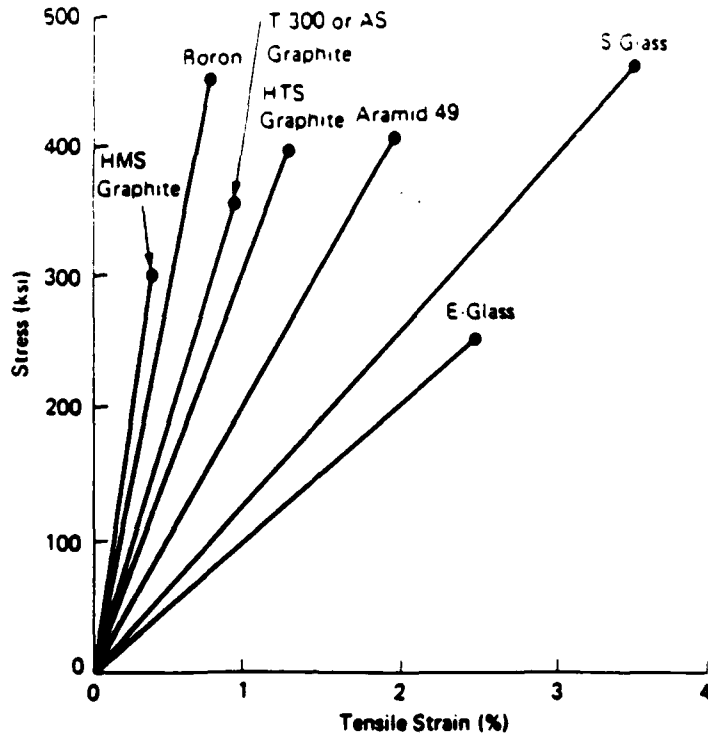


Figure 2.1-2. Stress-Strain Diagrams of Various Fibers (Reference 2-3)

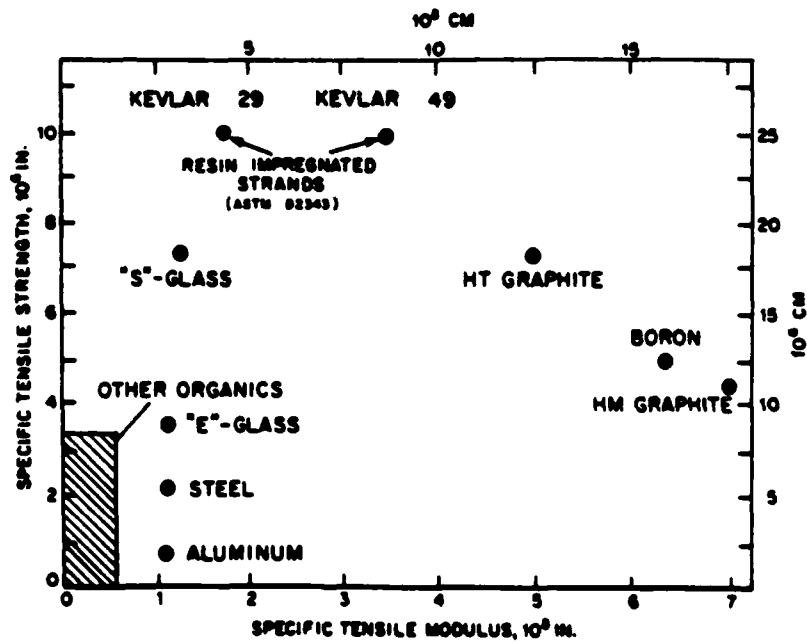


Figure 2.1-3. Specific Tensile Strength and Modulus of Reinforcing Fibers
(tensile strength or modulus divided by density)
(Reference 2-4)

TABLE 2.1-2. Suppliers of Reinforcing Fiber and Preform Materials
(Reference 2-5)

Fibers	Supplier, United States
Graphite	Hercules, Union Carbide, Celanese, Great Lakes Carbon, Stackpole Carbon
Boron/borsic	AVCO, Composite Materials Corporation
Silicon carbide filament	AVCO
Silicon carbide whiskers	EXXON
Fiberglass (E, S, quartz)	Owens Corning Fiberglass Company, PPG Industries
Aluminum oxide filament	TYCO, DuPont Company
Aramid (Kevlar) and other polymers	DuPont Company, 3M Company
Preforms and Prepregs	
Graphite	Fiber Materials, Inc., The 3M Company, U.S. Polymeric, NARMCO, Composite Materials Corporation, Ferro Corporation
Boron/borsic	Composite Materials Corporation
Fiberglass	Fiberite, U.S. Polymeric, NARMCO, Composite Materials Corporation, 3M Company
Graphite/aluminum	Fiber Materials, Inc.
Boron/borsic aluminum	DWA Composite Specialties, Inc., General Technologies Corporation

2.2 Properties of Reinforcement Materials.

2.2.1 Graphite Fibers. High-strength, high-modulus graphite fibers are manufactured by treating an organic base material fiber (precursor) with heat and tension, leaving a highly ordered carbon structure. The most commonly used precursors include rayon-base fibers, polyacrylonitrile (PAN), and pitch. The following paragraphs present an introduction to the various processes involved with each precursor. Typical properties of the representative classes of graphite (carbon) fibers are listed in Table 2.2-1, and typical properties of specific commercially available carbon fiber materials are listed in Table 2.2-2. Other unique properties of carbon fiber materials can be found in Tables 2.2-3 and 2.2-4 and Figures 2.2-1 and 2.2-2.

2.2.1.1 Rayon-Base Fibers. Rayon carbon filaments are stretched in a series of steps at temperatures of around 2700 °C (4900 °F) while in an inert atmosphere. The tension, along with the high temperatures, causes

the graphite layer planes to align with the fiber axis, giving them the high-strength, high-modulus characteristics.

2.2.1.2 Polyacrylonitrile (PAN) Carbon Fibers. PAN is a long chain linear polymer composed of a carbon backbone with attached carbonitrile groups. Fibers are made by first holding a stretched polymer in an oxidizing environment at 205 to 240 °C (400 to 460 °F) for 24 hours. This cyclization process produces a "ladder" type structure. The fiber is then heated in an inert atmosphere to temperatures ranging from 1400 to 3000 °C (2550 to 5400 °F), depending on desired characteristics.

2.2.1.3 Pitch Carbon Fibers. Coal tar pitch is heated for up to 40 hours at approximately 450 °C (800 °F). This forms a viscous liquid with a high degree of molecular order known as mesophase. The mesophase is then spun through a small orifice, aligning the mesophase molecules along the fiber axis. The fibers are thermoset at relatively low temperatures and then heat treated at 1700 to 3000 °C (3100 to 5400 °F).

TABLE 2.2-1. Comparative Graphite Fiber Properties
(Reference 2-6)

Property	Pitch	Rayon	PAN
Tensile strength, 10^3 psi	225	300 to 400	450 to 360
Tensile modulus, 10^6 psi	55	60 to 80	30 to 50
Short beam shear, 10^3 psi			
untreated	6	4	10 to 4
treated	10	8	18 to 8
Specific gravity	2.0	1.7	1.8
Elongation, %	1	...	1.2 to 0.6
Fiber diameter, μm	...	6.5	7.5

TABLE 2.2-2. Commercial Graphite Fiber Properties
(Reference 2-7)

Fiber	Precursor	Average Strength, 10^3 psi	Modulus, 10^6 psi	Density, g/cm ³
Thornel 50	rayon	320 ± 20	57 ± 3	1.67
Thornel 75	rayon	385 ± 17	76 ± 3	1.82
Modmor 1	PAN	340	59	1.85
Celion 70	PAN	300	88	1.96
Courtaulds HMS	PAN	250 - 350	50 - 60	1.94
Fortafil 6T	PAN	420 ± 20	59 ± 3	1.91
Fortafil 5T	PAN	400 ± 20	48 ± 3	1.80
Courtaulds HT	PAN	325 to 375	35 to 40	1.86
Thornel 300	PAN	325	34	1.70
Hercules Type A	PAN	400	28 to 32	1.77
UCC Type P	pitch	160 to 200	50	...

TABLE 2.2-3. Thermal Conductivities of Different Carbon Fibers
(Reference 2-8)

Carbon fiber	Thermal conductivity (ω cm ⁻¹ k ⁻¹)
HM (PAN)	0.594
Type I (PAN)	1.02
Type II (PAN)	0.22
Thornel 50 (RAYON)	0.90 (1800 K)
Thornel 50 (RAYON)	0.60 (room temp.)
Morganite	0.20

TABLE 2.2-4. Comparison of Mechanical Properties of Carbon Fibers with Other Fibrous Reinforcing Materials (Reference 2-9)

Fiber	Specific gravity (SG)	Ultimate tensile strength (UTS) (GN m ²)	Relative specific strength (UTS/SG)	Young's modulus (E) (GN m ²)	Relative Young's modulus (E/SG)
Carbon fiber Type I	1.90	2.6	1.37	340	179
Carbon fiber Type II	1.77	2.9	1.64	240	136
Carbon Fiber Type III	1.76	2.6	1.48	190	108
E-glass	2.59	3.44	1.38	72	29
S-glass	2.49	2.60	1.06	80	32
Kevlar 29	1.44	2.7	1.80	60	42
Kevlar 49	1.45	2.7	1.86	130	90
Boron (on tungsten)	2.50	3.75	1.50	400	160
Asbestos crocidolite	3.40	3.50	1.03	190	58
Asbestos chrysotite	2.50	3.11	1.24	160	64
Silicon carbide (on tungsten)	3.50	3.50	1.00	400	114

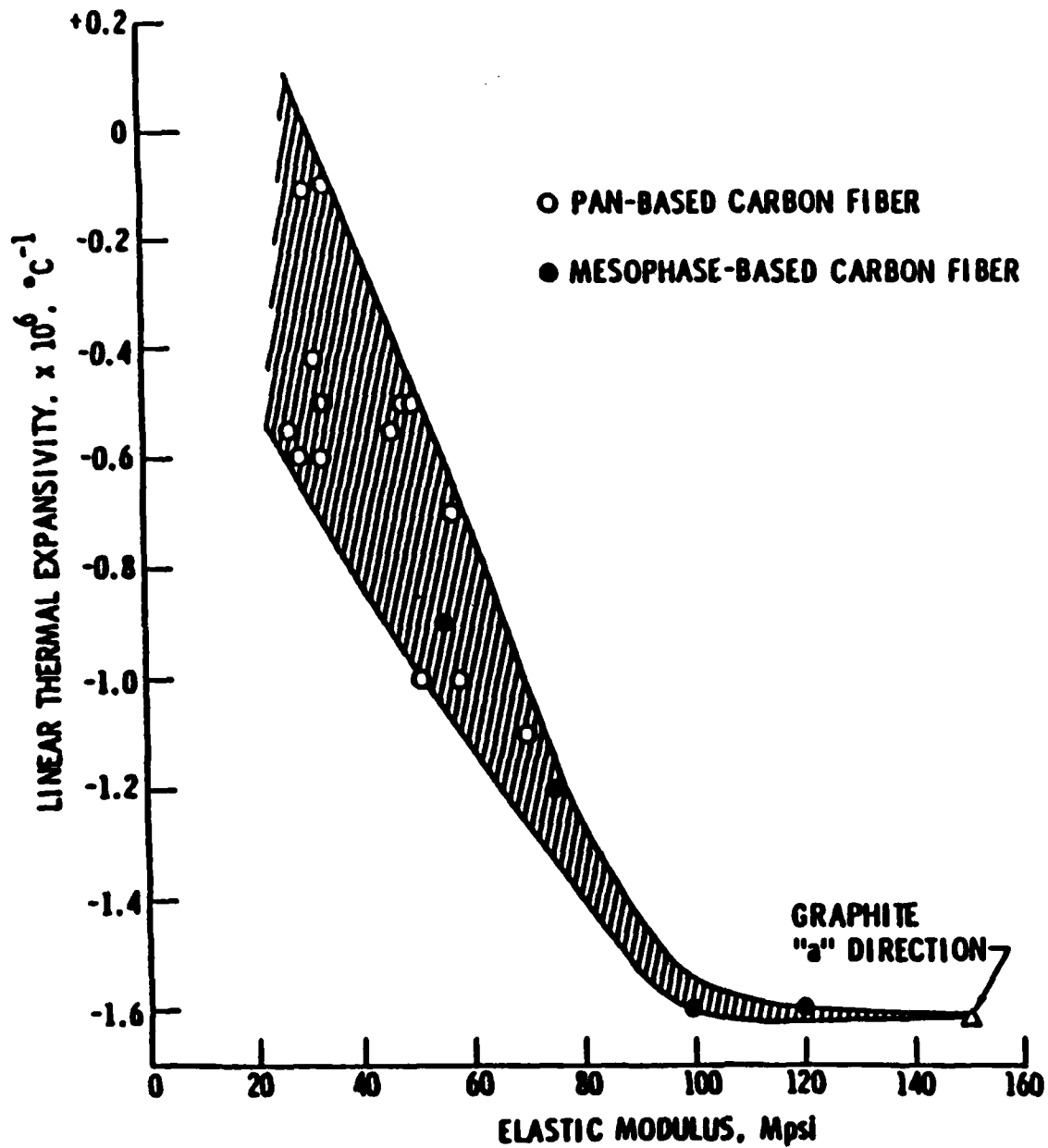


Figure 2.2-1. Linear Thermal Expansivity of Carbon Fiber
(Reference 2-10)

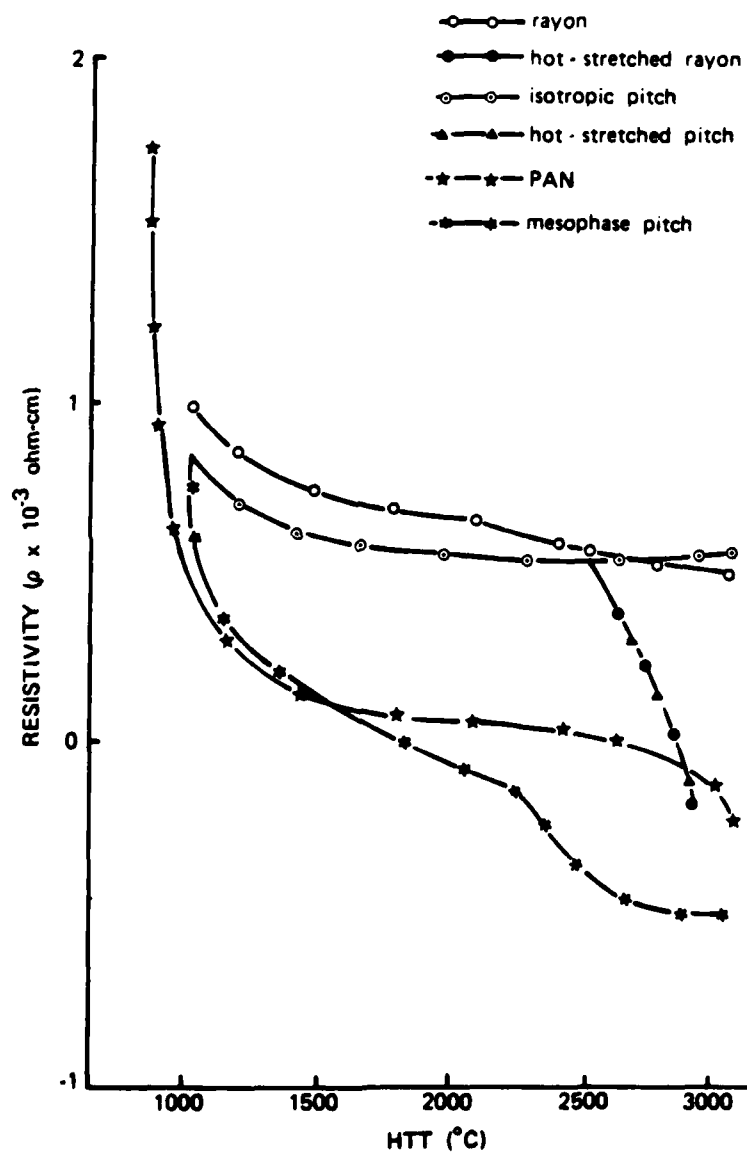


Figure 2.2-2. Resistivity of Different Carbon Fibers as a Function of Heat Treatment Temperature (Reference 2-11)

2.2.2 Boron Fibers. Boron fiber is made by deposits of chemical vapor onto a tungsten or carbon filament substrate. The filaments are heated to approximately 1260 °C (2300 °F) and then pulled through a boron trichloride/hydrogen environment. This deposits boron on the substrate at approximately 50mm per hour. Borsic filaments are made by depositing a layer of silicon dioxide onto the boron fiber in a similar process.

Table 2.2-5 shows fiber properties. Removing the tungsten core by continuous splitting and etching may produce a filament strength well above 6.895GPa (1,000,000 psi). Boron fibers have been produced for many years, and the accumulation of data is expected to further reduce costs and raise production volume. This has already been shown by the substitution of a carbon filament for tungsten. Other unique boron material properties can be found in Figures 2.2-3 through 2.2-5.

TABLE 2.2-5. Room Temperature Mechanical Properties of Boron-on-Tungsten Filament (Reference 2-12)

Ultimate tensile, 10^3 psi	500+	500+	500+
Tensile modulus, 10^6 psi	58	58	58
Shear modulus, 10^6 psi	24	24	...
Coefficient of thermal expansion, in./in./°F $\times 10^6$	2.7	2.7	2.7
Density, lb/in. ³	0.094	0.089	0.086
Length/pound, ft	70 000	37 800	19 000

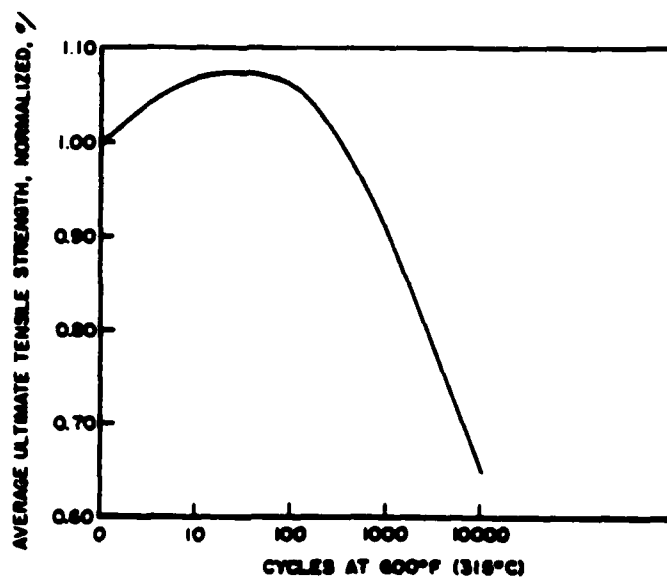


Figure 2.2-3. Boron Filament Strength as a Function of Cyclic Heat Treatment (Reference 2-13)

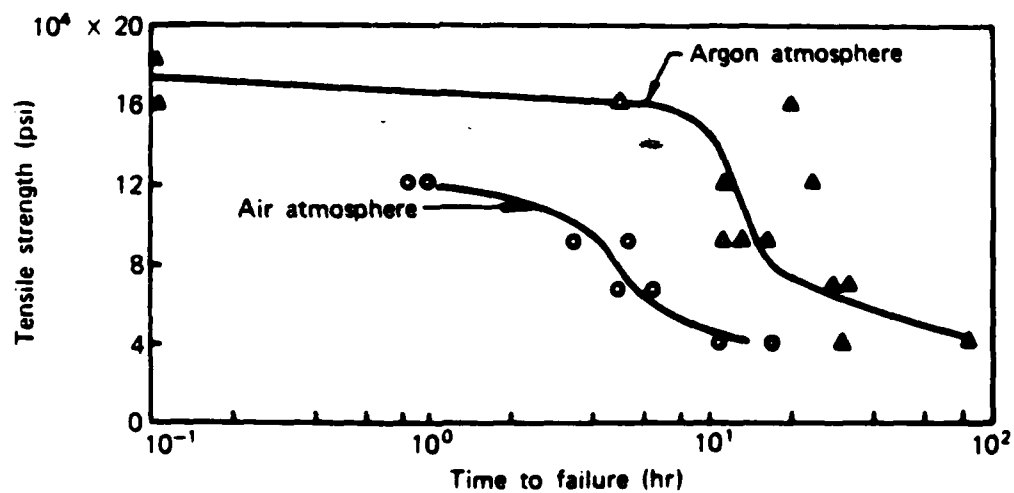
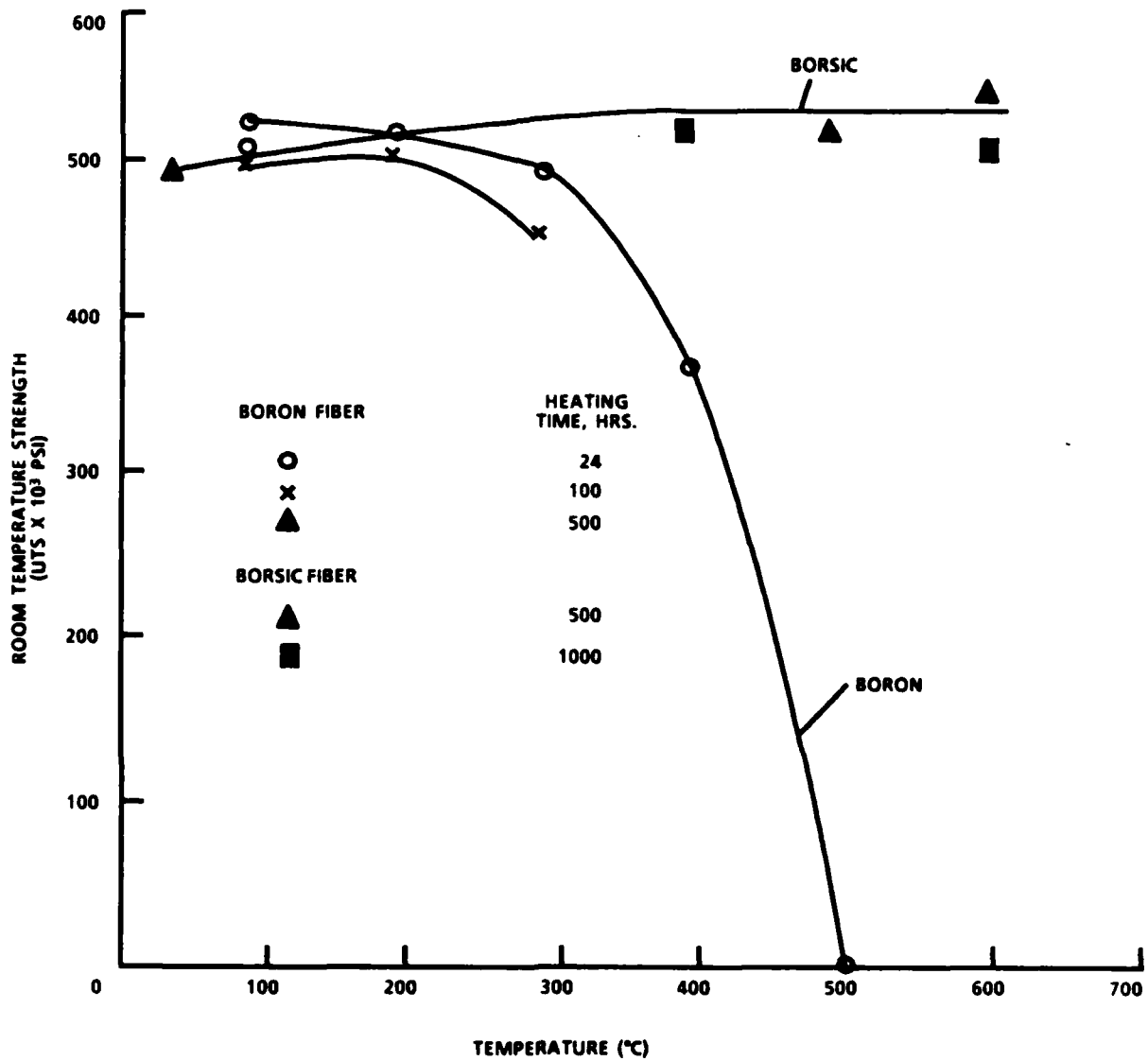


Figure 2.2-4. Stress-Rupture Properties of Boron Fibers (Reference 2-14)



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Figure 2.2-5. Room Temperature Strength of Boron and Borsic Fibers Heated in Air (Reference 2-15)

2.2.3 Kevlar Fibers. Kevlar aramid fibers possess high strength and high modulus properties. Table 2.2-6 shows the properties of three Kevlar materials, and Figure 2.2-6 shows the effect of stress on the creep of Kevlar 49. The negative coefficient of thermal expansion must be considered when using Kevlar materials. Kevlar materials are available in yarns, rovings, staple, and fabrics. Table 2.2-7 shows the chemical resistance of Kevlar 49, the most advanced Kevlar material. Figures 2.2-7 and 2.2-8 show the heat and moisture effects on Kevlar 49. The fibers will not melt, but will decompose at about 500 °C (930 °F).

TABLE 2.2-6. Kevlar Aramid Fiber Properties (Reference 2-16)

	Kevlar	Kevlar 29	Kevlar 49
Density, lb./in. ³	0.52	0.52	0.52
Tensile strength, 10 ³ psi	400	400	525
Tensile modulus, 10 ⁶ psi	9	9	18
Tensile elongation, %	3 to 4	3 to 4	2 to 8
Coefficient of thermal expansion, in./in./°F			
<i>Longitudinal Direction</i>			
32 to 212°F	-1.1×10^{-6}		
212 to 392°F	-2.2×10^{-6}		
392 to 500°F	-2.8×10^{-6}		
<i>Radial Direction</i>			
32 to 212°F	33×10^{-6}		

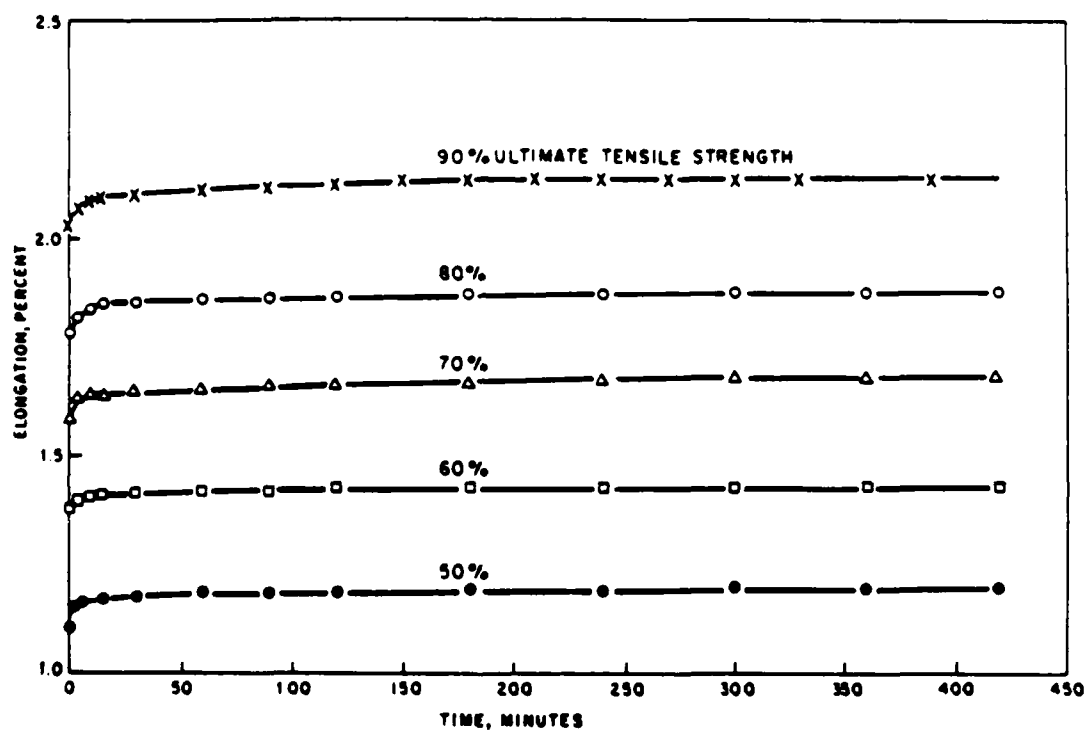


Figure 2.2-6. The Effect of Stress on the Creep of Kevlar 49
(Reference 2-17)

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TABLE 2.2-7. The Effect of Chemicals on the Tensile Properties of Kevlar 49
Aramid 24-h exposure^a (Reference 2-18)

Chemical	Tensile Strength, psi	Tensile Modulus, psi $\times 10^{-6}$
None (control)	411 000	18.33
Acetic acid (99.7% CH ₃ COOH)	431 600	18.16
Formic acid (HCOOH)	361 900	17.99
Hydrochloric acid (37% HCl)	419 200	17.80
Nitric acid (70% HNO ₃)	165 200	17.40
Sulfuric acid	too weak to test	
Ammonium hydroxide (28.5% NH ₃)	423 800	17.91
Potassium hydroxide (50% Solution)	305 900	17.69
Sodium hydroxide (50% Solution)	369 500	17.45
Acetone	423 100	18.22
Benzene (C ₆ H ₆)	420 900	17.91
Carbon tetrachloride (CCl ₄)	422 000	18.46
Dimethylformamide (DMF)	418 600	17.97
Methylene chloride (CH ₂ Cl ₂)	425 900	18.30
Methyl ethyl ketone (MEK)	424 600	17.98
Trichloroethylene ("Triclene")	404 700	18.17
Chloroethene (1,1,1-trichloroethane)	418 600	18.32
Toluene (C ₆ H ₅ CH ₃)	413 600	18.27
Benzyl alcohol (C ₆ H ₅ CH ₂ OH)	412 300	18.08
Ethyl alcohol (CH ₃ OH)	417 000	18.02
Methyl alcohol (methanol)	407 500	17.90
Formalin (HCHO)	405 500	17.87
Gasoline (regular)	419 900	18.37
Jet Fuel (Texaco "Abjet" K-40)	393 400	18.09
Lubricating oil ("Skydrol")	422 700	18.08
Salt water (5% solution)	410 100	16.92
Tap water	417 200	18.27

^aYarns were tested using air-actuated 4-C cord and yarn clamps on an Instron test machine, at 10 in. gage length with 3 turns per inch twist added, 10 percent per minute elongation, and at 55 percent relative humidity and 72°F.

Conversion factor—MPa = lb/in.² $\times 6.895 \times 10^{-3}$.

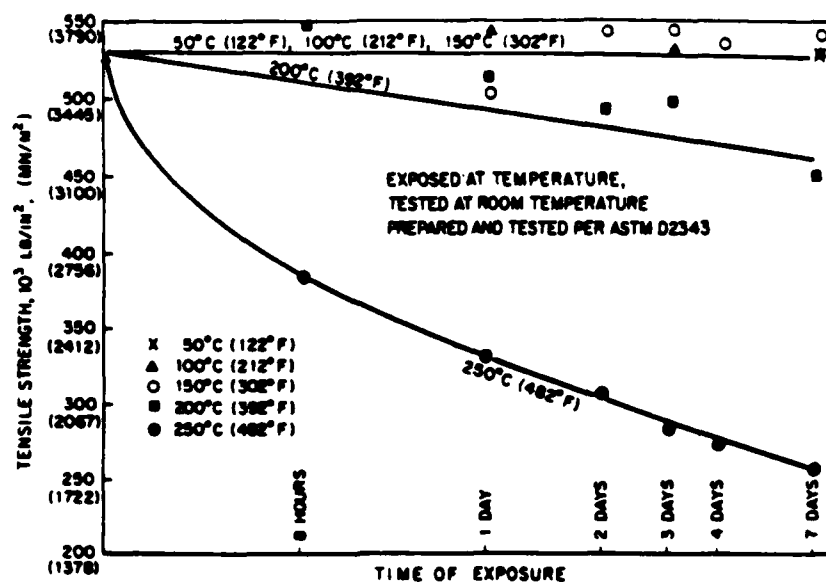


Figure 2.2-7. The Effect of Elevated Temperature Exposure on the Tensile Strength of Kevlar 49/epoxy Roving Strands (Reference 2-19)

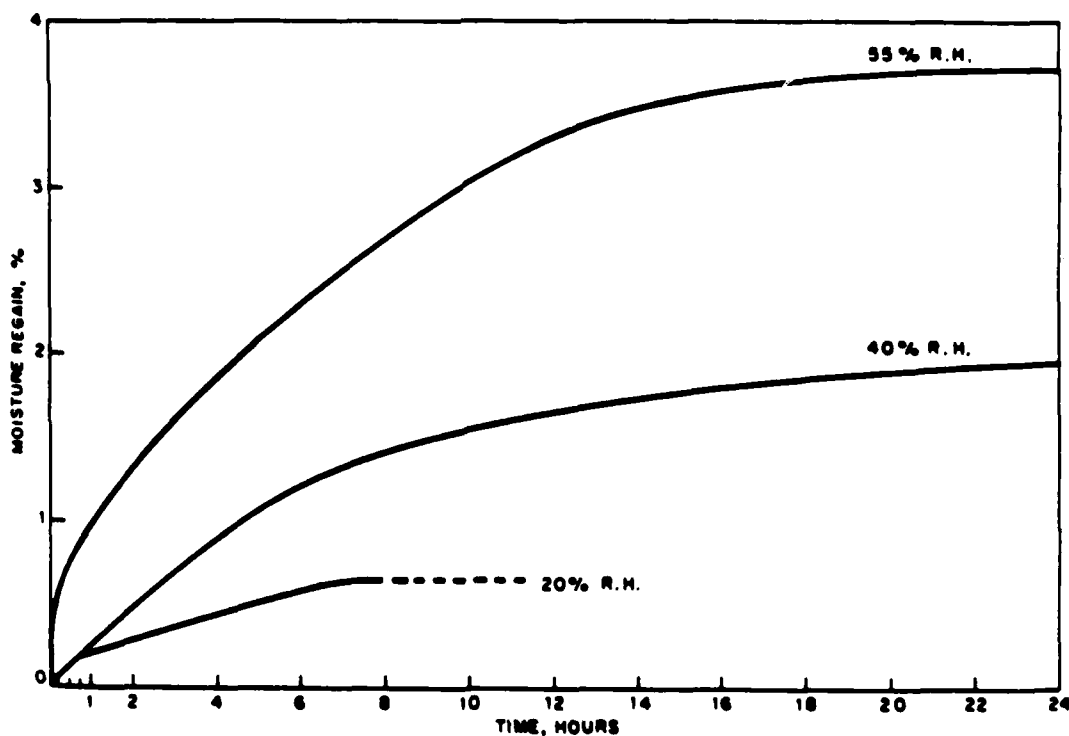


Figure 2.2-8. The Effect of Relative Humidity on the Equilibrium Moisture Regain and Regain Rate of 380 Denier Yarn of Kevlar 49 Aramid (Reference 2-20)

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2.2.4 Silicon Carbide Reinforcements. Because of their compatibility with molten aluminum, their high temperature stability, and their low cost, silicon carbide fibers have become desirable components of advanced metal matrix composites. Silicon carbide fibers are produced by vapor deposition on either a tungsten or carbon filament substrate. This is done by heating the substrate and running it through a hydrogen/silane environment. Table 2.2-8 describes various properties of silicon carbide fibers, which are comparable to that of boron fibers. Silicon carbide fibers retain usable strengths at up to 1000 °C (1900 °F), and they have the unique characteristic of retaining basic fiber strength in molten aluminum for up to 30 minutes, as described in Figure 2.2-9. This characteristic greatly reduces the cost and difficulty of producing silicon carbide-aluminum composites. Silicon carbide (SiC) filament is a potentially low cost/high performance filament suitable for many advanced metal matrix applications.

TABLE 2.2-8. Silicon Carbide Filament Room Temperature Properties
(Reference 2-21)

Diameter, in.	0.0056
Ultimate tensile strength, 10^3 psi	485 +
Tensile modulus, 10^6 psi	58
Shear modulus, 10^6 psi	24
Coefficient of thermal expansion, in./in./°F ($\times 10^6$)	2.7
Density, lb/in. ³	0.111
Length/lb, ft	30 500

Conversion factors—

10^3 psi = 6.9 MPa,
 10^6 psi = 6.9 GPa,
in./in./°F = 0.556 cm/cm/°C,
lb/in.³ = $0.036 \times \text{g/cm}^3$,
1 ft = 0.305 m, and
1 lb = 0.45 kg.

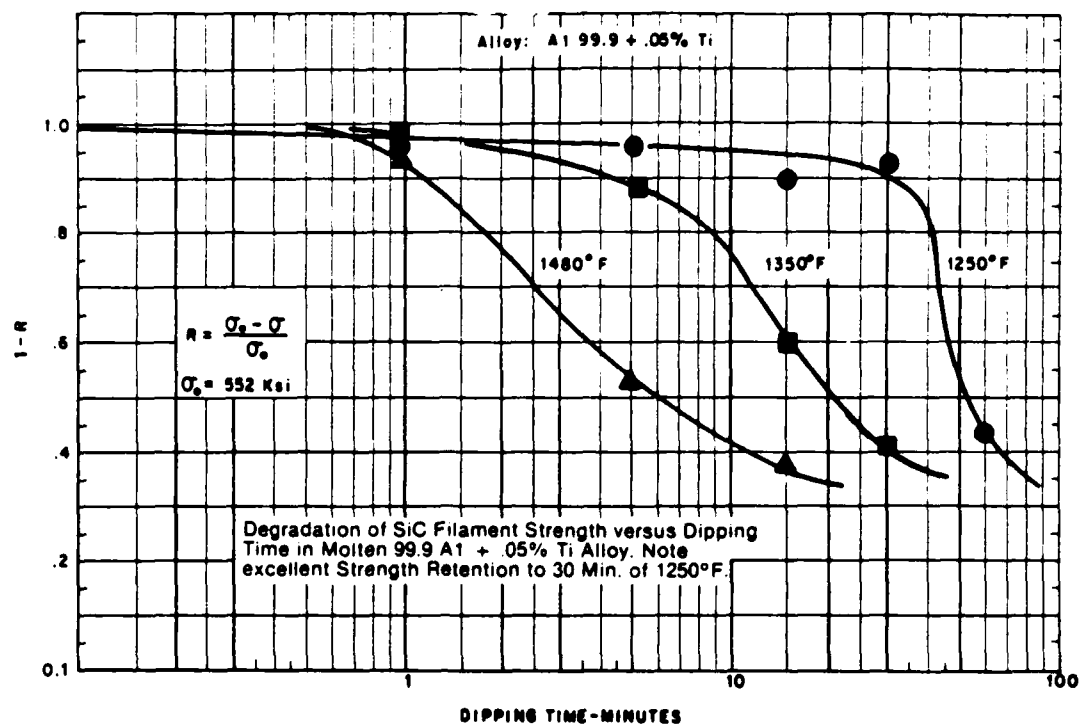


Figure 2.2-9. SiC Strength Versus Temperature and Time of Exposure to Molten Aluminum (Reference 2-22)

2.2.5. Fiberglass Reinforcements. The most common reinforcing fiber for polymer matrix composite materials is fiberglass. Table 2.2-9 compares the properties of two common glasses and quartz to that of other fibers. The advantages of fiberglass include low cost, high tensile and impact strengths, and high chemical resistance. The disadvantages include low modulus, self-abrasiveness, low fatigue resistance, and poor adhesion to matrix resins. Quartz fibers are produced from natural quartz crystals and are used when dielectric properties and high temperature resistance are important.

Molten glass is produced from melting a dry mixture of sand, limestone, boric acid in a high refractory furnace. This molten glass is either poured directly into the fiber drawing furnace or made into marbles and remelted later. Continuous fibers are produced by mechanically attenuating droplets of molten glass. Discontinuous fibers are made by blowing jets of air across an orifice at the bottom of the molten glass, forming

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filaments 20 to 38cm long. These are collected and gathered into a strand. Other unique properties can be found in Table 2.2-10 and Figure 2.2-10.

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TABLE 2.2-9. Comparative Properties of Glass Type Fibers (Reference 2-23)

Type of Fiber	E-Glass	S-Glass	Quartz	Boron	Graphite Type "A"	Kevlar 49
Fiber density						
lb/in. ³	0.092	0.090	0.079	0.079	0.063	0.052
g/cm ³	2.54	2.49	2.2	2.68	1.74	1.44
Tensile strength						
10 ³ psi	500	665	450	500	250 to 300	525
MPa	3448	4585	3100	3448	1724 to 2069	3620
Modulus of elasticity						
10 ⁶ psi	10.5	12.4	10	60	24/32	19
GPa	72.4	85.5	68.9	413.7	172.4 to 220.6	131.0
Range of diameters						
mils	0.1 to 0.8	.3 to .7	6.4	4 to 8	0.35 to 0.5	0.47
mm	0.003 to 0.020	0.008 to 0.013	0.010	0.10 to 0.20	0.009 to 0.013	0.0119
Coefficient of thermal expansion						
in./in./°F × 10 ⁻⁶	2.8	1.6	1.6	2.8	-0.6	-1.1
cm/cm/°C × 10 ⁻⁶	5.0	2.9	2.9	5.0		-2

TABLE 2.2-10. Fiberglass Filament Designations (Reference 2-24)

Filament Designation	Filament Diameter	
	in.	μm
B	1.5×10^{-4}	3.8
C	1.8×10^{-4}	4.5
D	2.1×10^{-4}	5
DE	2.5×10^{-4}	6
E	2.9×10^{-4}	7
G	3.6×10^{-4}	9
H	4.2×10^{-4}	10
K	5.1×10^{-4}	13

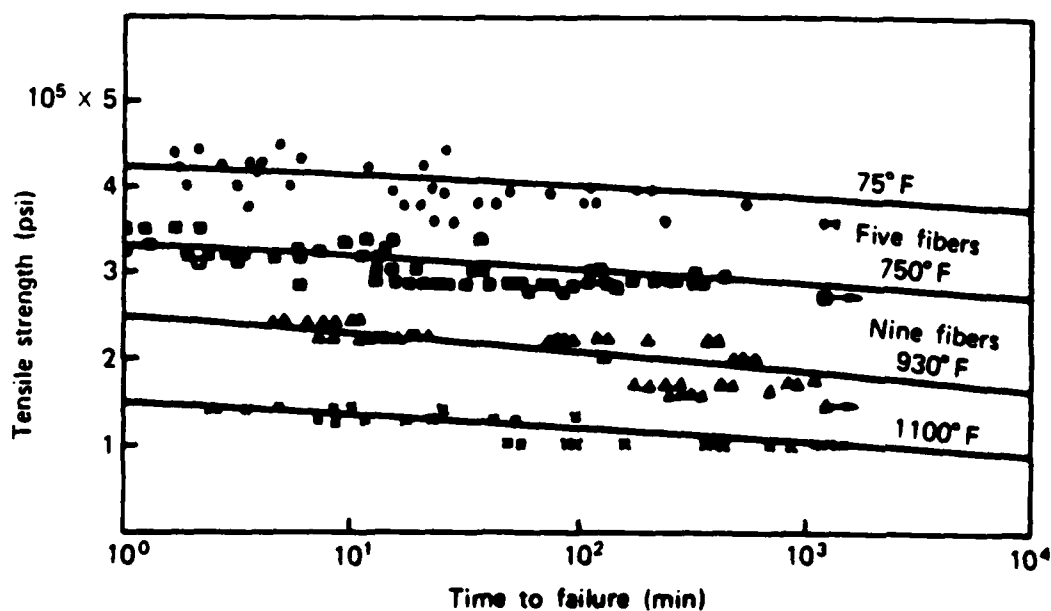


Figure 2.2-10. Static Fatigue Test Results for E-Glass Fibers (Reference 2-25)

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2.3 Manufacturing Processes for Composite Structures.

2.3.1 Fabrication Methods for Metal Matrix Composites. Metal matrix composites are produced in two basic steps. The first step is the creation of the metal matrix composite from its components. The form is usually not in its final state after this step, and a second step is required to finish by machining, rolling, forming, or metallurgical bonding.

A major consideration of the metal matrix formation is the reaction of the reinforcing fibers to the molten metal. This may limit the use of many fibers, but a protective coating may be put on the fibers to facilitate their use.

One fabrication procedure involving larger diameter fibers, such as boron and silicon carbide fibers, creates a monolayer tape by hot pressing a layer of fibers between two foils. The metal flows around the fibers, and diffusion bonding occurs. The same method is employed to make laminates with fibers oriented in a specific direction.

Composite materials may also be produced by infiltrating molten metal into fabric or preform. The preform fibers are usually held together by ceramic or organic materials which burn away during infiltration. This process may be done under pressure, in a vacuum, or both. This is the most common method for producing graphite/aluminum and graphite/magnesium composites. The procedure may sometimes involve the intermediate step of producing a bundle of infiltrated fibers called a "wire." The wire is then formed into final shape using hot press techniques similar to that of the larger fibers. Direct casting is used when an "air stable" coating is used on the fibers.

Whisker and particulate reinforcements are usually mixed with powdered metal to form composites. A liquid metal method is used, but details are proprietary. The actual mixing takes place either in a ball mill or with the aid of a liquid, which is removed later. Mixtures are hot pressed into billets and then formed using rolling, extrusion, spinning, forging, or

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creep-forming. Machining may also be used, but may present difficulties because of the hardness of reinforcements.

2.3.2. Fabrication Methods for Polymer Matrix Composites. Polymer matrix composites can be produced by many different methods including wet layup, filament winding, compression molding, autoclave molding, injection molding, and pultrusion.

In the wet layup method, precut materials are fitted into a female mold. Resin is then applied, worked in, and allowed to cure at room temperature. Some materials such as Kevlar are not available for this fabrication method.

The filament winding technique involves winding fibers on a slowly turning mandrel which is the shape of the inside of the desired form. The winding process may be hand fed, but is usually electronically controlled. Winding patterns may vary from nearly parallel to nearly perpendicular to the axis of rotation. The entire assembly is cured and the mandrel is removed. Machining may be necessary to achieve the desired finished dimensions. The advantages of this method include the ability to place large amounts of composite precisely with little manpower, automated processing, repeatable processing, and low scrap rate. The disadvantages include low longitudinal strength and stiffness, and the expense of producing and removing mandrels, especially for complex parts.

In the compression molding technique, the fiber and resin are placed within a metal cavity, pressurized, and heated until cured. The material will then have a rigid shape in the form of the cavity. Either continuous or chopped fibers may be used in this method, or a combination of the two may be used. If continuous fibers are used, they must be preformed to closely match the cavity shape.

Autoclave molding is used for molding thermoset preimpregnated materials. This method provides low cost fabrication of complex parts. Starting materials include prepreg tape, woven cloth, or mat. The process itself involves laying up the prepreg laminates on a mold, covering them with

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flexible sheets, and vacuum sealing. The assembly is then cured at a specified heat and pressure in a vacuum. The process is inexpensive and is most commonly used for limited production run parts.

Injection mold processing consists of heating the materials in a barrel and transferring the flowable material into a cooler metal cavity with a plunger. The materials are rapidly cooled and ejected in the form of the final part. Two thirds of the plungers used are reciprocating screw type, the other third are ram plungers. The advantages of this method include high production rates, low labor cost, compatibility to small parts, and precise dimensions with little finishing. The major disadvantage of this method is that continuous reinforcements cannot be used.

Pultrusion continuously produces constant cross-section continuous parts. A continuous yarn of carbon, glass, or Kevlar is resin coated and pulled through a heated forming die. The resin sets during passage through the die. This process is generally limited to thermoset resins such as epoxies and polyesters. The advantages of this method include almost no scrap loss, low labor costs, and high strength and stiffness. The disadvantages include the restriction to constant cross-section parts and difficulties in using mat fabric and industrial fibers.

CHAPTER 3
METAL MATRIX COMPOSITES

3.1 Introduction. In metal matrix composites, various mechanical properties are superior to their unreinforced monolithic metal counterparts. Specifically, this is true in the areas of high temperature stability, specific strength, and modulus. As a result, metal matrix composites offer promise for many different aerospace applications. In Table 3.1-1 some of the advantages of metal matrix composites over resin matrix composites in different applications are shown.

Because of low temperature and low cost fabrication methods, resin matrix composite development has remained ahead of the higher temperature, higher cost fabrication methods of metal matrix composites. However, there are three important general classes of metal matrices that are reinforced by the high-performance fiber materials. These are aluminum, magnesium, and titanium. Table 3.1-2 provides some properties of these metal matrices for advanced metal composites.

Aluminum and magnesium matrices have advantages over polymer-matrix composites because of their higher melting temperatures and lower densities. As a result of oxidation and corrosion considerations, aluminum is a better metal matrix than magnesium even though it is more dense. Because of these considerations, the discussion will focus primarily on aluminum matrix composites.

Aluminum alloy metal matrix composites that contain boron or Borsic SiC coated fibers have been the most extensively studied and developed metal-matrix composite system. As a result of carbon fibers being less expensive, carbon fiber-reinforcement is of continuing interest. Other composites such as magnesium that can be based on these fibers are also being investigated. Silicon carbide and aluminum oxide are other examples of reinforcements for magnesium composite systems.

Because of its material properties such as higher temperature melting point, there has been substantial interest in titanium-matrix composites.

TABLE 3.1-1. Metal-Matrix Material Characteristics (Reference 3-1)

Key characteristics of metal matrix composite (compared to plastic matrix composite)	Potential advantages in space applications
Greater matrix strength and modulus possible	Compared to uniaxial plastics:
(a) tensile	More efficient in plate buckling
(b) shear	More efficient for transverse and off-axis loads
(c) compressive	More efficient in combined loads of tension, compression, or shear
(d) bearing	Less tendency for matrix crazing
Harder surface	Greater erosion resistance (potential nozzle or leading edge applications)
Higher-temperature matrix capabilities	Higher temperature applications for uniaxial material, particularly above 600 F, where plastics are limited
Greater thermal conductivity	Avoids local hot spots by spreading out heat; operates at lower temperature; better for nozzles, flame impingement surfaces, and leading-edge applications
Higher electrical conductivity	Better lightning protection (aircraft, boosters)
Matrix is inorganic	Bleeds off static electricity, avoiding explosion of fuels (aircraft boosters)
Available in sheet form	Reduces electromagnetic interference problems
Post-buckling shear strength	Better behavior for spacecraft applications where flammability (in F ₂ , O ₂ atmospheres), lower temperatures (-300 F), and radiation may result in problems with plastics
	More conventional methods of manufacturing possible
	More efficient shear-skin panels can be designed (since buckling can be tolerated)

TABLE 3.1-2. Properties of Aluminum, Magnesium, and Titanium Matrix Metals
(Reference 3-2)

Base Metal	Metal Matrix		Density, g/cm ³	Modulus, psi	Ultimate Tensile Strength, psi	Thermal Expansion Coefficient × 10 ⁶ , 70 to 200°F
		Alloy				
Aluminum			2.71	10 000 000	12 000 (annealed)	13.2
		Alloy 1100	2.71	10 000 000	13 000 (annealed)	13.1
		Alloy 2024	2.77	10 600 000	27 000 (annealed)	12.9
					65 000 (T-3)	
		Alloy 5052	2.69	10 200 000	28 000 (annealed)	13.2
					38 000 (H-34)	
		Alloy 5056	2.63	10 300 000	42 000 (annealed)	13.4
					60 000 (H38)	
		Alloy 6061	2.71	10 000 000	18 000 (annealed)	13.0
					45 000 (T-6)	
Magnesium		Alloy 7075	2.80	10 400 000	33 000 (annealed)	13.1
					83 000 (T-6)	
		Alloy 201	2.80	...	65 000 (solar treated and aged)	10.7
					40 000 (T-6)	11.9
					27 000	...
Titanium		AM100A	1.74	6 300 000	40 000 (T-6)	14.5
		AZ63A	1.80	6 500 000	34 000 (T-6)	14.5
		EZ33A	1.83	...	20 000 (T-5)	14.5
		HK31A	1.79	6 500 000	29 000 (annealed)	14.5
			4.5	16 200 000	34 000	...
		commercial Ti	...	...	80 000	...
		Ti-6Al-4V	...	...	170 000 (aged)	...
		Ti-4Al-4Mo	...	...	185 000 (aged)	...
		Ti-7Mo	...	...	150 000	...

Even though titanium has a greater density than magnesium and aluminum, it is still a high temperature, low density material with good mechanical properties. In general, titanium matrix is very reactive. It does not form protective oxide barriers on its surface. Therefore, in most cases the melt infiltration fabrication method proves to be unusable, and possible combinations of materials are restricted by fiber matrix interactions. Silicon carbide, silicon carbide-coated boron, and boron have been the reinforcements of the greatest importance.

High operating temperatures for metal matrix composite materials reactively alter the strength of the composite, and a great amount of work is being done to lessen or overcome these adverse effects.

3.2 Aluminum Metal Matrix Composites.

3.2.1 Background. The aluminum series 1000, 2000, 5000, 6000, and 7000 are generally the types of aluminum matrix materials employed in advanced composites. To date, the aluminum alloys 2024, 2219, 6061, 7090, and 7091 are most often used with different temperatures. Table 3.2-1 shows each series with its principal alloying elements. Displayed in Table 3.2-2 are the physical and mechanical properties of commonly used aluminum alloys. Each alloying element imparts distinct properties to the aluminum. The most widely and best developed aluminum matrix composite systems are those made using reinforcement with graphite, silicon carbide, and boron fibers.

Because of their low graphite cost, matrix attainability, better performance as well as decreased manufacturing and fabrication expenses as compared with other composite systems, graphite/aluminum composites have higher long term possibilities. The DoD has widely funded programs for development of graphite/aluminum composites since the late 1960's.

The composite system that has been suggested more than any other in structural applications is the boron and borsic/aluminum composite system. This fiber-reinforced, high modulus, metal matrix composite system is the most developed and has the most extensive use. Also under development, silicon carbide/aluminum composites have great possibilities for commercial applications dealing with cost and physical properties.

TABLE 3.2-1. Aluminum Matrix Series and Their Principal Alloying Element
(Reference 3-3)

Alloy Series	Alloying Element
1xxx	None
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium Silicide
7xxx	Zinc

TABLE 3.2-2. Mechanical and Physical Properties of Aluminum Matrix Alloys (Reference 3-4)

Property	Alloys			
	1100	2024	6061	7075
Solidus ($^{\circ}\text{C}$)	643	554	582	477
Liquidus ($^{\circ}\text{C}$)	657	649	652	635
Density (gm/cm^3)	2.71	2.75	2.70	2.80
Elastic Modulus (ksi)	10.0	10.2	10.0	10.3
Specific Modulus ^a (ksi)	3.69	3.71	3.70	3.68
Yield Strength at 0 (ksi)	5.0 ^b	14.0	8.0	15.0
Yield Strength at T6 (ksi)	5.0 ^b	48.0	40.0	73.0

^a Specific modulus is E/ρ where E is the elastic modulus and ρ is the density.

^b 1100 Al is not heat treatable and the yield strength increases with work hardening to the maximum value.

3.2.2 Properties of Aluminum Matrix Composites.

3.2.2.1 Graphite-Reinforced Aluminum. The consolidation process greatly affects the longitudinal properties in graphite/aluminum composites. The chemical interplay between the matrix and fiber during consolidation possibly causes large drops in the strength of the consolidation plates. This was discovered after consolidation by an increase in the aluminum carbide (Al_4C_3) compound at the interface.

Production for rayon based carbon fiber is ending even though it has the most congruent actions in dispersion and composite properties in the aluminum matrix. Basically, it is being discontinued because of its high cost. Therefore, it cannot be supported as a viable means for the reinforcement of aluminum.

When exposed to molten aluminum alloys, PAN based carbon fibers are reactive and somewhat unpredictable. For example, in T-300 fiber reduction and low precursor wire, strengths result from exposure to molten aluminum alloys when HM-300 produces high strength precursor plates and wires. This could possibly be caused from the different exterior features of each fiber.

The desirable transverse strength for a typical metal matrix composite is 137.9 MPa. Using additional titanium and boron in the aluminum alloys increases the longitudinal graphite/aluminum properties, but does nothing for the crosswise properties. Graphite/aluminum composites have low crosswise properties and low crosswise strengths. The rayon based graphite/alloy 201 composite has a crosswise strength of 34.5 MPa, which is much less than 137.9 MPa. Graphite/aluminum composites have considerably low transverse strengths.

Corrosion resistance has been studied in graphite/aluminum composites. Galvanic corrosion is present in graphite/aluminum composites because of the galvanic couples of graphite and aluminum that exist, and also because couples are present in the aluminum matrix and strengthening foils. At low stress levels, fracture tracks and galvanic action can cause early failure.

The unique physical and mechanical properties of graphite-reinforced aluminum can be found from Figures 3.2-1 to 3.2-7 and from Tables 3.2-3 to 3.2-5.

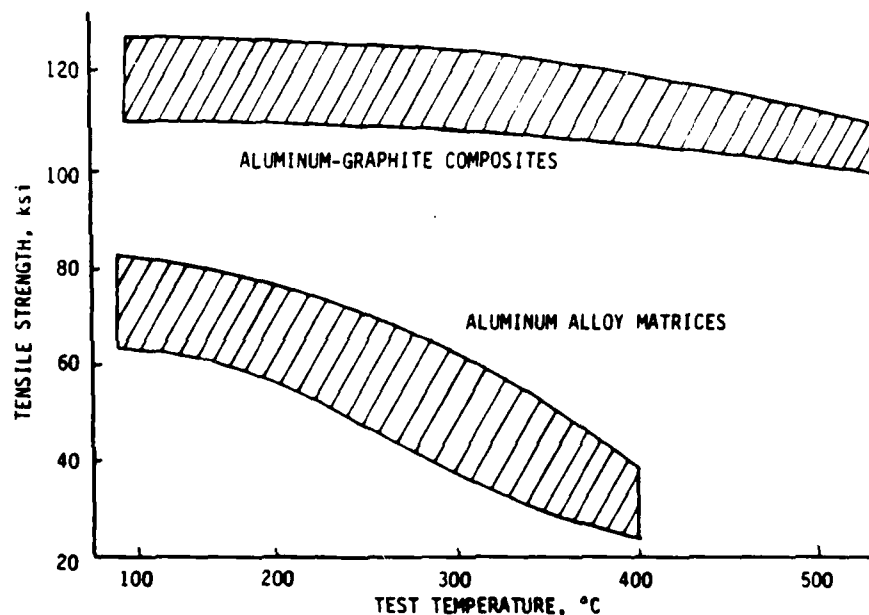


Figure 3.2-1. Typical Elevated Temperature Properties of Aluminum/Graphite Composites (Reference 3-5)

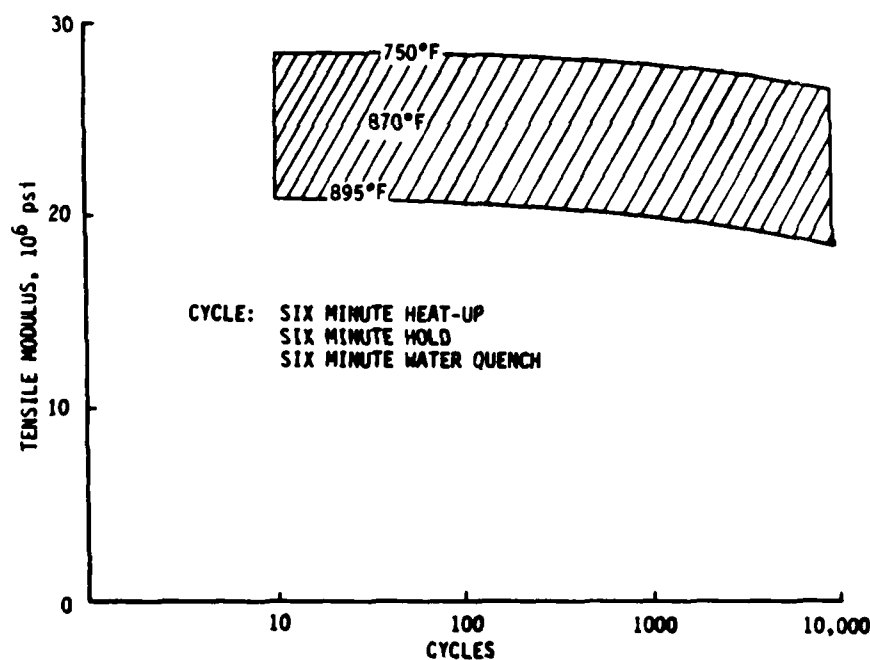


Figure 3.2-2. Typical Retained Room Temperature Tensile Modulus of 32 (v/o) T50 Graphite/Aluminum Composite Wire after Thermal Cycling (Reference 3-6)

TABLE 3.2-3. Tensile Properties of Various Aluminum Alloy--
Thornel-75 (Graphite) Composites (Reference 3-7)

Matrix composition	Specimen condition	Volume percent fiber	Strength				Average modulus (GN/m ²)	Average modulus (psi)
			Average	Number of samples	Low value	High value		
			MN/m ²		(psi)	(psi)		
Commercially pure aluminum	As-infiltrated Pressed	32	68	8	65,000	116,000	178	25.7
		35	65	7	85,000	104,000	147	21.3
Aluminum-7 w/o zinc	As-infiltrated Pressed	32	71	7	59,000	132,000	166	24.1
		38	87	10	102,000	155,000	190	27.5
Aluminum-7 w/o magnesium	As-infiltrated	31	68	4	87,000	124,000	195	28.1
Aluminum-13 w/o silicon	As-infiltrated	22	55	7	73,000	88,000	165	23.8

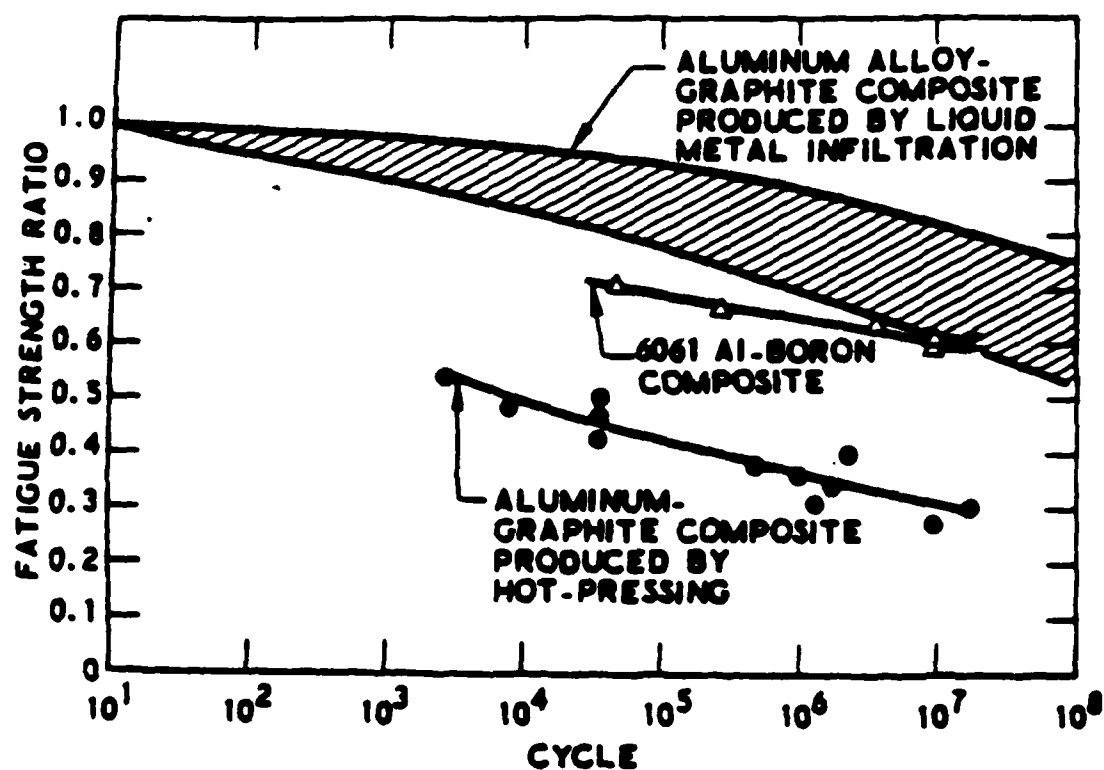


Figure 3.2-3. Comparison of Fatigue Behavior between Aluminum-Graphite Composites and Other Metal Matrix Composites
(Reference 3-8)

TABLE 3.2-4. Corrosion Behavior of Aluminum--Thornel-50 (Graphite) Composite for 1000 Hr (Reference 3-9)

Environment	356 aluminum		356 aluminum-- 25 v o Thornel-50	
	(23°C)	(50°C)	(23°C)	(50°C)
Distilled water	Nil	Nil	1.2	1.2
3.5% NaCl solution	1.1	4.9	4.7	9.8

^aMils per year (1mil = 25 μ m).

TABLE 3.2-5. Summary of Transverse Tensile Strengths of Various Aluminum--Graphite Composite Systems (Reference 3-10)

Composite		Average		High (psi)	Low (psi)	Number of tests
Fiber	Matrix	(MN/m ²)	(psi)			
Thornel-50	Al-12Si	26	3777	6500	433	9
Courtaulds	220 Al	42	6117	8690	3760	20
Courtaulds	356 Al	70	10,008	14,600	5500	26
Courtaulds HM	Al-10Mg	29.5	4280	4500	3600	5
Whittaker-Morgan	356 Al	50	7300	11,300	4100	5
Whittaker-Morgan	7075 Al	21	3040	5100	400	5

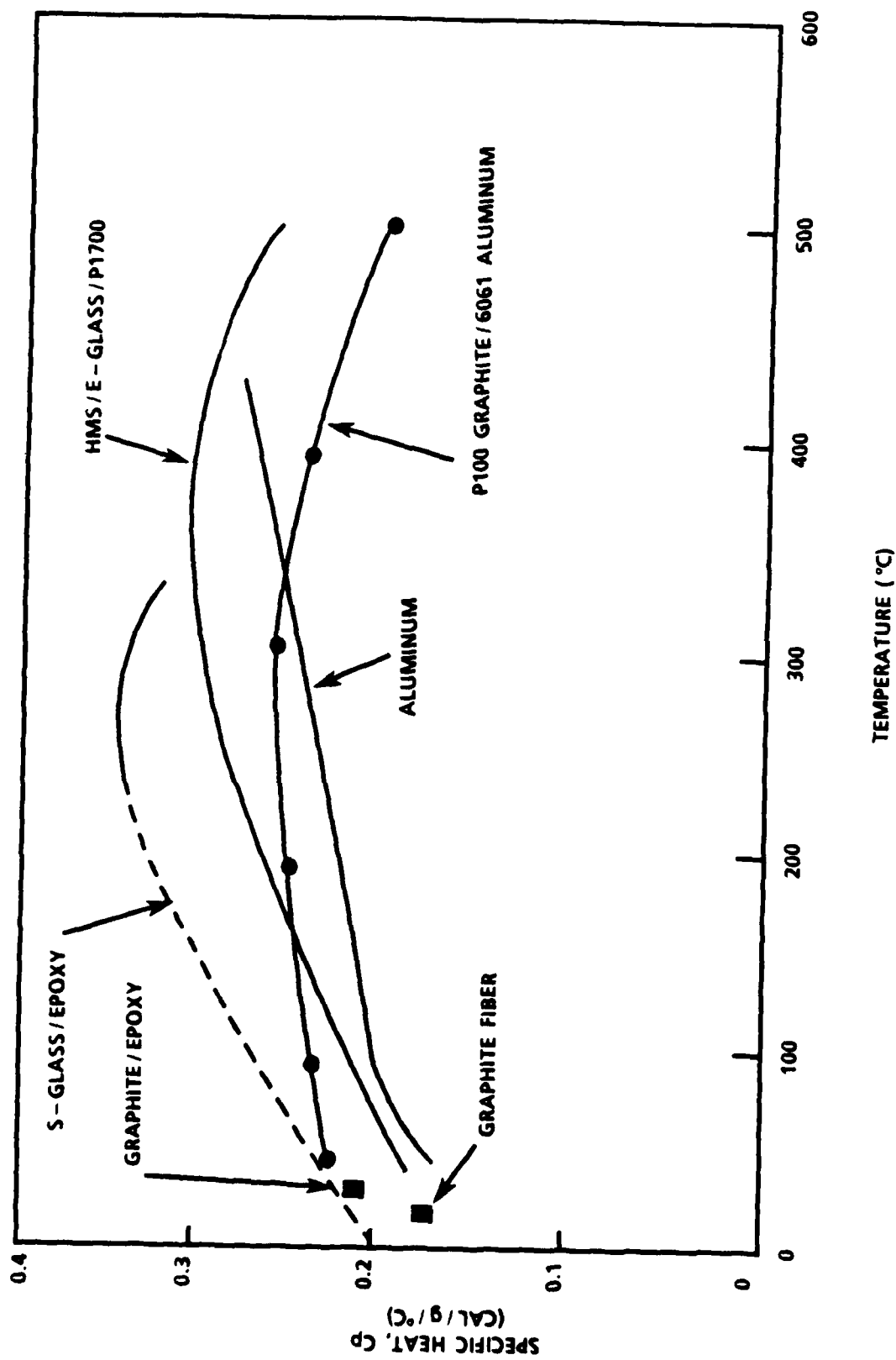


Figure 3.2-4. Specific Heat of Graphite/Aluminum Composite (Reference 3-11)

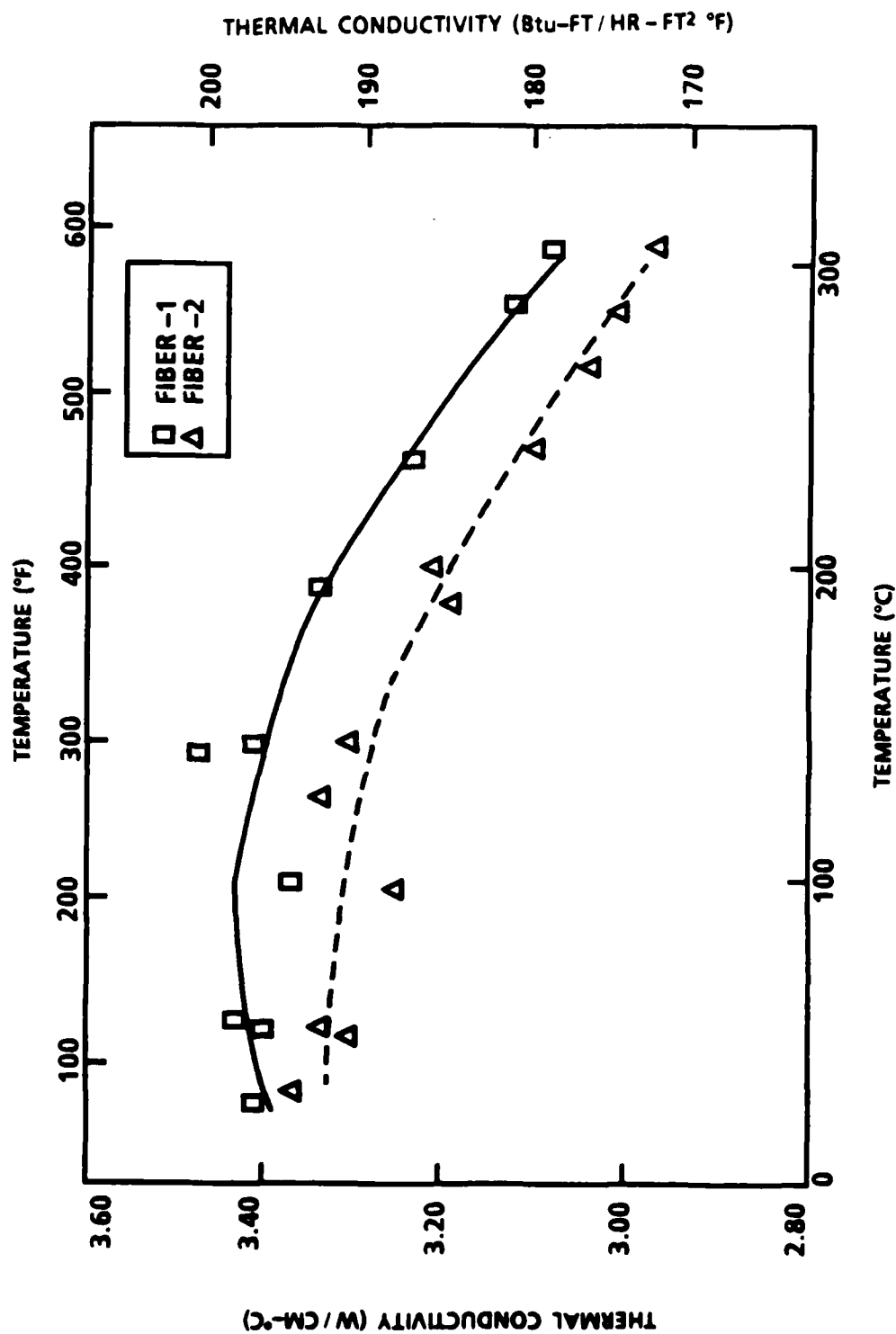


Figure 3.2-5. Thermal Conductivity P100 Graphite/6061 Aluminum Composite
(Reference 3-12)

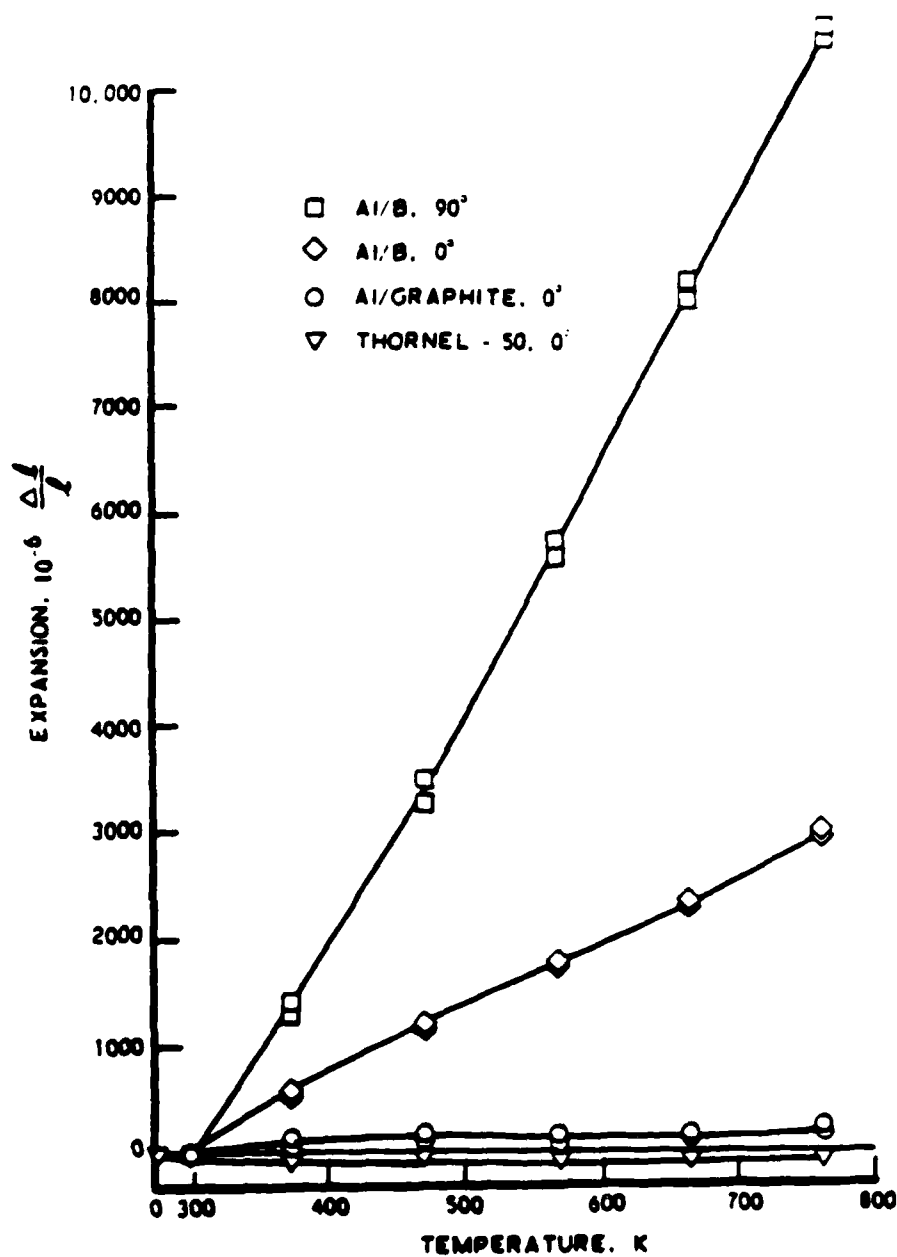


Figure 3.2-6. Thermal Expansion versus Temperature for Graphite/Aluminum
(Reference 3-13)

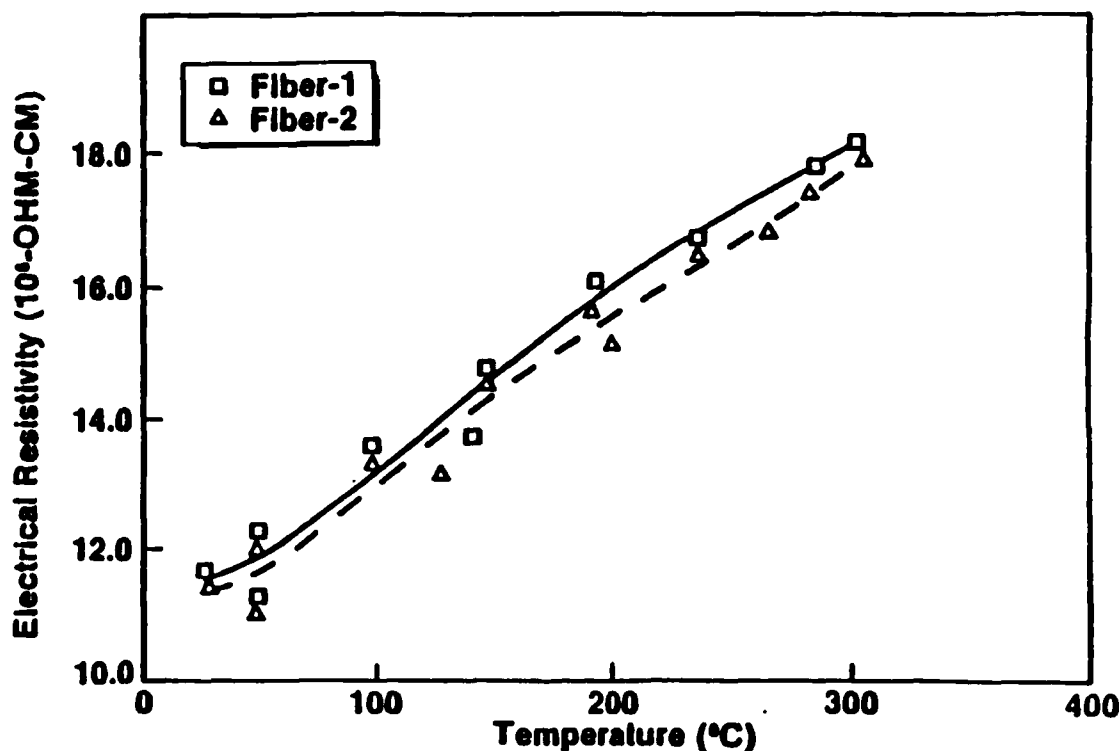


Figure 3.2-7. Electrical Resistivity of Graphite P100/6061 Aluminum Composite
(Reference 3-14)

3.2.2.2 Boron-Reinforced Aluminum. Borsic/aluminum and boron/aluminum composites can display tensile strengths greater than 1379 MPa. This is due to high strength boron fibers when the borsic/aluminum composite nears the rule of mixture levels. The size of the filament's diameter affects the properties of the composite. It is often found that the smaller the filament diameter, the weaker the composite properties (Table 3.2-6).

Graphite/aluminum composite transverse properties are inferior compared with boron/aluminum and borsic/aluminum composite properties. In Table 3.2-7 common values of transverse properties for some boron/aluminum and borsic/aluminum systems are shown. A composite with 45 percent boron in 2024-T6 alloys displays transverse strengths of 331 MPa while a composite with 50 percent boron in 6061F alloys normally has transverse tensile strengths of 124.1 MPa. The average transverse strength is dependent upon the quality and the matrix of the alloy.

When compared, the longitudinal strengths of these composites are on the order of 10 to 20 percent greater than the crosswise strengths. As a result of this large difference, boron/aluminum and borsic/aluminum composites are often produced with the filaments arranged in random directions.

Fatigue loading in boron/aluminum composites is superior, and is valuable in system for structural applications. Fatigue strength is dependent upon many things, including work hardening, tensile strength, modulus, notch sensitivity as well as chemical reaction properties and products. At 60 percent volume, boron/aluminum composites at $\times 10^7$ cycles have obtained fatigue strengths of 1379 MPa. The reaction of composite materials can also be affected by the modulus and strength of the filament matrix bond as well as previous or consolidation-generated defects. Other unique physical and mechanical properties of boron-reinforced aluminum can be found from Figures 3.2-8 to 3.2-15 and from Tables 3.2-7 to 3.2-9.

TABLE 3.2-6. Longitudinal Tensile Properties of B/Al Composites
(Reference 3-15)

Matrix	Fiber, volume %	Fiber Type and Diameter	Ultimate Ten- sile Strength, psi	Modulus, psi
2024	47	boron, 5.6 mil	212 000	32 000 000
6061	50	boron, 5.6 mil	208 000	32 000 000
6061	54	boron, 5.7 mil dia	203 000	36 600 000
6061	30	boron, 5.7 mil dia	115 000	17 600 000
6061	50	boron, 4.0 mil	180 000	...
6061	50	boron, 8.0 mil	210 000	...

TABLE 3.2-7. Typical Transverse Properties of B/Al and Borsic/Al Composites
(Reference 3-16)

Matrix	Boron, volume %	Borsic, volume %	Transverse Strength, 10 ³ psi	Modulus, 10 ⁶ psi
2024 F	45 (5.6 mil)		27	...
2024-T6	45 (5.6 mil)		48	...
6061 F	50 (5.6 mil)		18.9	...
6061-T6	50 (5.6 mil)		41.7	...
6061 F		52 (5.7 mil)	20	...
6061-T6		52 (5.7 mil)	36	19
2024 F		56 (5.7 mil)	22	23
2024-T6		56 (5.7 mil)	46	25

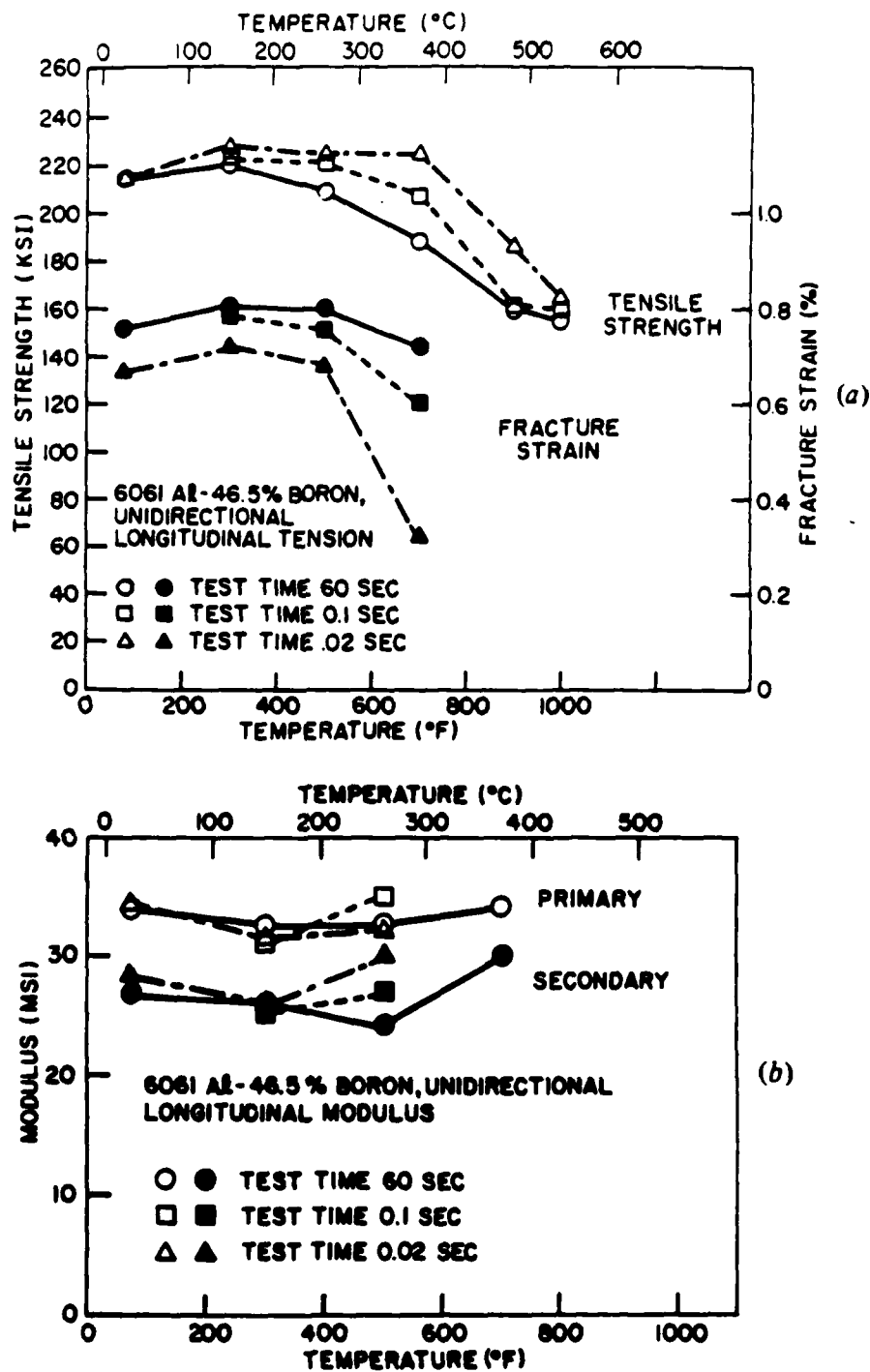


Figure 3.2-8. Tensile Properties of 6061 Aluminum-46.5 Percent Boron Unidirectional Composite at Several Temperatures and Strain Rates. (a) Longitudinal Ultimate Strength and Fracture Strain; (b) Longitudinal Young's Moduli (Reference 3-17)

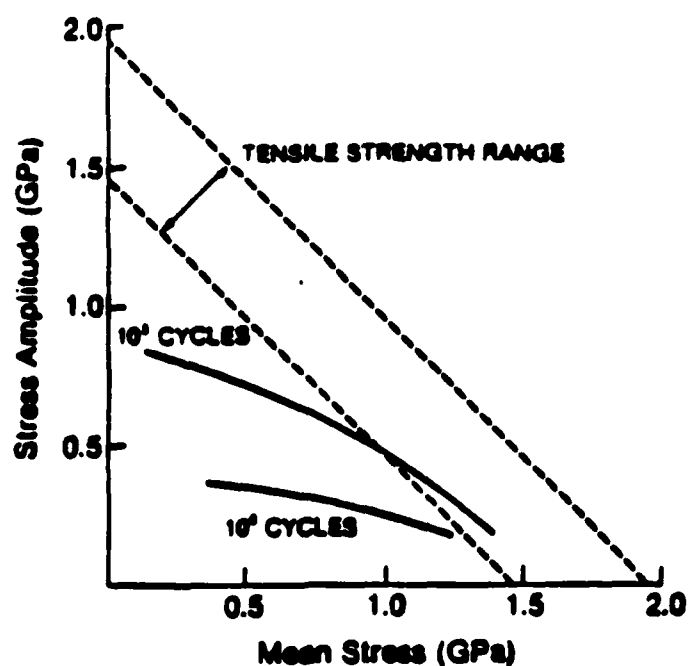


Figure 3.2-9. Fatigue Failure Envelopes for Boron-Aluminum
(Reference 3-18)

TABLE 3.2-8. Maximum Temperatures for Metals Reinforced with
Boron and Carbon Fibers (Reference 3-19)

System	Temperature (C)	Remarks
C-Al	500	Al contains 12% Si
B-Al	540	B coated with SiC
B-Ti	650	B coated with SiC
B-Ti	540	Oxygen present; B coated

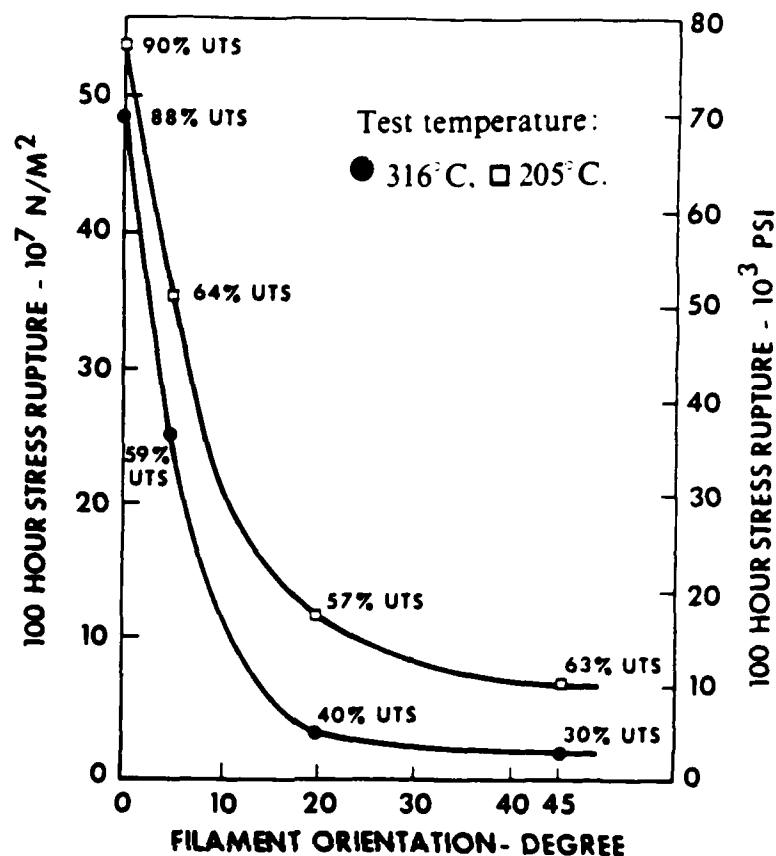


Figure 3.2-12. Applied Tensile Stress to Cause Rupture at 100 Hr as a Function of Angle to Principal Fiber Axis for Aluminum Reinforced with 100µm Boron (Reference 3-22)

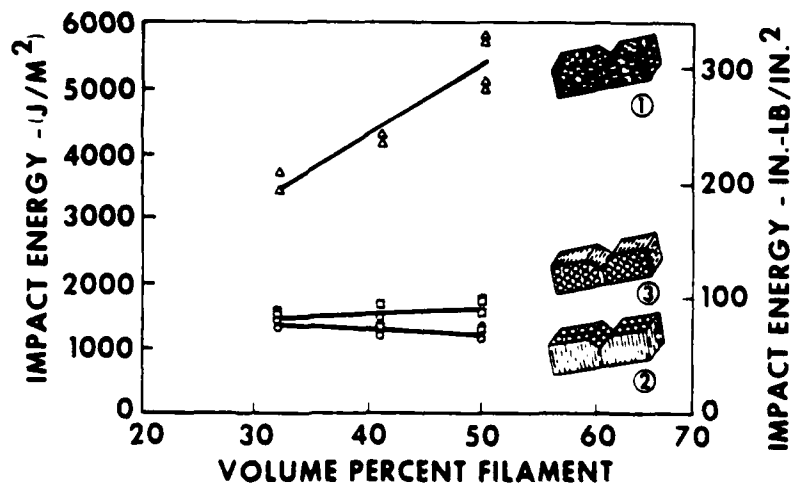


Figure 3.2-13. Notched Charpy Impact Energy as a Function of Specimen Orientation and Volume Fraction of Fiber. Material is 6061 Aluminum Reinforced with 100-µm Borsic (Reference 3-23)

TABLE 3.2-9. Notched Charpy Impact Energy at 23 °C for
Boron/Aluminum Composites Containing 50-60
Percent Fiber by Volume
(Reference 3-24)

Spec #	Matrix*	Fiber	Fabrication Conditions			Orientation	Impact Energy	
			Temp °C	Pressure 10 ⁶ N/m ²	Time min		J	ft-lbs
1	6061-F	BORSIC	565	145.0	60	LT	6.7	5.0
2	6061-F	BORSIC	565	145.0	60	TT	2.0	1.5
3	6061-F	BORSIC	565	145.0	60	TL	1.3	1.0
4	6061-F	BORSIC	490	72.5	30	LT	7.8	5.8
5	6061-F	BORSIC	450	72.5	30	LT	9.4	7.0
6	6061-F	Boron	450	145.0	30	LT	17.7	13.1
7	6061-F	Boron	480	145.0	30	LT	13.2	9.7
8	6061-F	Boron	450	72.5	30	LT	18.5	13.7
9	1100	BORSIC	450	72.5	30	LT	18.4	13.6
10	1100	Boron	450	72.5	30	LT	26.0	19.2
11	1100	Boron	450	72.5	30	LT	22.8	16.9
12	1100	Boron	450	72.5	30	LT	28.4	21.0
13	1100	Boron	450	72.5	30	LT	30.0	22.2
14	1100	Boron	450	72.5	30	LT	>30.0	>22.3
15	1100	Boron	450	145.0	30	LT	26.1	19.3
16	1100	Boron	450	145.0	30	LT	21.5	15.9
17	1100	Boron	450	145.0	30	LT	28.2	20.9
18	2024-F	Boron	450	72.5	30	LT	8.1	6.0
19	2024-F	Boron	450	72.5	30	LT	15.4	11.4
20	5052/S6	Boron	450	145.0	30	LT	8.0	5.9
21	6061/1100-F	Boron	450	145.0	30	LT	26.6	19.7
22	6061/1100-F	Boron	450	145.0	30	LT	25.6	18.9
23	6061/1100-T6	Boron	450	145.0	30	LT	22.3	16.5

* F and T 6 indicate the as-fabricated and heat treated conditions respectively

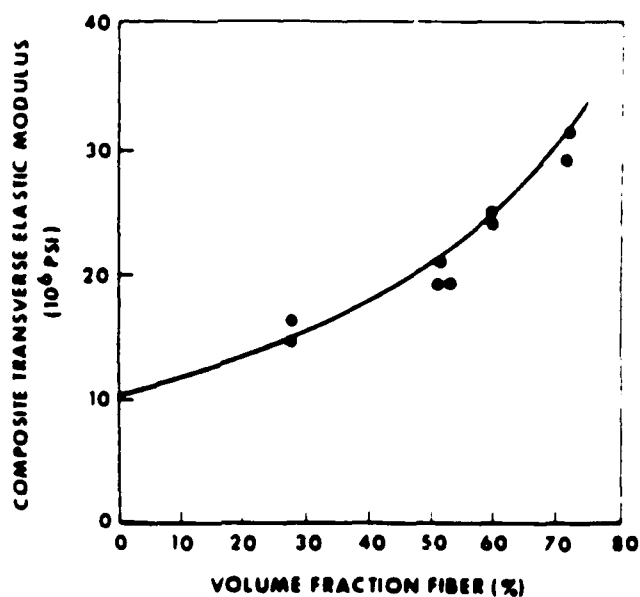


Figure 3.2-14. Transverse Tensile Elastic Modulus for 5.7 mil Borsic-6061 Composites (Reference 3-25)

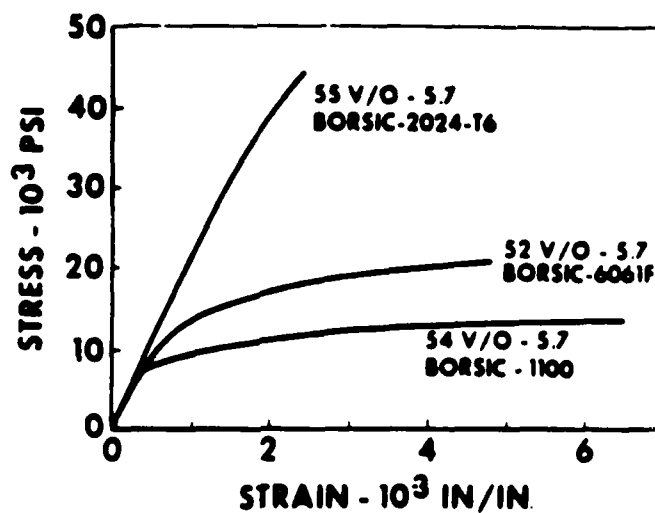


Figure 3.2-15. Transverse Tensile Stress-Strain Curves for Borsic-2024 Composites (Reference 3-26)

3.2.2.3 Silicon Carbide-Reinforced Aluminum. Silicon carbide aluminum composite stands to be a competitor of boron-aluminum systems because of high environmental resistance and mechanical properties such as its ability to mix well with molten aluminum, high temperature reliability, and low raw material cost. As a result silicon carbide (SiC) filament is possibly a high performance/low cost metal matrix filament that can be used in composite structural applications. In an attempt to keep cost down, die casting and extrusion fabrication methods have been employed in the production of the aluminum/SiC whisker composites.

SiC whiskers have a high tendency to align when directed forces like forging, rolling and extrusion are applied to the composite. They align in the direction of the applied load. Because of their small size, desirable orientation is gained. This amplifies the aluminum alloy's longitudinal properties. The whiskers can also be wetted and bonded easily to the aluminum alloy. The composites also have very appealing crosswise properties. For example, 344.7 MPa is the lowest crosswise strength. Crosswise modulus was measured with values of 103.4 GPa. The parts that were measured had undergone high extrusion. The ratio of extrusion was 30 to 40. A 2 in. (50 mm) diameter billet was extruded to a .2 in. (.5 mm) sheet. Tubes can also be extruded.

Al/SiC whiskers components impact and corrosion characteristics have been evaluated in introductory studies. The results obtained have not uncovered any problems. Other unique physical and mechanical properties of silicon carbide reinforced aluminum can be found in Figures 3.2-16 through 3.2-27 and in Table 3.2-10.

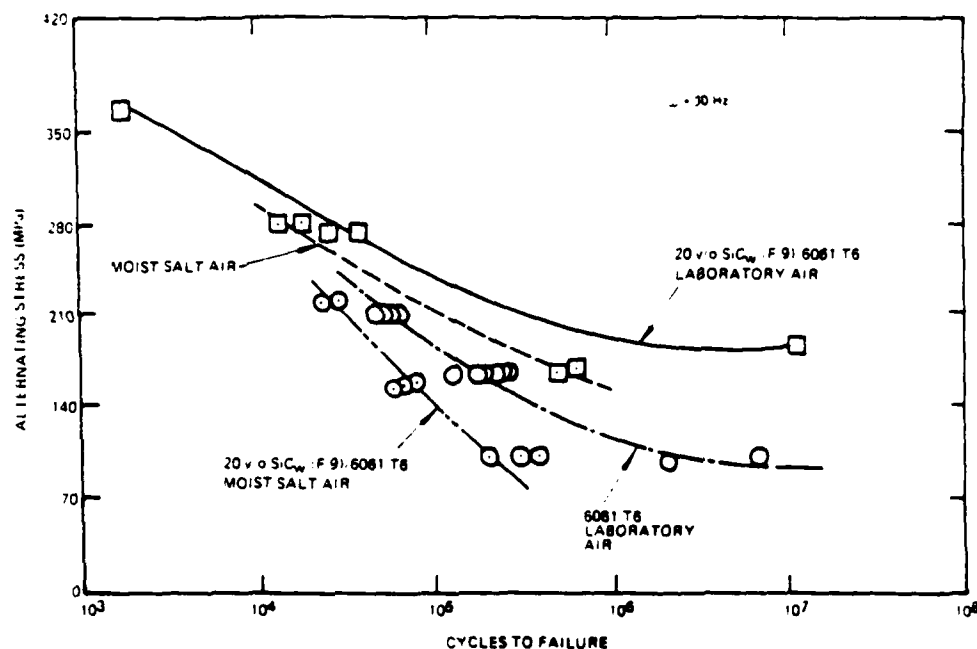


Figure 3.2-16. Alternating Stress versus Number of Cycles for 20 v/o SiC_w (F-9)/6061-T6 Al Specimens Compared to 6061-T6 Subjected to Corrosive Environments (Reference 3-27)

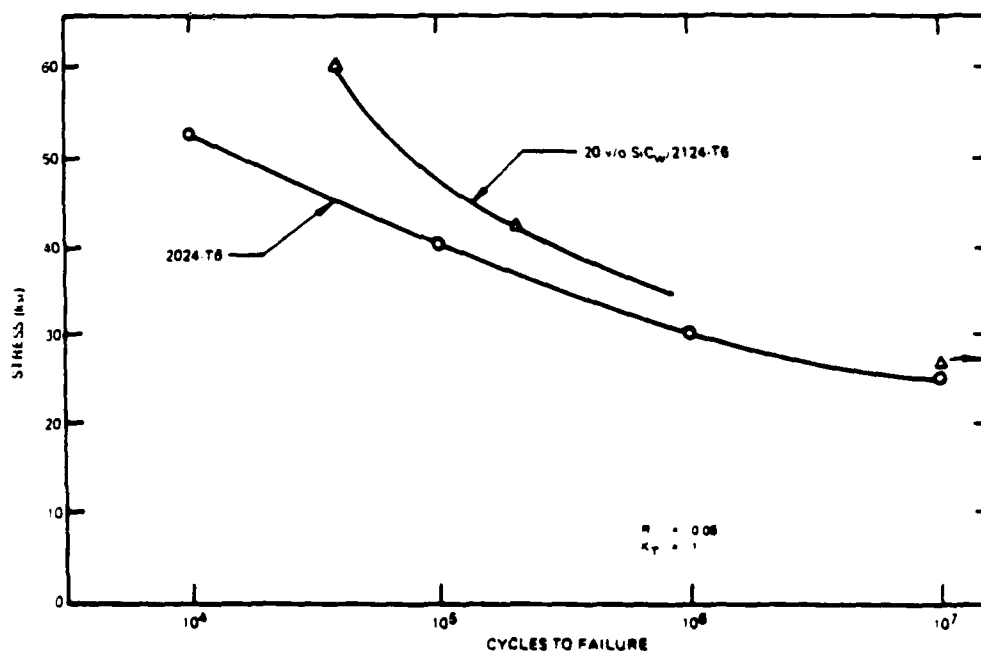


Figure 3.2-17. Room Temperature Fatigue Data for Unreinforced and Reinforced 2124-T6 Al Composite (Reference 3-28)

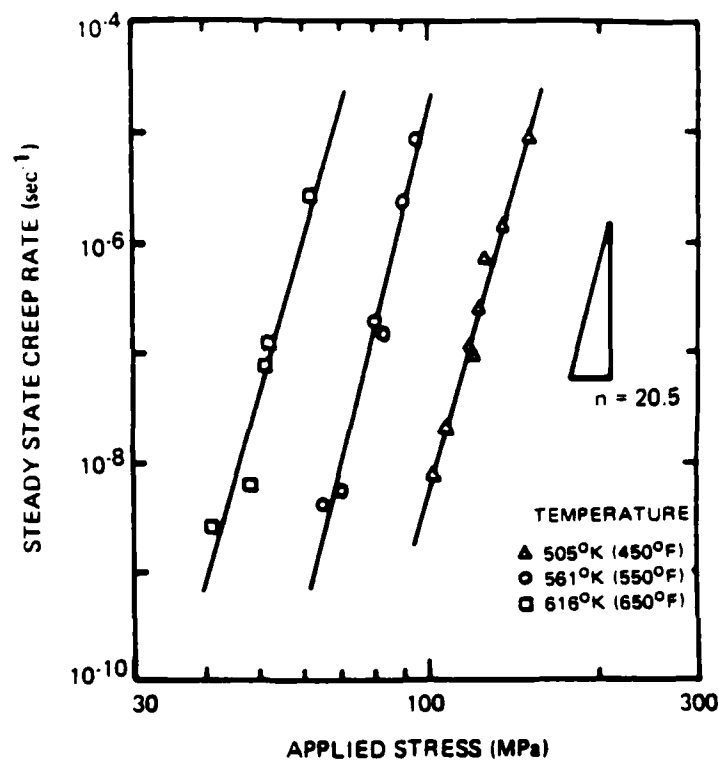


Figure 3.2-18. Steady State Creep Rate as a Function of Applied Stress for 20 w/o SiC_w/6061 Al at Temperatures between 505° and 616°K (Reference 3-29)

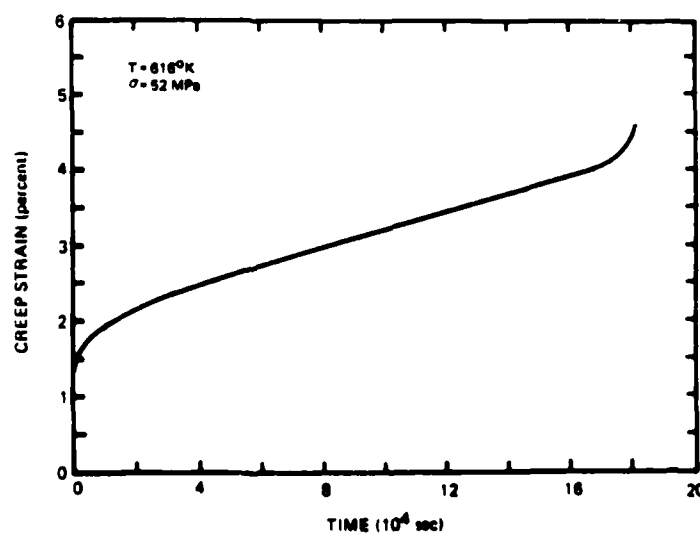


Figure 3.2-19. Typical Creep Curve for 20 w/o SiC_w/6061 Al Composite (Reference 3-30)

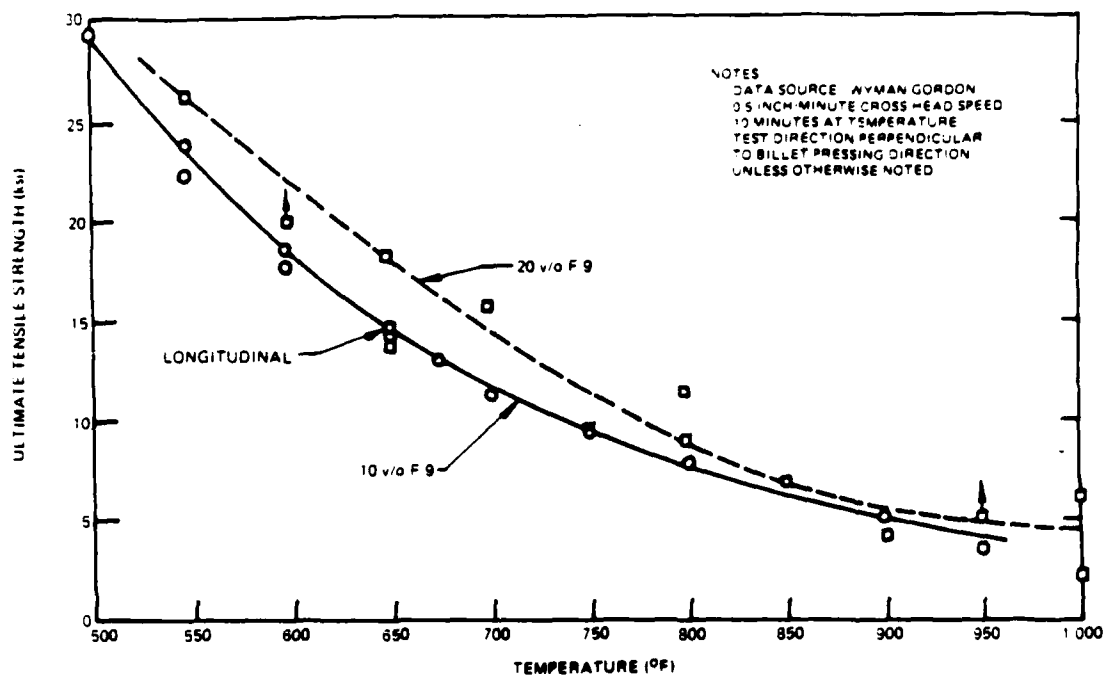


Figure 3.2-20. Ultimate Tensile Strength versus Temperature for SiC_w (F-9)/2124 Al (SXA™ 24) Billet (Reference 3-31)

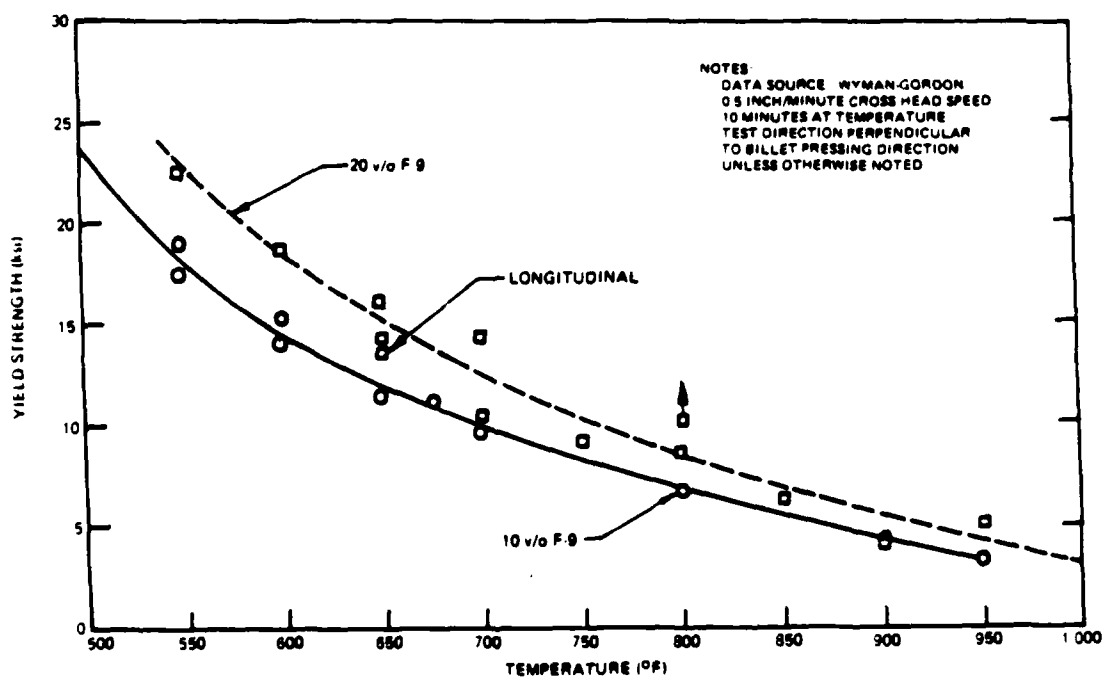


Figure 3.2-21. Yield Strength versus Temperature for SiC_w (F-9)/2124 Al (SXA™ 24) Billet (Reference 3-32)

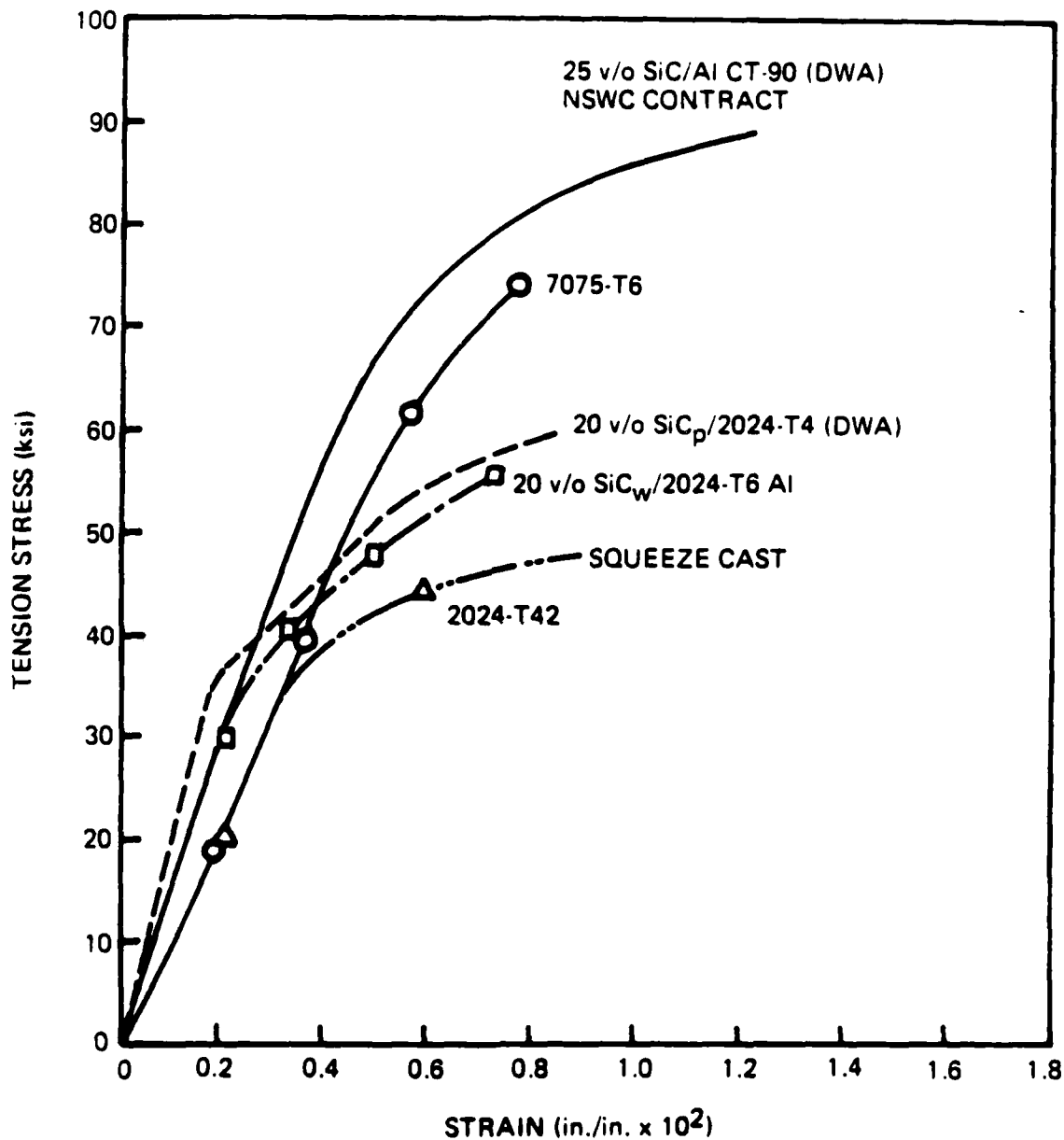


Figure 3.2-22. Stress-Strain Curves for a Number of SiC/Al Composites
(Reference 3-33)

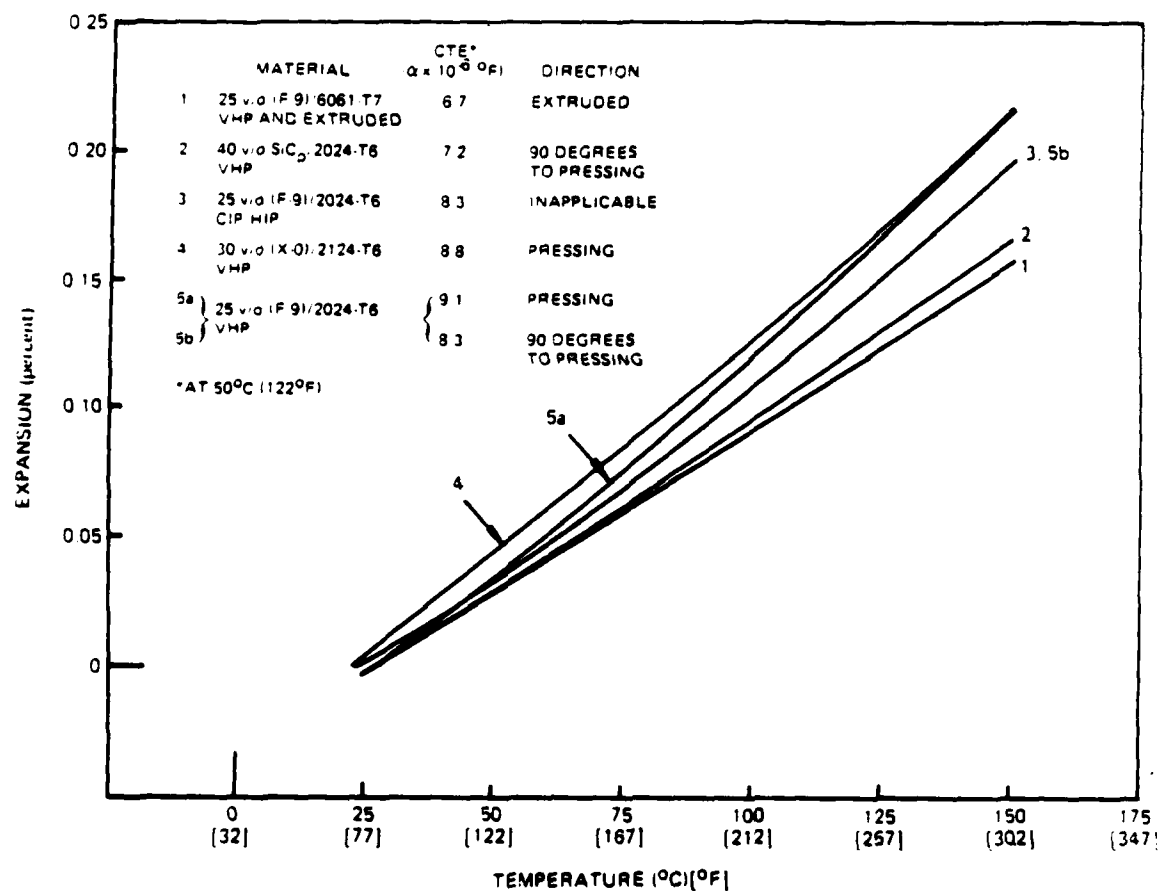
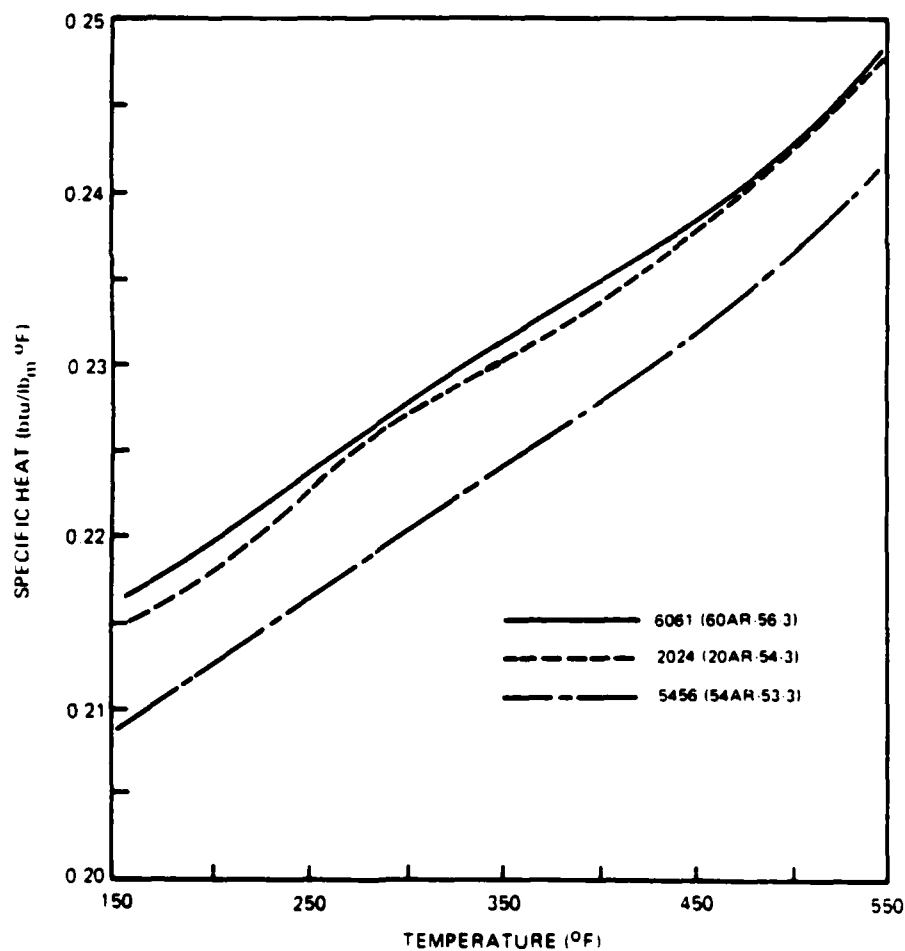


Figure 3.2-23. Linear Coefficient of Thermal Expansion for Five SiC/Aluminum Matrix Composites (Reference 3-34)

TABLE 3.2-10. Thermal Properties of SiC_w/2024 Al at Room Temperature
(Reference 3-35)

Material	Conductivity, k (Btu/ft/sec °F)	Specific Heat, C _p (Btu/lb _m °F)	Density (lb _m /ft ³)
5083 Al	0.019	0.23	165.9
7075 Al	0.025	0.23	165.9
15.7 v/o SiC _w /2024 Al	0.0158	0.24	177.9
25 v/o SiC _w /2024 Al	0.0125	0.24	177.9

Figure 3.2-24. Specific Heat Versus Temperature for 15 v/o SiC_w/Al
(Reference 3-36)

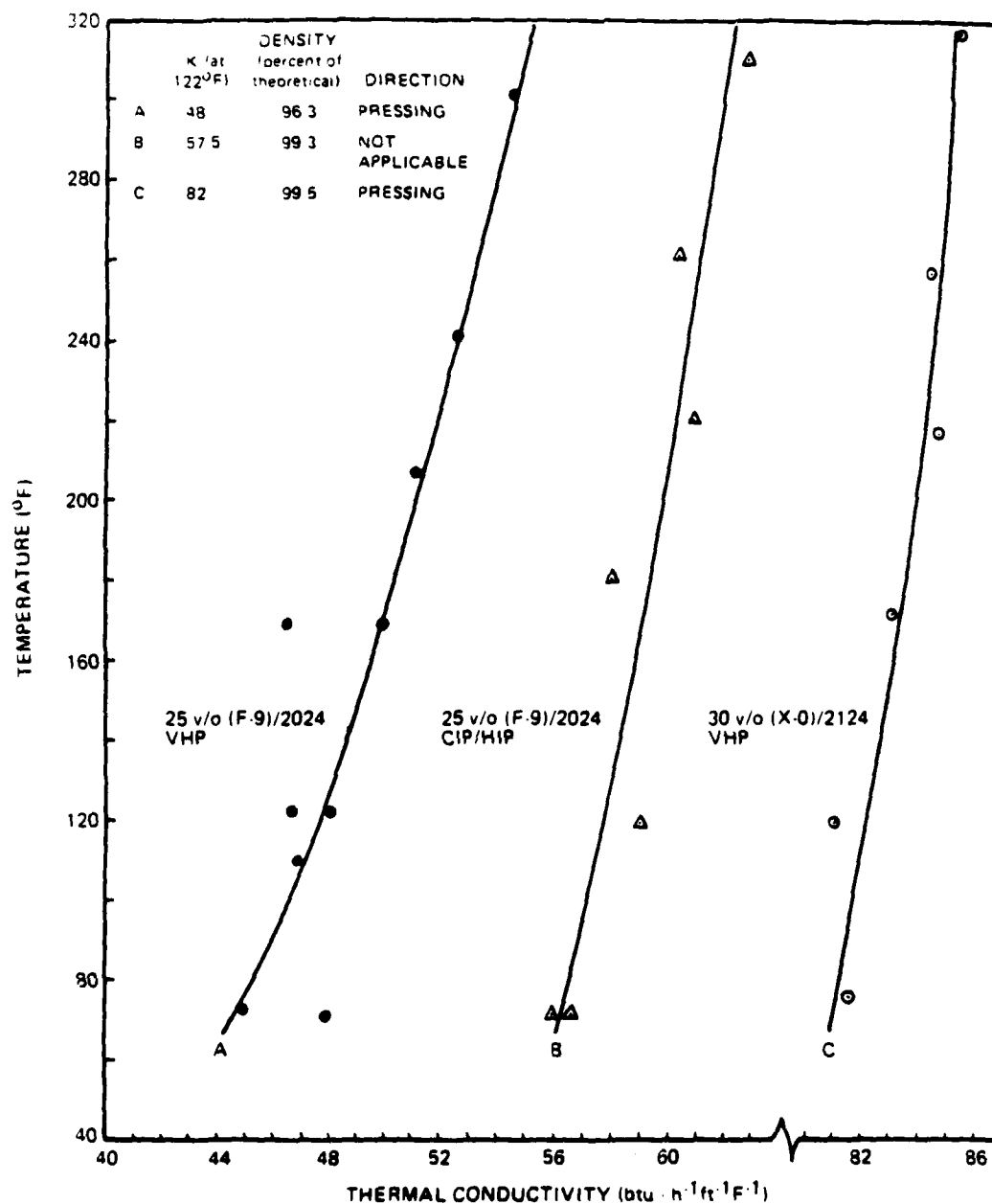


Figure 3.2-25. Thermal Conductivity of Three SiC/Aluminum Matrix Composite
(Reference 3-37)

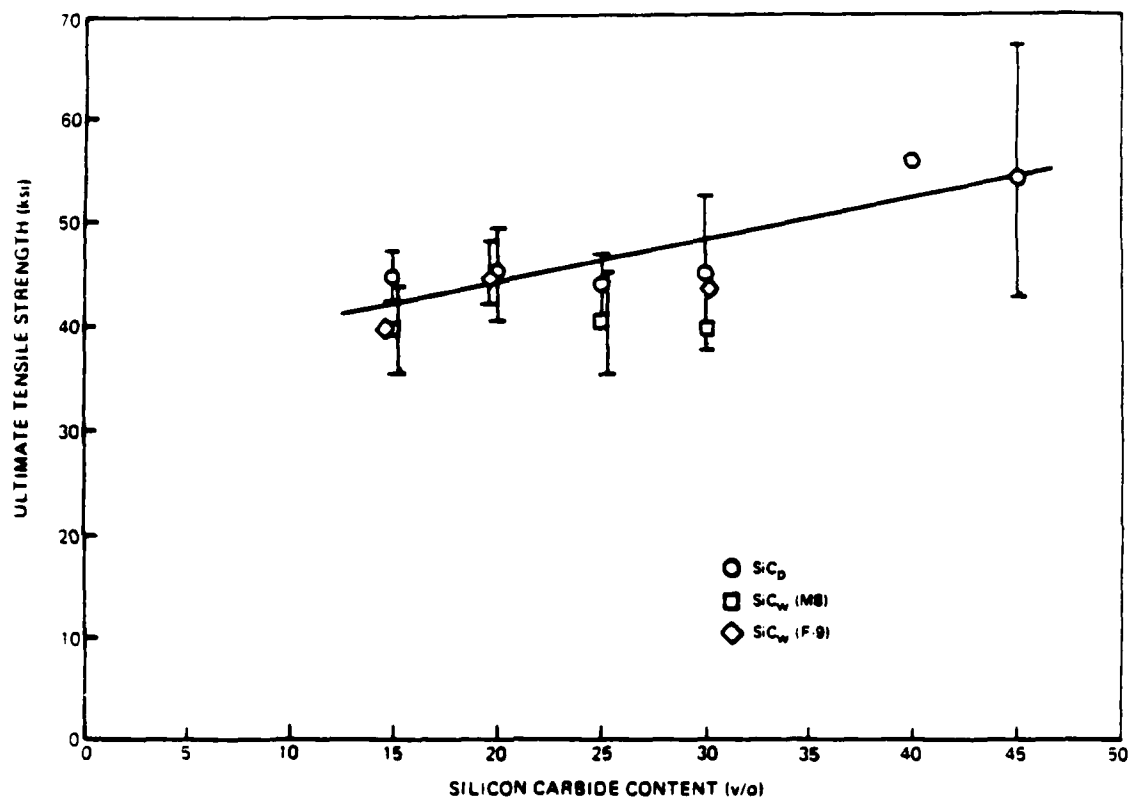


Figure 3.2-26. Ultimate Strength as a Function of SiC Reinforcement Content for as-Fabricated 2024 Matrix Composites (Reference 3-38)

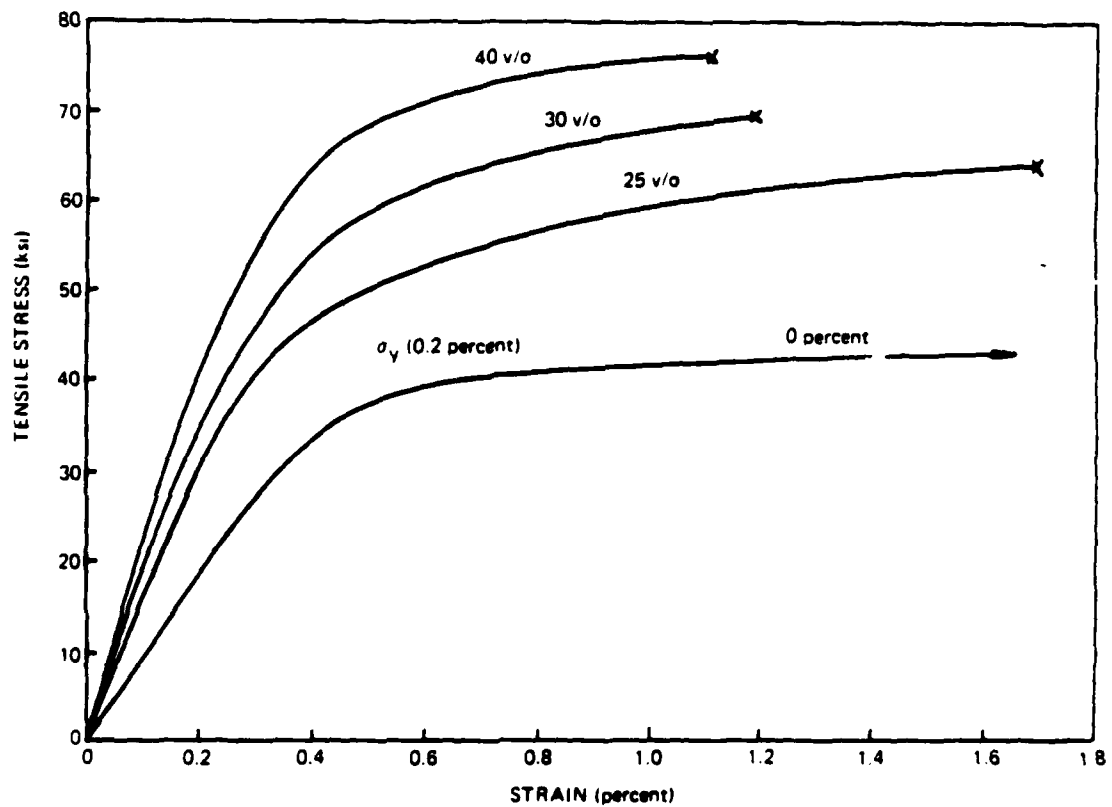


Figure 3.2-27. Stress-Strain Curves for 6061-T6 Aluminum with Various Levels of SiC_p Reinforcement (Reference 3-39)

3.3 Magnesium Metal Matrix Composites.

3.3.1. Background. Magnesium is an excellent candidate for lightweight, high strength composite matrix material. Advantages of magnesium matrices include a low density and low reaction rate between the matrix and fiber during fabrication. Magnesium matrices have been used with brittle fibers such as boron, silicon carbide, and graphite filaments. Magnesium matrix composites typically have weights 30% lighter than aluminum alloys. The specific properties of magnesium composites are excellent, and thermal expansion remains zero or near zero through a wide range of temperature. This excellent thermal expansion is due to the combination of properties of the matrix and fiber, and like strength properties, may be tailored to meet specific application requirements.

Magnesium matrix composites are currently available in cast shapes including flat plates, T-sections, rods, hollow cylinders, and irregular specialty parts. Production methods for new cast shapes must take into account the orientation and holding of the fibers during fabrication. For complex systems, this may prove difficult and expensive. Costs are expected to decrease as less laborious production techniques are developed. Initial production costs substantially more than subsequent castings.

3.3.2 Properties of Magnesium Matrix Composites. Magnesium is one of the few lightweight metals which does not offer problems in interaction with the advanced reinforcement fibers such as boron, silicon carbide, and graphite. At the present time graphite, alumina, and boron fibers are being strongly considered for use with magnesium matrix. Graphite/magnesium offers the unique advantages of near-zero thermal expansion over a wide range of temperatures. Graphite reinforced magnesium with 40 percent by fiber volume possesses a typical tensile strength of 120,000 psi and an elastic modulus of about 25 million psi. Unique physical and mechanical properties of advanced fibers reinforced magnesium matrix are summarized and presented from Figures 3.3-1 through 3.3-6 and from Tables 3.3-1 through 3.3-3.

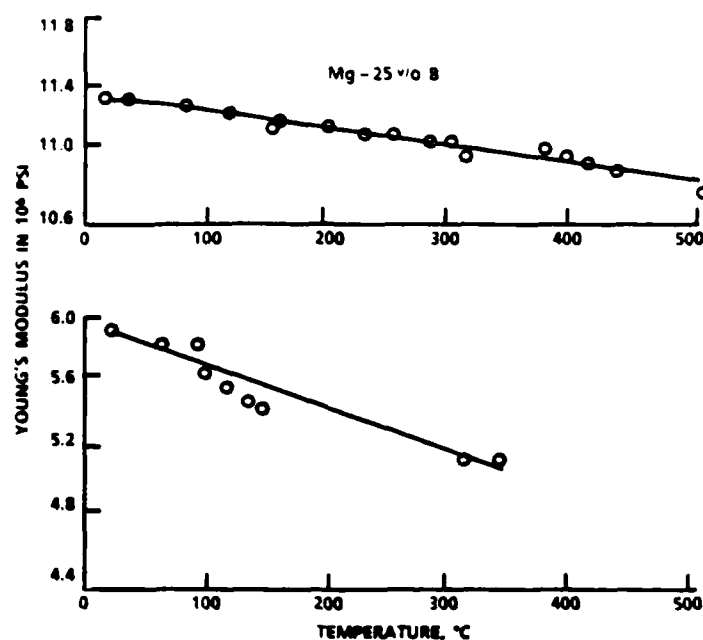


Figure 3.3-1. Elastic Modulus of Magnesium Matrix With and Without Boron Filament as a Function of Temperature
(Reference 3-40)

Table 3.3-1 Charpy Fracture Energy for Alumina/Magnesium
(50 percent V_f) (Reference 3-41)

MATERIAL CONDITION	TEST TEMPERATURE	FIBER DIRECTION	TEST DIRECTION	CHARPY IMPACT ENERGY (FT-LBS)
AS RECEIVED	RT	0°	0°	0.43
		0°	90°	0.32
		±22½°	0°	0.54
		±22½°	90°	0.45
	300 F	0°	0°	0.49
		0°	90°	0.25
		±22½°	0°	0.32
		±22½°	90°	0.28
TS (HEAT TREATED)	RT	0°	0°	0.44
		0°	90°	0.26
		±22½°	0°	0.44
		±22½°	90°	0.35
	300 F	0°	0°	0.38
		0°	90°	0.24
		±22½°	0°	0.36
		±22½°	90°	0.229

6027

Table 3.3-2 Average Ultimate Tensile Strength and Elastic Modulus Properties of Boron-Magnesium Composites (Reference 3-42)

FILAMENT (PERCENT VOLUME)	U. T. S. (KSI)	ELASTIC MODULUS (MSI)
50	16.7	7.3
35	69.5	22.0
28	79.0	17.2
19	45.2	15.9
10	22.4	8.6
6	15.6	8.4

6027

Table 3.3-3 Average Ultimate Tensile Strength and Elastic Modulus Properties of Tantalum-Magnesium Composites (Reference 3-43)

FILAMENT (PERCENT VOLUME)	U. T. S. (KSI)	ELASTIC MODULUS (MSI)
40	28.8	13.2
32	32.2	13.0
28	30.2	11.8
19	23.1	10.4
10	15.9	5.2
0	12.9	6.4

6027

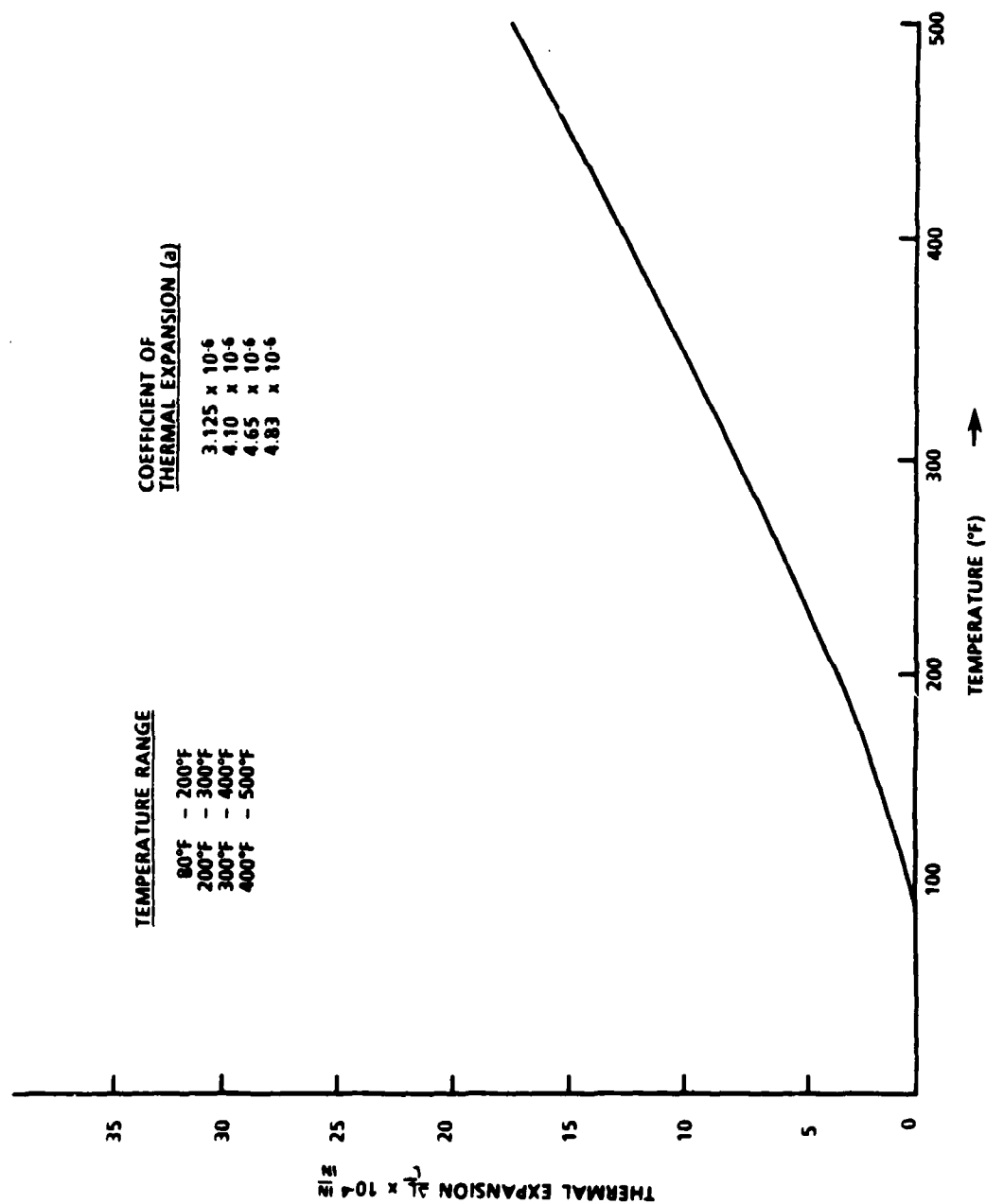


Figure 3.3-2 Thermal Expansion Versus Temperature for Alumina Reinforced Magnesium in 00-00 Fiber Direction. (Reference 3-44)

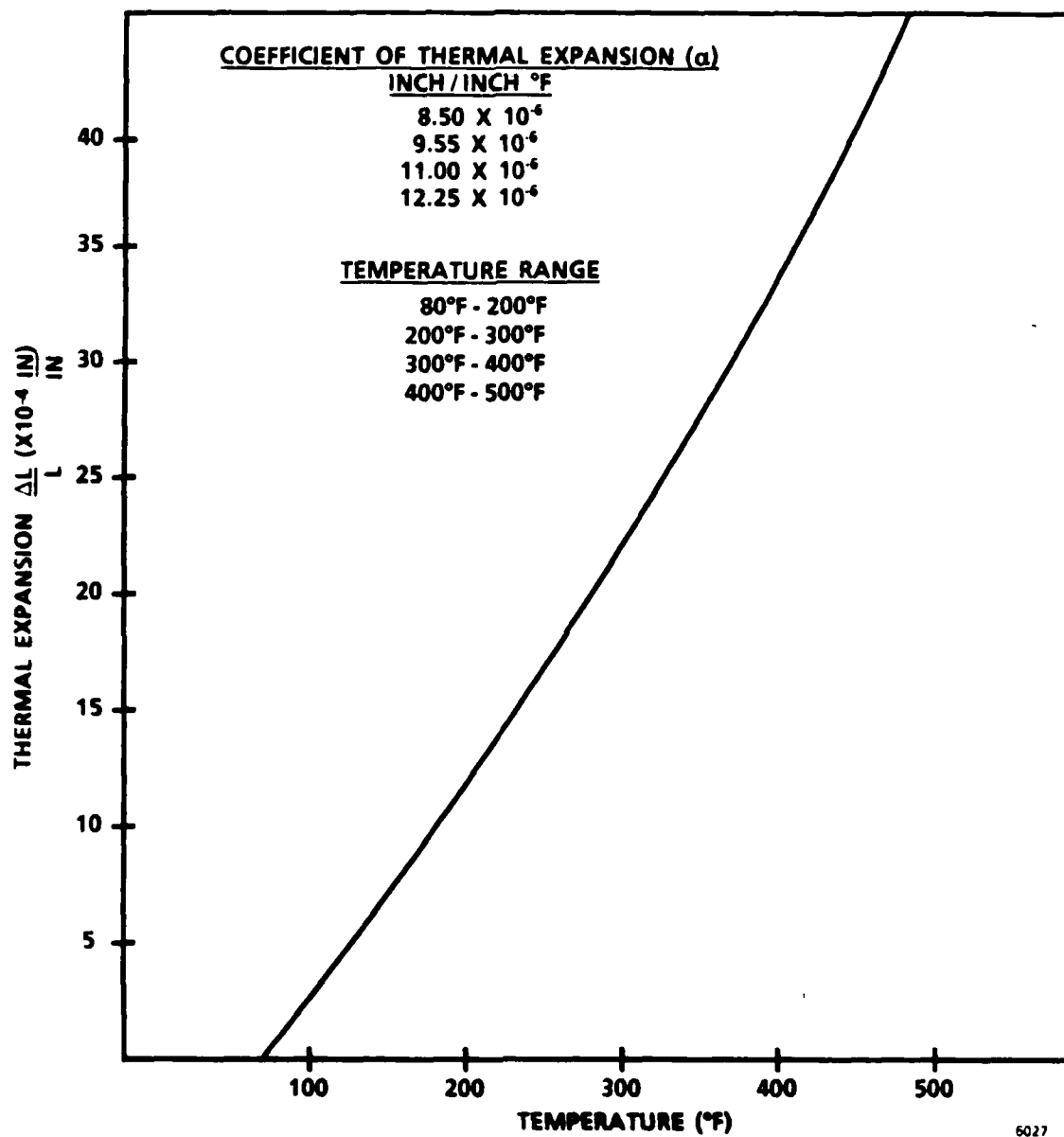


Figure 3.3-3 Thermal Expansion Versus Temperature For Alumina Reinforced Magnesium in 0-90° Fiber Direction.
 (Reference 3-45)

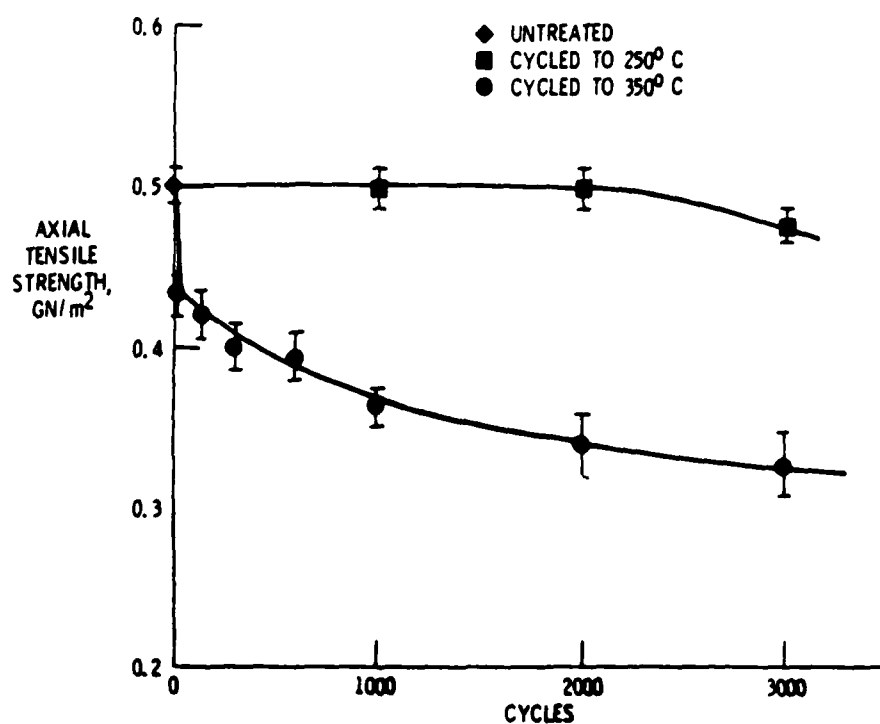


Figure 3.3-4. Room Temperature Axial Tensile Strengths of 55 Volume Percent FP-Al₂O₃/EZ33Mg Composites after Cycling to 250 °C or 350 °C for Indicated Number of Cycles. Strengths of Untreated Composites are Shown at Zero Cycles (Reference 3-46)

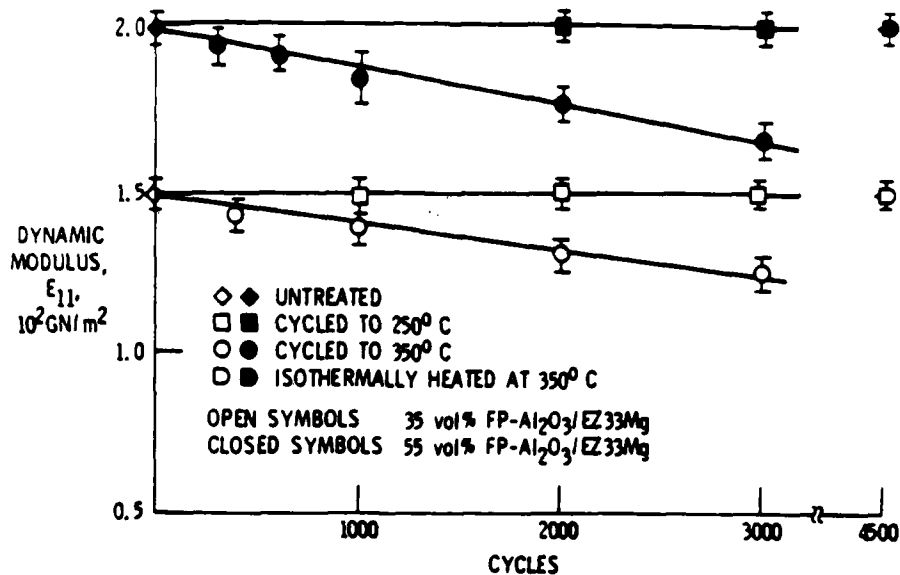


Figure 3.3-5. Room Temperature Dynamic Moduli of FP-Al₂O₃/EZ33Mg Composites after Cycling to 250 °C or 350 °C for Indicated Number of Cycles. Dynamic Moduli of Composites Isothermally Heated at 350 °C for 150 Hours as Shown. Dynamic Moduli of Untreated Composites are Shown at Zero Cycles (Reference 3-47)

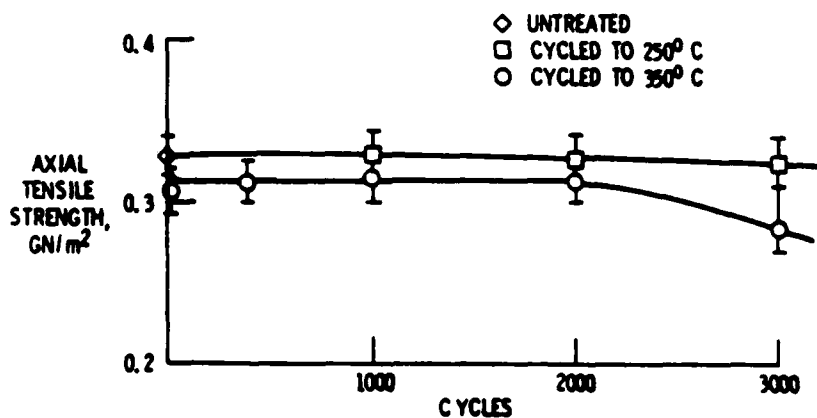


Figure 3.3-6 Room Temperature Axial Tensile Strengths of 35 Volume Percent FP-Al₂O₃/EZ33Mg Composites after Cycling to 250 °C or 350 °C for Indicated Number of Cycles. Strengths of Untreated Composites are Shown at Zero Cycles (Reference 3-48)

3.4 Titanium Metal Matrix Composites.

3.4.1 Background. Metals with good ductility and strengths are often combined with fibers of higher strength and stiffness, lower density, and low ductility to provide composites with increased stiffness and lower weight. An excellent example of this combination uses titanium, which has a high specific strength and excellent corrosion resistance, reinforced with boron-based or silicon-carbide-based fibers. The resulting composite possesses significantly increased stiffness and reduced weight. The composite may also have reduced fatigue strength, resulting from many factors including residual stress and the reaction between the fibers and the matrix during the high temperatures of fabrication. Recent developments in boron-based and silicon-carbide-based fibers have significantly reduced this problem of low fatigue strength.

Many advances have been made in titanium matrix composite technology in recent years, but more are still needed. Among these is the need to improve transverse strength through better control of the fiber/reaction zone interfacial bond strength. The major advances need to be in the area of fabrication cost reduction. Methods of continuous fabrication are expected to reduce cost by using coated reinforcements and methods of consolidation. Presently, cost seems to be the major obstacle in the application of titanium-matrix composites to advanced high-performance material systems.

3.4.2 Properties of Titanium Matrix Composites. A number of reinforcements for titanium have been examined in work to date. Table 3.4-1 summarizes comparative data for composites fabricated from these reinforcements. Because of the high reactivity of titanium matrix with the reinforcements, these fibers have been limited to the continuous type as opposed to short fibers or whiskers. At the present time only boron-based and silicon-carbide-based fibers are commercially available and are being strongly considered for use with titanium matrix. Fabrication methods have been developed for Titanium-BORSIC fibers that have given longitudinal strengths of over 200,000 psi with 45 to 50 percent by fiber volume and transverse strength of 65,000 psi. The creep and relaxation properties of

Titanium-Boron composite are also important. Boron-reinforced titanium possesses good creep strength at 1000 °F.

Silicon Carbide-reinforced Titanium with 22 percent by fiber volume possesses a typical tensile strength of 130,000 psi and an elastic modulus of 30 million psi. Other unique physical and mechanical properties of boron and silicon carbide reinforced titanium can be found from Figures 3.4-1 through 3.4-12 and from Tables 3.4-2 through 3.4-5.

TABLE 3.4-1. Summary of Properties of Titanium-Matrix Composites
(Reference 3-49)

Reinforcement	Specific strength			Stiffness	Ductility	Stability	Fabricability
	Room temp.	High temp.	High temp.				
Beryllium	Same as matrix	Same to low	High	High	Good	Good	Good, may be shaped by forging
Molybdenum	Same as matrix	High	High	Same as matrix	Moderate	Good	Good
Boron	High	High	High	High	Low	Good	Difficult
Silicon carbide-boron	High	High	High	High	Low	Good	Difficult
Silicon carbide	High	High	High	High	Low	Good	Difficult
Alumina	Same as matrix	Moderate	Moderate	Moderate	Low	Fair	Very difficult

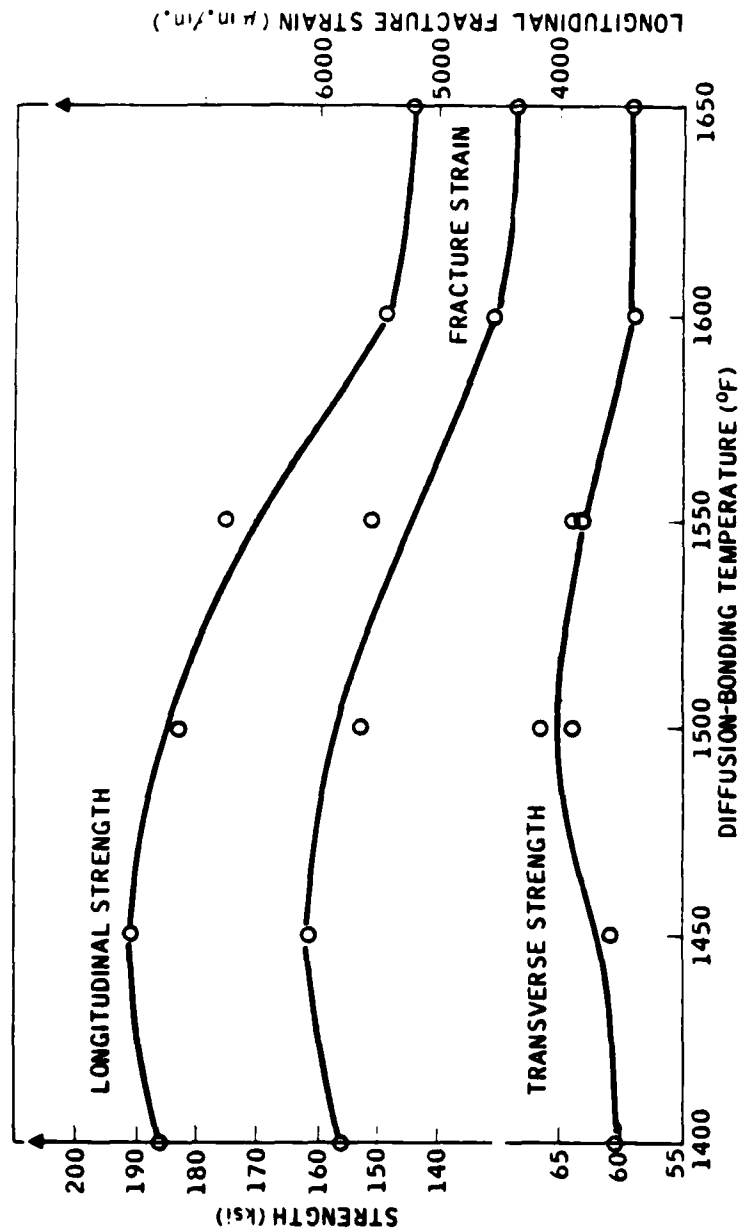


Figure 3.4-1. Effect of Diffusion-Bonding Temperature on Properties of Ti-6Al-4V-Borsic Composites (Reference 3-50)

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TABLE 3.4-2. Properties of Ti-6Al-4V-50 v/o Borsic Composites
(Reference 3-51)

Temperature (°F)	Orientation (degrees)	Tensile strength (ksi)	Failure strain (μ in./in.)	Elastic modulus (10^6 psi)		Coefficient of expansion (10^{-6} /°F)
				Tensile	Flexure	
70	0	140	3340	41.5	34.4	2.50
70	15	100	3220	36.8	33.3	—
70	45	66	4220	31.2	31.8	—
70	90	42	3130	29.8	31.2	3.17
500	0	119	—	—	33.2	2.80
700	0	107	—	—	32.4	—
850	0	109	—	—	31.5	3.17
850	15	86	—	—	29.9	—
850	45	53	—	—	27.6	—
850	90	35	—	—	24.4	3.64

TABLE 3.4-3. Off-Axis Tensile Properties of Ti-6Al-4V-28 v/o SiC
(Reference 3-52)

Filament orientation (degrees)	Average Strength (ksi)			Elastic modulus (10^6 psi)	Poisson's ratio
	Ultimate tensile strength	Proportional limit			
0	142	117		36	0.275
15	135	117		35	0.277
30	113	104		32	0.346
45	107	75		31	0.346
90	95	53		28	0.250

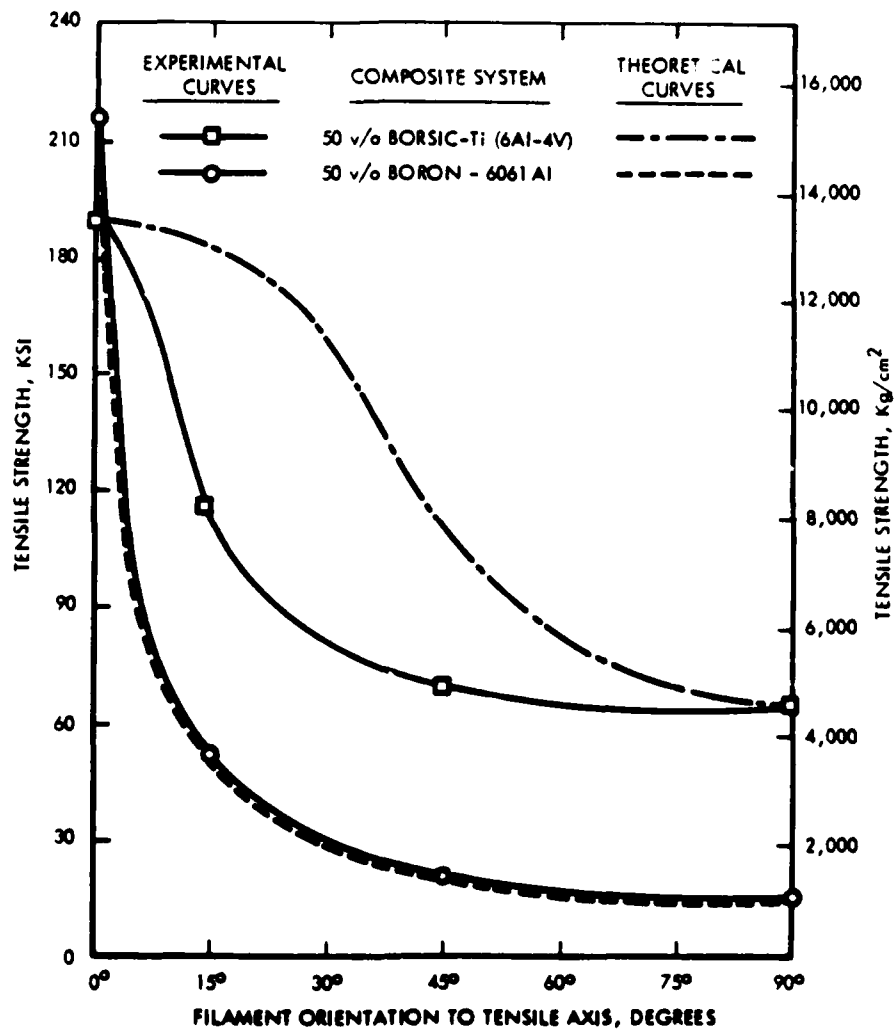


Figure 3.4-2. Comparison of Off-Axis Tensile Strength of As-Fabricated B-Al and B/SiC-Ti, using Experimental Data (Reference 3-53)

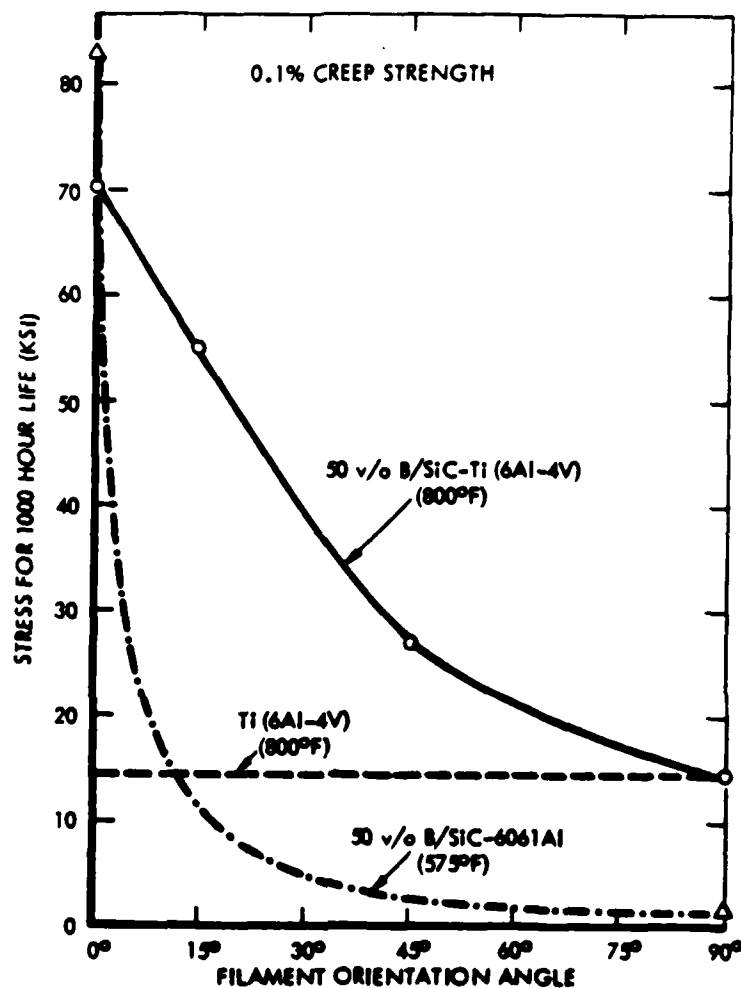


Figure 3.4-3. Creep-Strength Comparison of Reinforced and Unreinforced Titanium at 800 °F (427 °C) and Reinforced Aluminum at 575 °F (302 °C) (Reference 3-54)

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TABLE 3.4-4. Tensile (Room-Temperature) Properties of Titanium Matrix Composites (Reference 3-55)

R = +0.1; σ_{max} = 515 MPa (75 ksi), R.T.				
System	Cycles to Failure, h_f	UTS		
		MPa	ksi	
Ti-6Al-4V**	6×10^4	890	129	
BORSIC/Ti-6Al-4V	6×10^4	895	130	
SiC/Ti-6Al-4V	2×10^4 - 2×10^6 †	820	119	
SCS-6/Ti-6Al-4V	2×10^5	1455	211	
B ₄ C/B/Ti-6Al-4V	1×10^7	1055	153	

*4-ply, unidirectionally reinforced, 35-40 vol. %
 **Mill annealed, 1350°F 2 h AC
 †Significant scatter encountered

TABLE 3.4-5. Axial Fatigue Properties of As-Fabricated Titanium Matrix Composites (Reference 3-56)

System	UTS (Long.)		UTS (Trans.)		Modulus (Long.)†	
	MPa	ksi	MPa	ksi	GPa	msi
Ti-6Al-4V**	890	129	890	129	120	17.5
SiC/Ti-6Al-4V†	820	119	380	55	225	32.6
BORSIC/Ti-6Al-4V†	895	130	365	53	205	30.0
B ₄ C/B/Ti-6Al-4V†	1055	153	310	45	205	30.0
SCS-6/Ti-6Al-4V†	1455	211	340	49	240	34.8

*4-ply, unidirectionally reinforced, 35-40 vol. %
 **Mill annealed, 1350°F 2 h AC
 †After fabrication and low temperature 595°C (1100°F)/512 h exposure

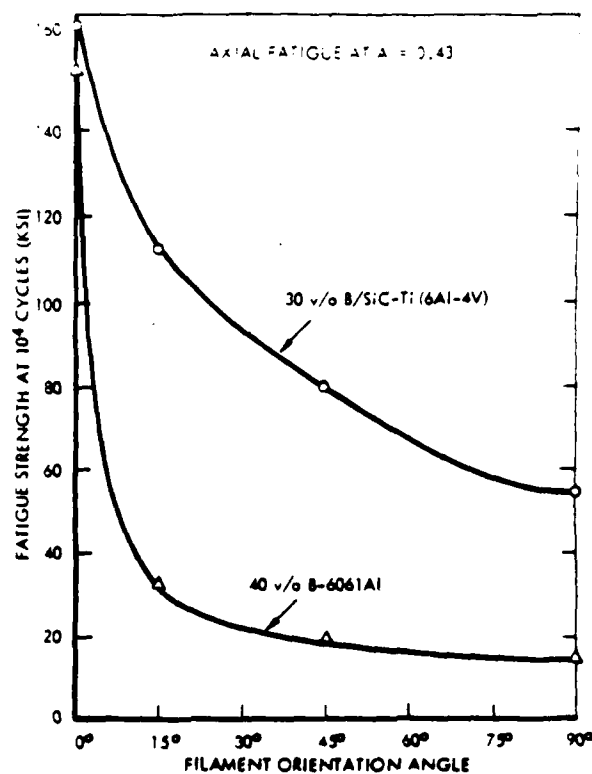


Figure 3.4-4. Low-Cycle Fatigue Strength of As-Fabricated Aluminum and Titanium Matrix Composites (Reference 3-57)

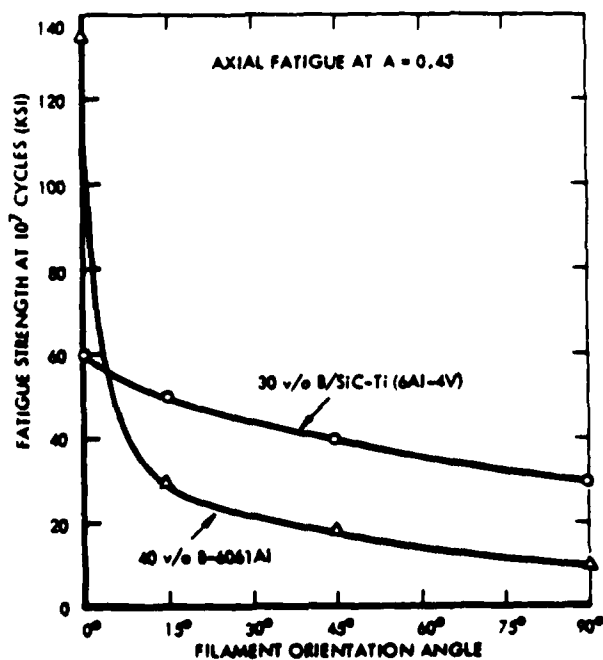


Figure 3.4-5. High-Cycle Fatigue Strength of As-Fabricated Aluminum and Titanium Matrix Composites (Reference 3-58)

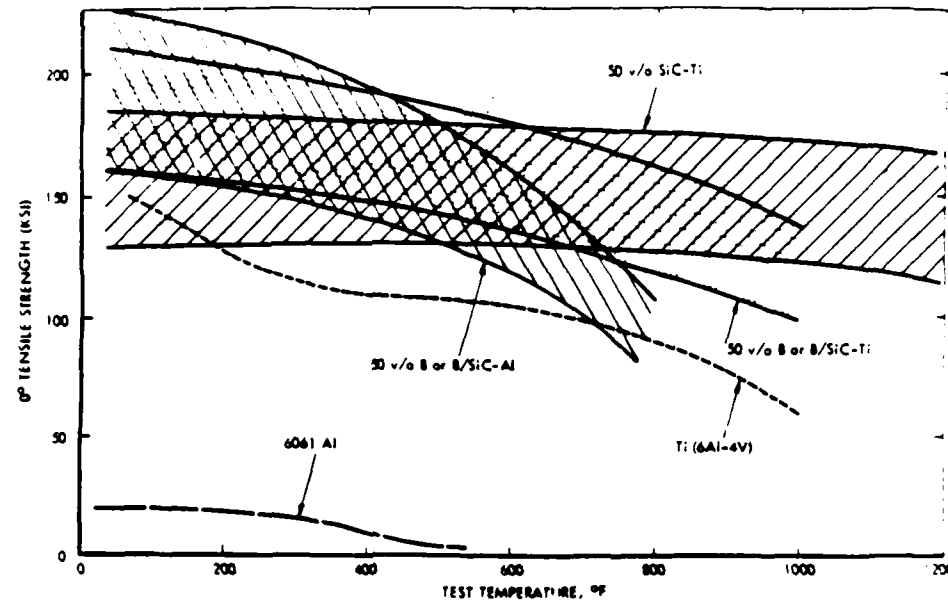


Figure 3.4-6. Variation of Longitudinal Tensile Strength with Test Temperature for Unidirectional Aluminum and Titanium Matrix Composites (Reference 3-59)

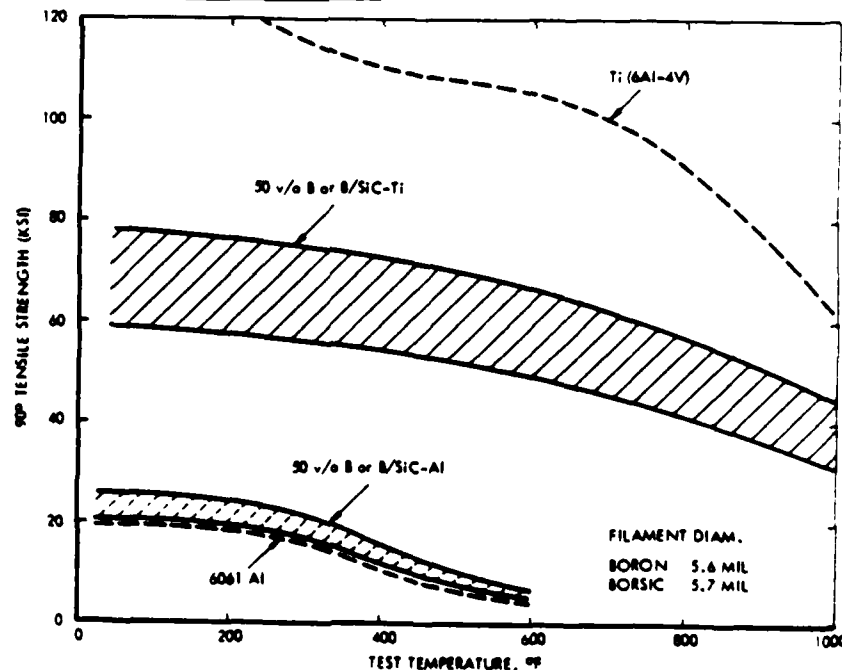


Figure 3.4-7. Comparison of Transverse Tensile Strength as a Function of Test Temperature for Aluminum and Titanium Matrix Composites in As-Fabricated Condition (Reference 3-60)

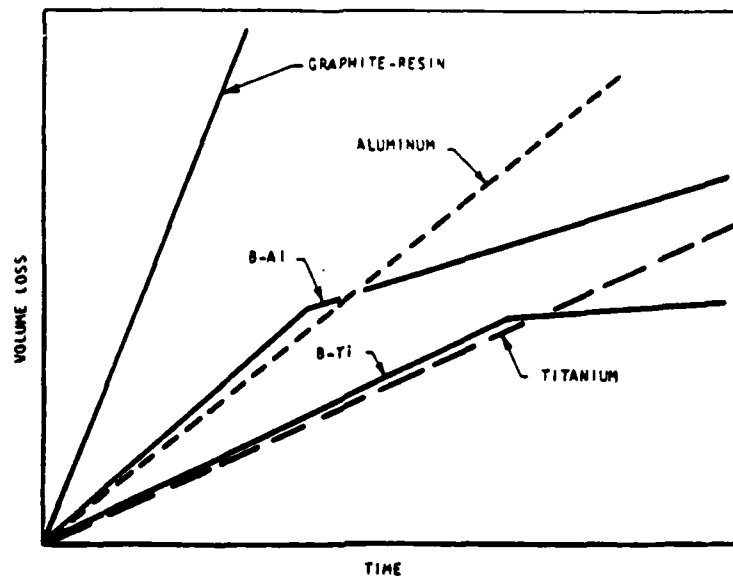


Figure 3.4-8. Schematic Comparison of Dust Erosion Behavior
(Reference 3-61)

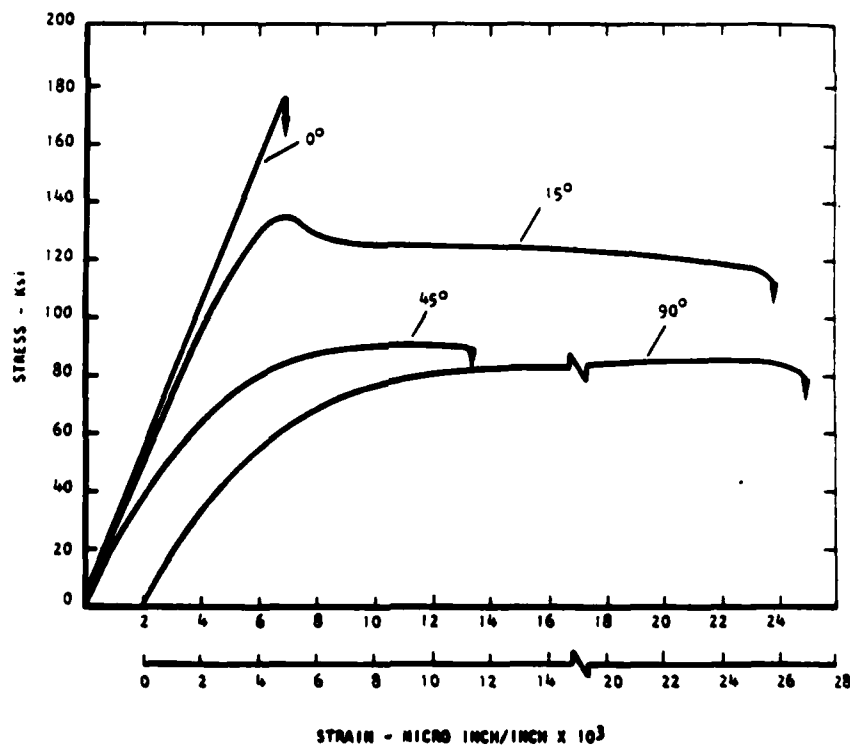


Figure 3.4-9. Typical Stress-Strain Curves for 30 v/o B/SiC-Ti (6Al-4V)
Tested at Room Temperature (Reference 3-62)

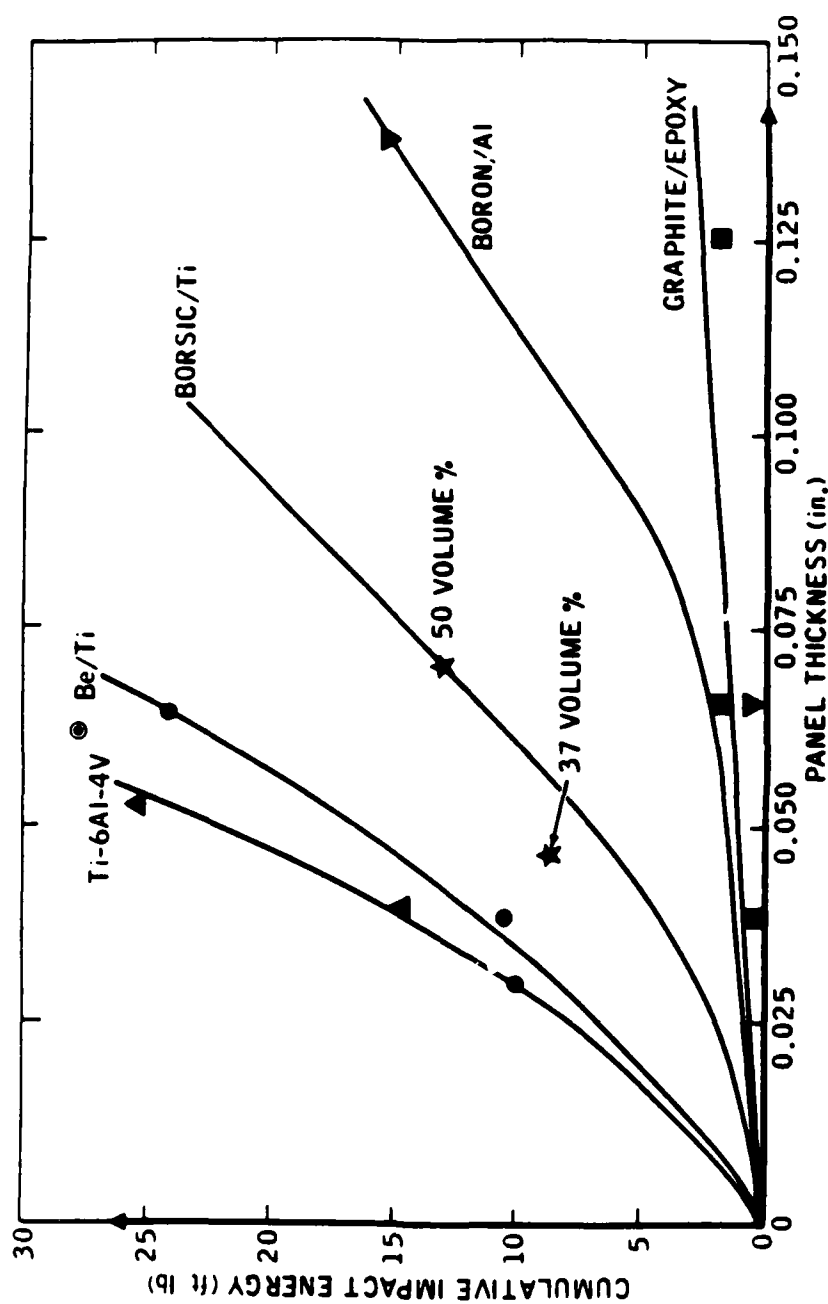


Figure 3.4-10. Ballistic Impact Strength of Titanium Composites for 1/2-in Wide Panels under Static Stress (Reference 3-63)

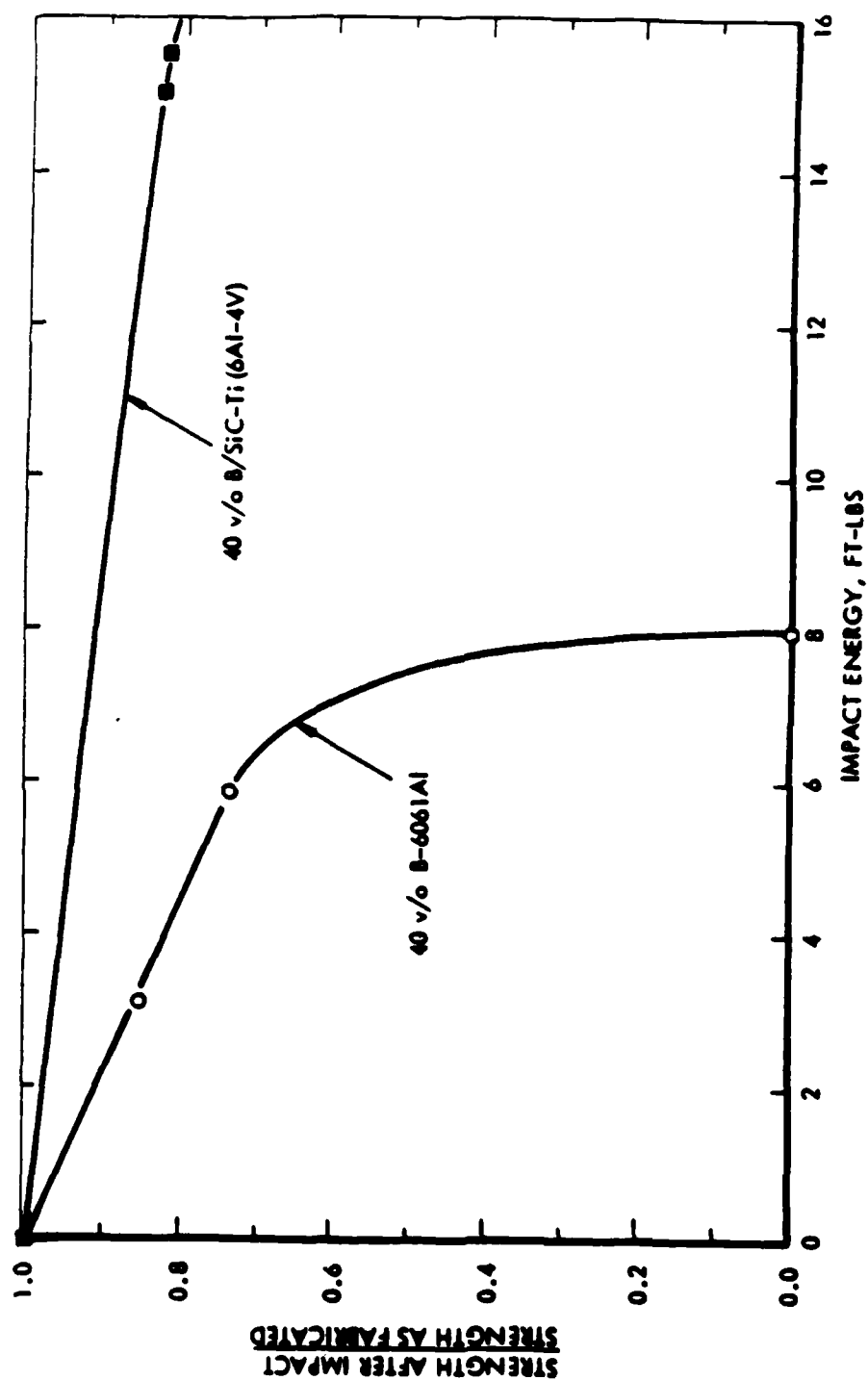


Figure 3.4-11. Comparison of the Ballistic Impact Resistance of Aluminum and Titanium Matrix Composites (Reference 3-64)

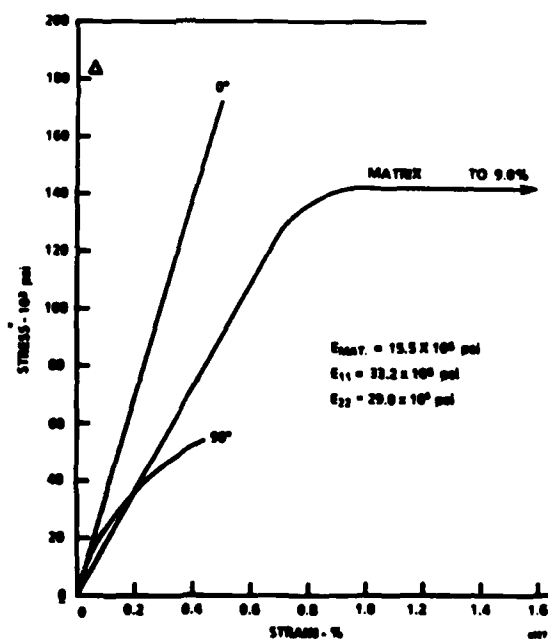
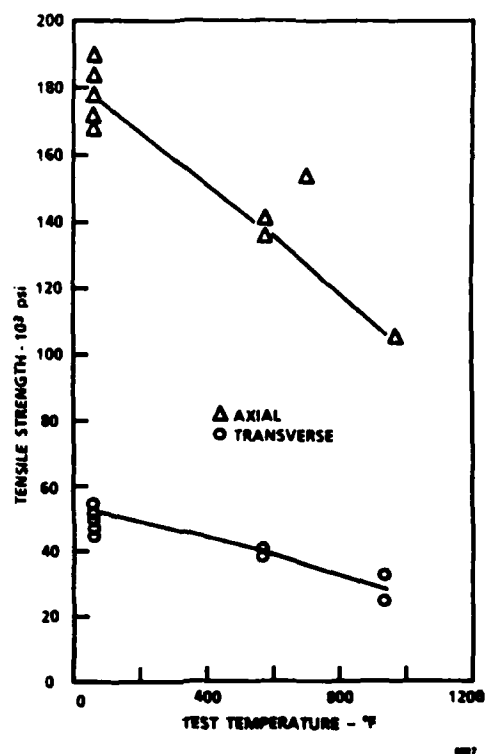


Figure 3.4-12. Tensile Stress-Strain Curves for 43 Percent - 5.7 mil Borsic Reinforced Ti-6Al-4V (Reference 3-65)

CHAPTER 4
POLYMER MATRIX COMPOSITES

4.1 Introduction. Plastics or polymer matrix composites are quite different from metal matrix composites. Table 4.1-1 compares the key characteristics of polymer matrix composites to metal matrix composites. Plastic or polymer matrix materials result in composites that have higher specific tensile strength and stiffness properties. Plastic composites are more advanced in the fabrication technology and are lower in raw material cost and fabrication cost. There are three important general classes of plastic matrices that are reinforced by the high-performance fiber materials. These are epoxies, phenolics, and polyimides.

Epoxy matrix material can be used with all high-performance fibers. They are cured under a pressure of about 100 psi at a temperature of about 350 °F. Epoxies have been considered quite stable; however, there is some evidence indicating that a loss of properties may occur at temperatures of 250-300 °F as a result of moisture pickup.

Phenolics are highly heat resistant, and composites may be used at temperatures of up to 500 °F for up to 200 hours. Used with glass, high silica, quartz, and graphite fibers, phenolic composites have been employed extensively in nose cones and rocket motor chambers. Difficulty in using reinforcements other than glass occur because of the release of large quantities of volatile substances during curing.

Polyimides are the primary candidates for high-temperature applications. They produce sounder and more heat resistant composites than phenolics. Boron, graphite, and glass fibers have been used with polyimides to provide usable properties at up to 300 °F. Polyimides are powders and must be mixed in a solvent to be impregnated. This presents a problem because the solvent must be removed along with the water to leave a void content of less than three percent. If the process is not carefully controlled, significant strength loss will result. Polyimides are more complex to process than epoxies and require greater pressure and quicker heating.

TABLE 4.1-1. Plastic-Matrix Material Characteristics
(Reference 4-1)

Key characteristics of plastic matrix composite (compared to metal matrix composite)	Potential advantage in space applications
Greater strength-to-density and modulus-to-density (due to lower density and high v/o possible) More advanced in state of the art	More efficient in uniaxial tensile loads and bending Less deflection, more resistant to dynamic loads More readily available More design data and experience available More test and flight experience available More consistent raw material properties High-strength joints are more fully developed Cost is approximately one-fourth of that of boron-aluminum
Lower cost Lower fabrication costs possible	Unit construction possible resulting in less pieces and less joints Less scrap generated (due to cutouts and trimming for metal matrix) More moldable, hence, more shape and thickness variation possible with minimum cost Lower temperature and pressures needed for consolidation Changes in loading magnitude or direction can be easily accommodated by adding extra layers onto existing structure Less costly to handle Less impact on schedules if damaged Desirable property for thermally-isolated structures, such as spacecraft heat shield substructures
More adaptable to design changes More easily repaired Matrix is an insulator	

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4.2 Epoxy Polymer Matrix Composite.

4.2.1 Background. Epoxy resin developments for composite materials began in the early 1950's. Their excellent adhesion characteristics have resulted in notable success with graphite composites. They also have a good balance of physical and electrical properties and have a lower order of shrinkage than other thermosetting materials. Added requirements from the aerospace industry for better heat stability and resistance have caused substantial improvements in the materials. All high-performance fibers may be used with epoxy matrices. Epoxies are generally cured at 350 °F, with useful service at up to 350 °F. Minor problems with moisture pickup and loss of some properties may be experienced at 250-350 °F.

4.2.2 Epoxy Resin Preparation. The most common epoxy resin systems are listed below followed by the most frequently used curing agents (Figure 4.2-1). Both of these are important factors for high temperature stability, along with proper curing techniques and procedures.

4.2.2.1 Types of Epoxy Resins.

4.2.2.1.1 Diglycidyl Ethers of Bisphenol (Standard Epoxy). Diglycidyl ethers of bisphenol are the most widely used epoxy resin. While not commonly used for heat resistant forms, widespread use is found in protective coatings, adhesives, sealants, impregnants, bonding, and laminating materials. High molecular weight resins are solid, low molecular weight resins are liquid. Many applications use this resin in conjunction with other types to improve performance.

4.2.2.1.2 Epoxidized Phenolic Novolacs. This resin is available in solid or liquid form, depending on the molecular weight. It generally reacts more quickly than standard epoxies, and it is substantially more heat stable.

4.2.2.1.3 Tetraglycidyl Ether of Tetrakis (Hydroxyphenol) Ether ("Epon" 1031). This epoxy resin brings about better heat stability through

greater crosslinking density. The solid "Epon" 1031 is usually used in conjunction with liquid nadic methyl anhydride cure agents to achieve greater fluidity. In the early 1960's, this resin was used to modify standard epoxy resins and was widely used with glass fibers for high temperature epoxy systems.

4.2.2.1.4 Tetraglycidyl Ether of 4,4-Diaminodiphenyl Methane (Ciba's MY-720). This tetrafunctional glycidyl ether is a viscous liquid at room temperature. It has been used in preparing graphite composites and, when reacted with liquid anhydrides, for laminates. It is also used in conjunction with cycloaliphatic epoxies. Water pickup must be avoided during application and lay up because MY-720 and anhydrides are hygroscopic.

4.2.2.2 Curing Agents for Epoxy Resins. A curing agent must be used to considerably decrease curing time. Many different types of curing agents are available, and the final structure may be altered by the choice of curing agents. Curing agents largely determine many behavior characteristics such as chemical resistance and thermal stability. For example, anhydride cures give good electrical insulating properties, thermal stability, and chemical resistance. Aliphatic amines are fast cures and are suited for room temperatures. Aromatic amines give a higher heat resistance, but a higher temperature is also required for cure. Base epoxies with multifunctionality increase the cross-link density and thermal stability. Figures 4.2-2 and 4.2-3 show the importance of using the correct curing agent. Table 4.2-1 compares the properties of different types of cast epoxy resins all cured with aromatic diamines. Other properties of epoxy resins can be found from Figures 4.2-4 through 4.2-7 and in Table 4.2-2.

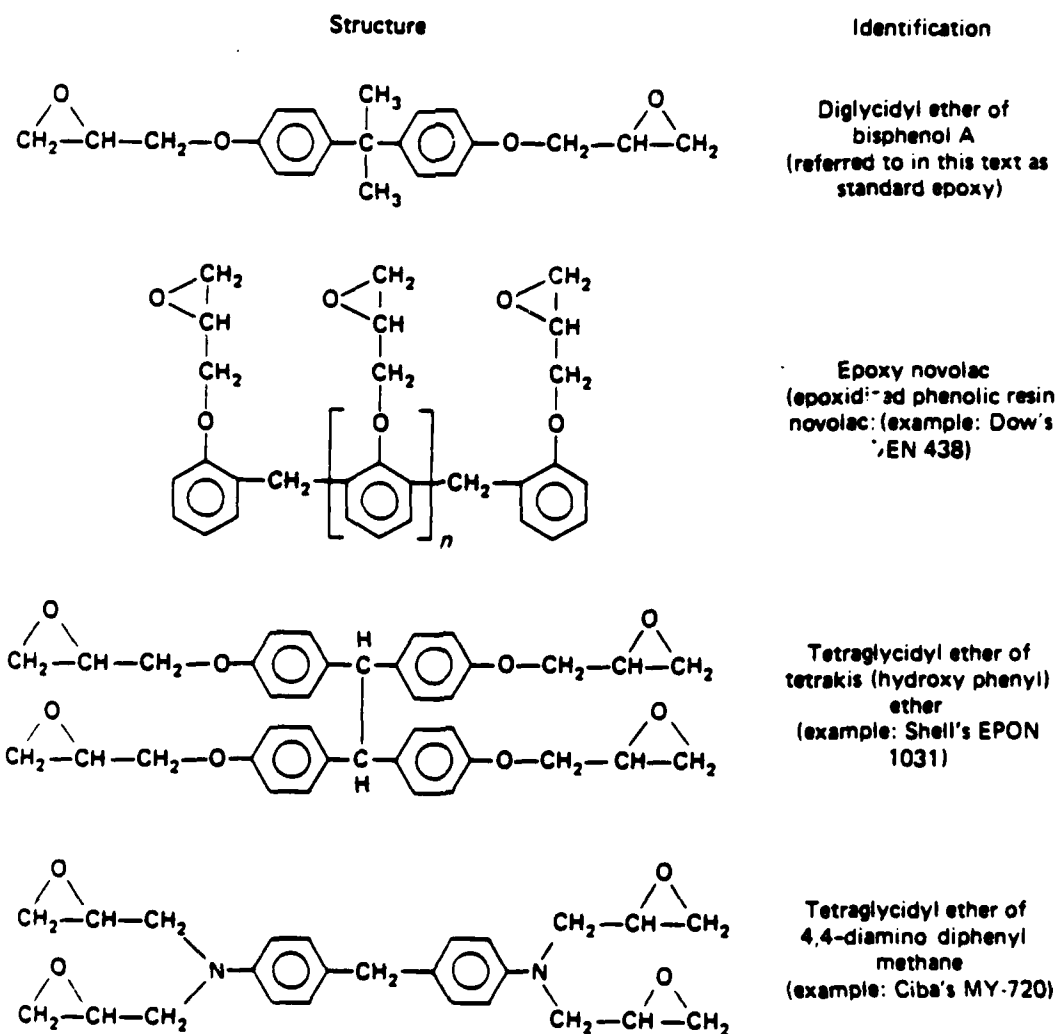


Figure 4.2-1. Basic Epoxy Resins Used in Advanced Composites
(Reference 4-2)

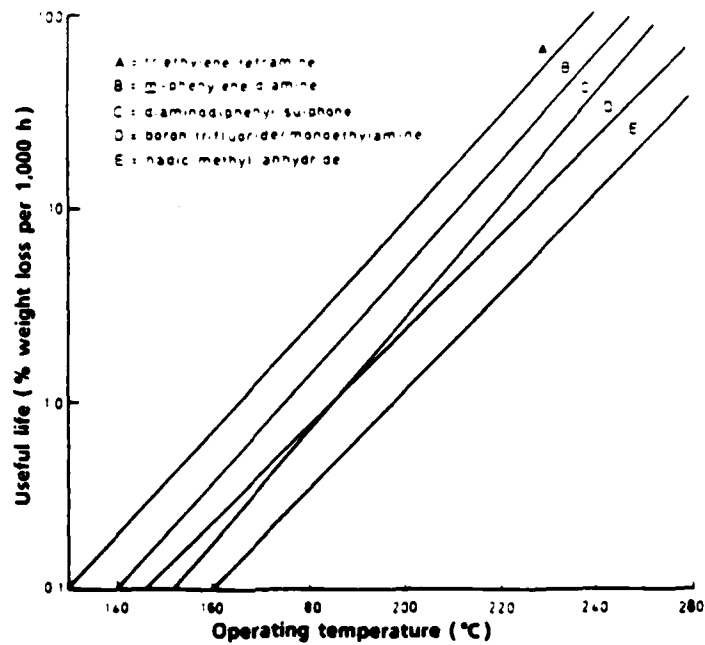


Figure 4.2-2. Continuous Operating Temperatures for a Bisphenol-A Epoxy Resin Cured with Different Agents Based on 16 Percent Weight Loss as End Point (Reference 4-3)

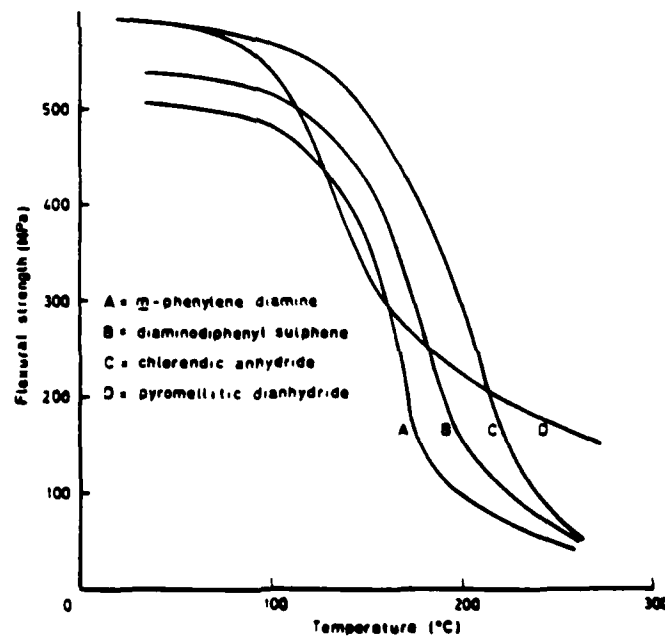


Figure 4.2-3. Flexural Strength Retention at Temperature of Bisphenol-A Epoxy Resin/Glass Cloth Laminates Cured with Different Agents (Reference 4-4)

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TABLE 4.2-1. Comparison of Properties of Cast Epoxy Resins (Reference 1-5)

Property	Bisphenol-A epoxy DDM cure	Bisphenol-A epoxy DDS cure	Cyclo aliphatic epoxy MPD cure	Tetrafunctional epoxy DDS cure
Tensile strength (MPa)				
at 20°C	53	59	89	41
150°C	19 (36)	37 (63)	78 (9)	33 (80)
Tensile modulus (MPa)				
at 20°C	2750	3070	6280	4100
150°C	1540 (56)	1470 (48)	432 (7)	3230 (79)
Compressive strength (MPa)				
at 20°C	> 111	107	227	178
150°C	> 29	63 (59)	65 (29)	115 (65)
Compressive modulus (MPa)				
at 20°C	2670	2000	4130	2930
150°C	721 (27)	1280 (64)	1290 (31)	2200 (75)
Flexural strength (MPa)				
at 20°C	116	102	159	86
150°C	41 (35)	49 (48)	84 (53)	86 (100)
Flexural modulus (MPa)				
at 20°C	2730	2790	6450	3920
150°C	1680 (62)	1160 (42)	2640 (41)	3200 (82)
Impact strength (MN/mm)				
at 20°C	0.21	0.17	0.21	0.083
150°C	0.19 (90)	0.21 (100)	0.15 (71)	0.073 (88)
Elongation at break (%)				
at 20°C	4.9	3.3	2.1	1.1
150°C	2.7	8.0	12.3	1.0

Figures in parentheses are percentage retention.

DDM = diaminodiphenylmethane DDS = diaminodiphenylsulphone

MPD = *m*-phenylene diamine

TABLE 4.2-2. Key Composite Properties for the Various Epoxy Resins (Reference 4-6)

RESIN MATRIX	4289	828	2256	4617
Cast resin properties				
Initial modulus (10^6 psi)	0.24	0.32	0.60	0.78
Proportional limit (10^3 psi)	1.7	3.2	2.4	7.2
Ultimate elongation (%)	81.0	8.1	6.5	2.2
Ultimate strength (10^3 psi)	5.4	8.0	15.2	14.8
Longitudinal composite properties				
Tensile strength (10^3 psi)	116.0	205.0	207.0	150.0
Tensile modulus (10^6 psi)	13.6	22.4	21.0	19.5
Proportional limit (10^3 psi)	38.1	80.7	70.4	56.7
Compressive strength (10^3 psi)	12.4	134.0	149.0	150.0
Compressive modulus (10^6 psi)	20.0	19.5	19.1	20.9
Proportional limit (10^3 psi)	7.8	44.3	76.2	36.0
Fiber content (% by Vol.)	67.8	62.0	62.7	61.3
Transverse composite properties				
Tensile strength (10^3 psi)	1.2	3.4	3.9	4.3
Tensile modulus (10^6 psi)	0.19	1.18	1.33	1.49
Proportional limit (10^3 psi)	0.08	1.13	2.3	4.0
Torsional stress (10^3 psi)	0.77	3.7	6.9	7.9
Torsional modulus (10^6 psi)	0.054	0.68	0.81	0.96
Proportional limit (10^3 psi)	0.13	1.2	1.7	3.2
Fiber content (% by Vol.)	64.8	68.2	66.7	61.2

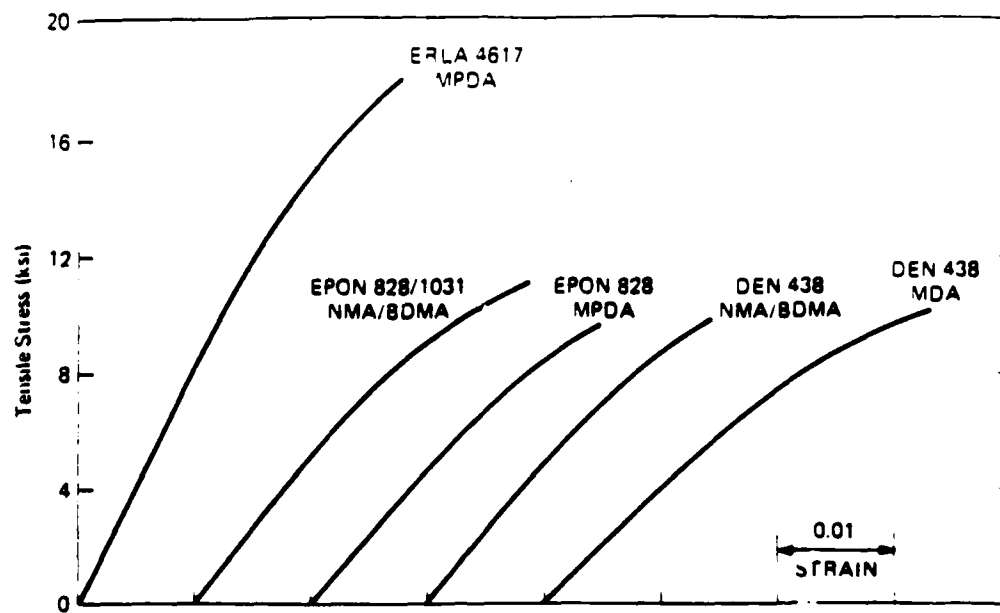


Figure 4.2-4. Tensile Stress-Strain for Epoxy Resins (Reference 4-7)

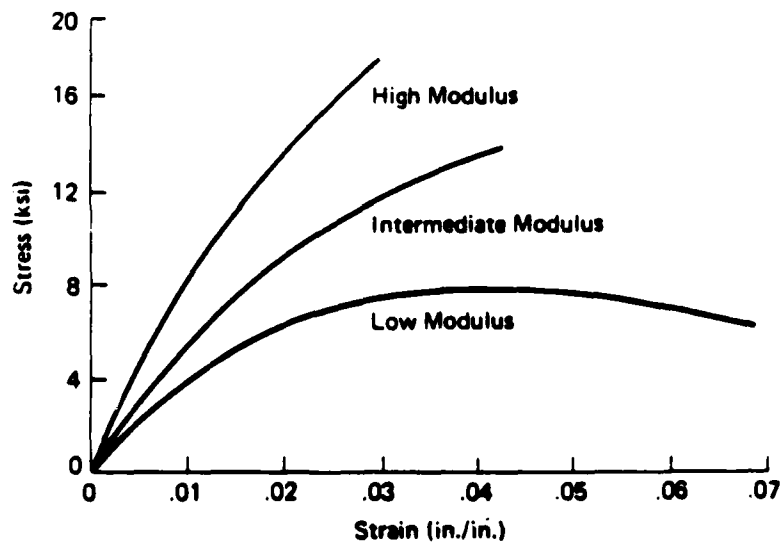


Figure 4.2-5. Stress-Strain Diagrams of Epoxy Matrix Resins (Reference 4-8)

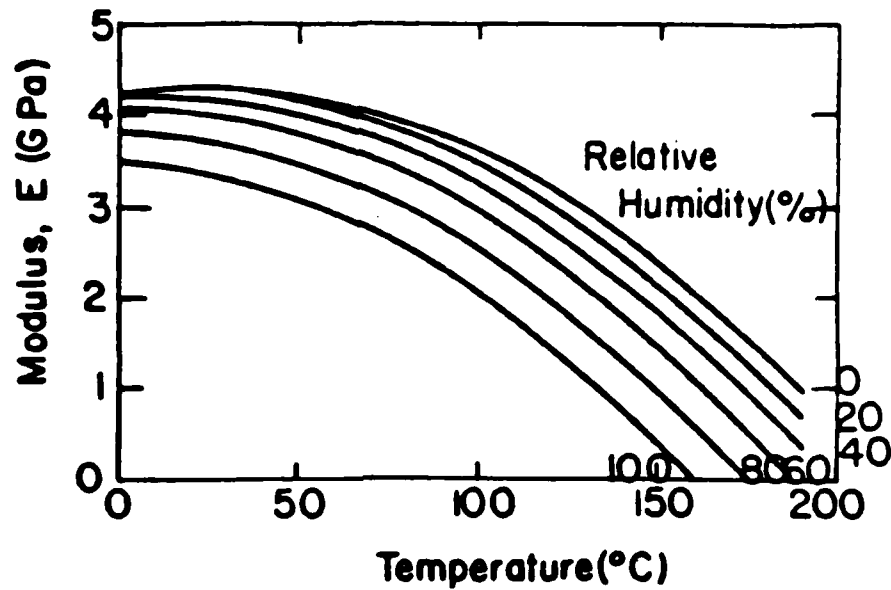


Figure 4.2-6. Epoxy Matrix Material (Hercules 3501-6) Young's Modulus Versus Temperature and Relative Humidity (Reference 4-9)

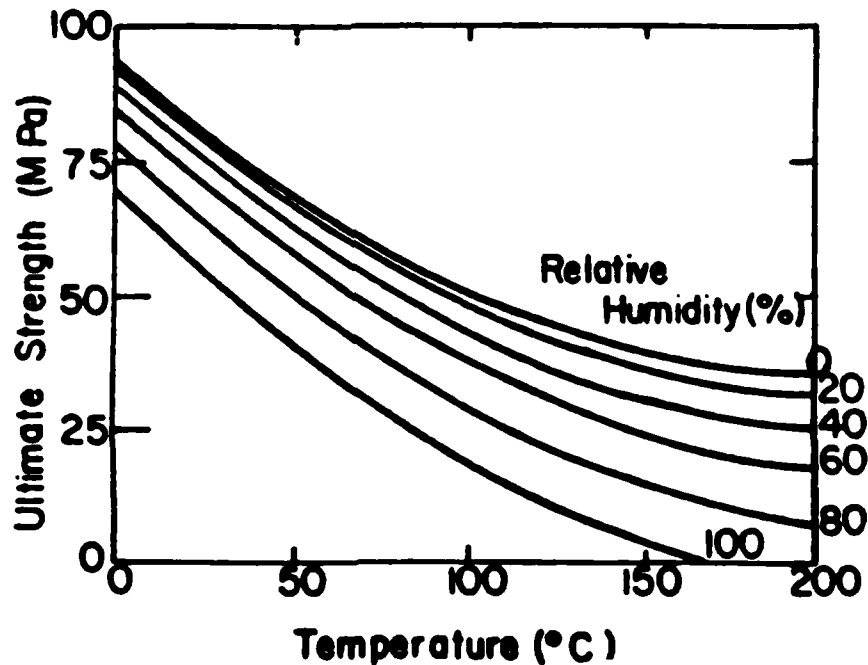


Figure 4.2-7. Epoxy Matrix Material (Hercules 3501-6) Ultimate Strength Versus Temperature and Relative Humidity (Reference 4-10)

4.2.3 Properties of Epoxy Matrix Composites. Epoxy matrix composite materials are recognized for their high performance applications and their compatibility with all fiber types. However, like other composite materials, certain types of epoxies combine best with a specific type of fiber for maximum performance. For example, if the specific requirement is for an increased impact strength or energy absorption composite, a low modulus epoxy would be used. Reasons for the high interest in epoxy matrix composite materials are revealed by the property comparisons with steel, titanium, and aluminum as shown in Figure 4.2-8.

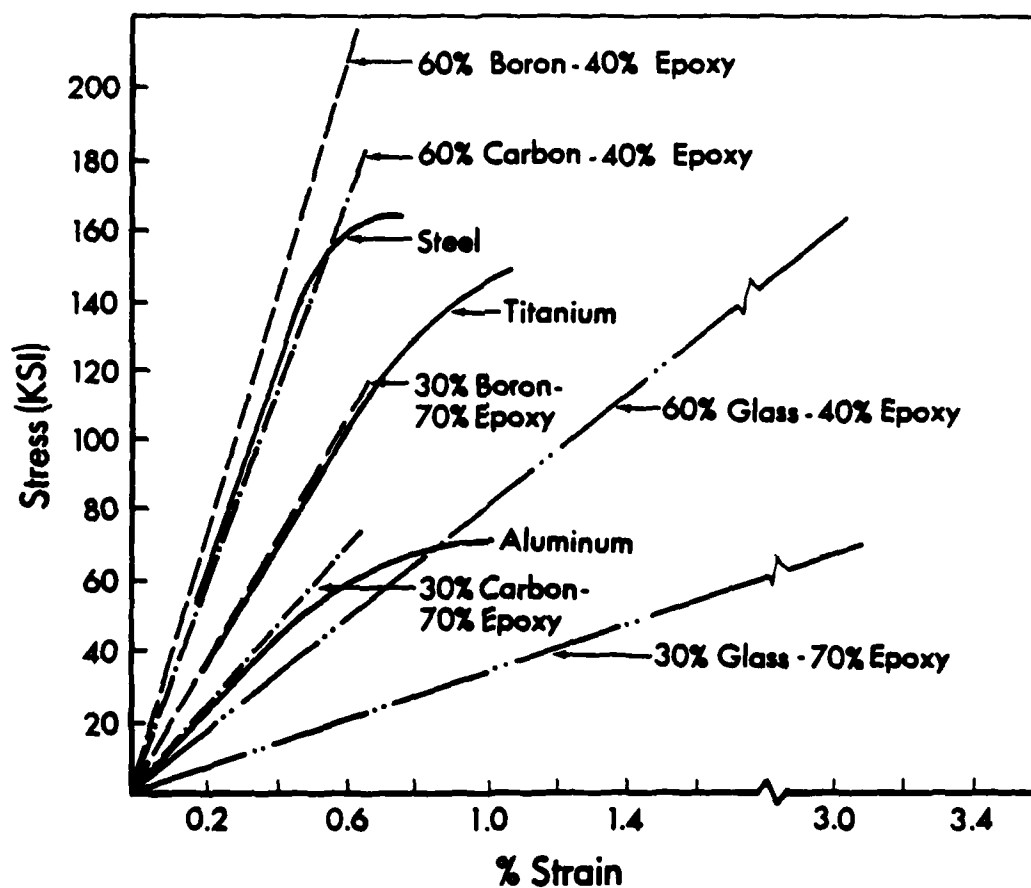


Figure 4.2-8. Comparison of Epoxy Composite Materials with Steel, Titanium, and Aluminum (Reference 4-11)

4.2.3.1 Graphite-Reinforced Epoxy. Graphite-reinforced epoxy composites provide a combination of strength and stiffness properties that are quite superior to monolithic metallic materials such as aluminum, steel, and titanium. In the graphite/epoxy system, graphite fibers provide the major strength in the direction of the fibers. Several plies of fibers at different angles can be used to provide adequate strength if the structure is designed to carry load along more than one axis. Some typical strength properties can be seen in Figures 4.2-9 and 4.2-10.

The relationship between thermal conductivity and fiber volume fraction for longitudinal and transverse direction of a graphite/epoxy composite is summarized in Figures 4.2-11 and 4.2-12. In general, a high thermal conductivity value is observed along the direction of the fiber, whereas a low conductivity value is observed in the transverse direction.

The electrical characteristics of graphite/epoxy composites are governed by the fiber volume fraction, orientation, void content, and moisture absorption of the epoxy matrix. Examples of typical values of electrical resistivity are given in Figures 4.2-13 and 4.2-14.

The electrical conductivity also governs the electromagnetic shielding characteristics of any material. Shielding effectiveness is defined as a measure of the ability of a material to control the passage of radiated electromagnetic energy. Whenever the composite does not meet the shielding effectiveness design requirements, a more conduction protective coating such as aluminum mesh or aluminum flame spray is used to boost the value of the overall thermal conductivity. An example of this comparison can be found in Figure 4.2-15. Other unique physical and mechanical properties of graphite-reinforced epoxy can be found in Figures 4.2-16 through 4.2-21 and from Tables 4.2-3 through 4.2-5.

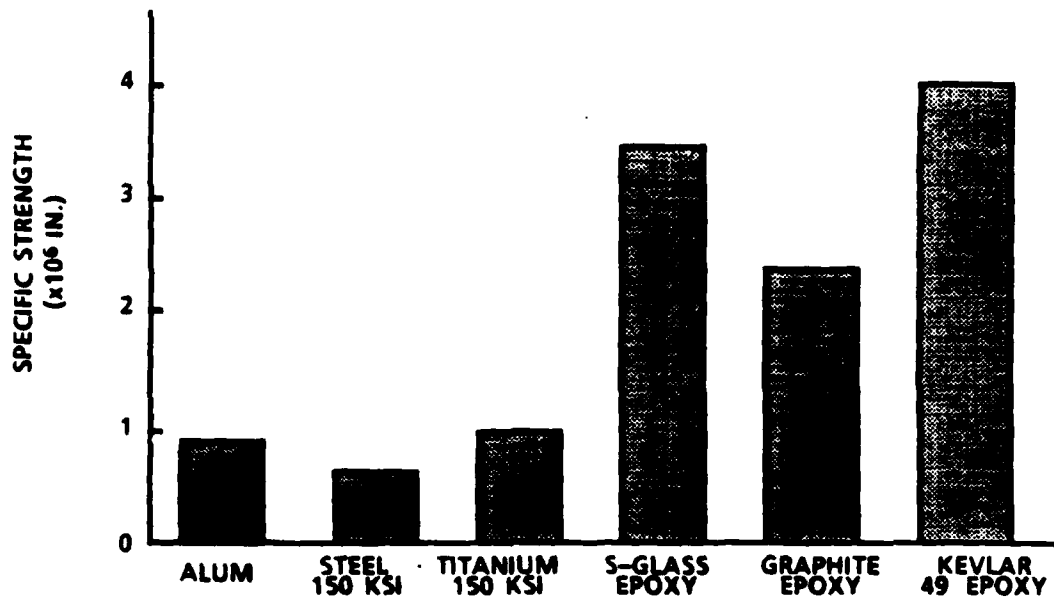


Figure 4.2-9. Tensile Strength/Density Comparison (Reference 4-12)

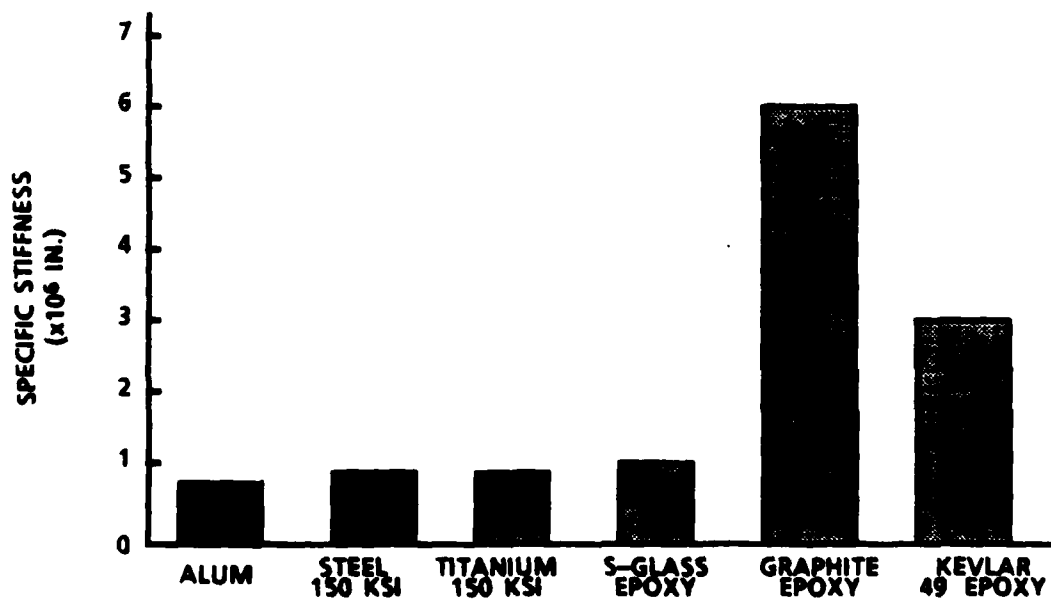


Figure 4.2-10. Stiffness/Density Comparison (Reference 4-13)

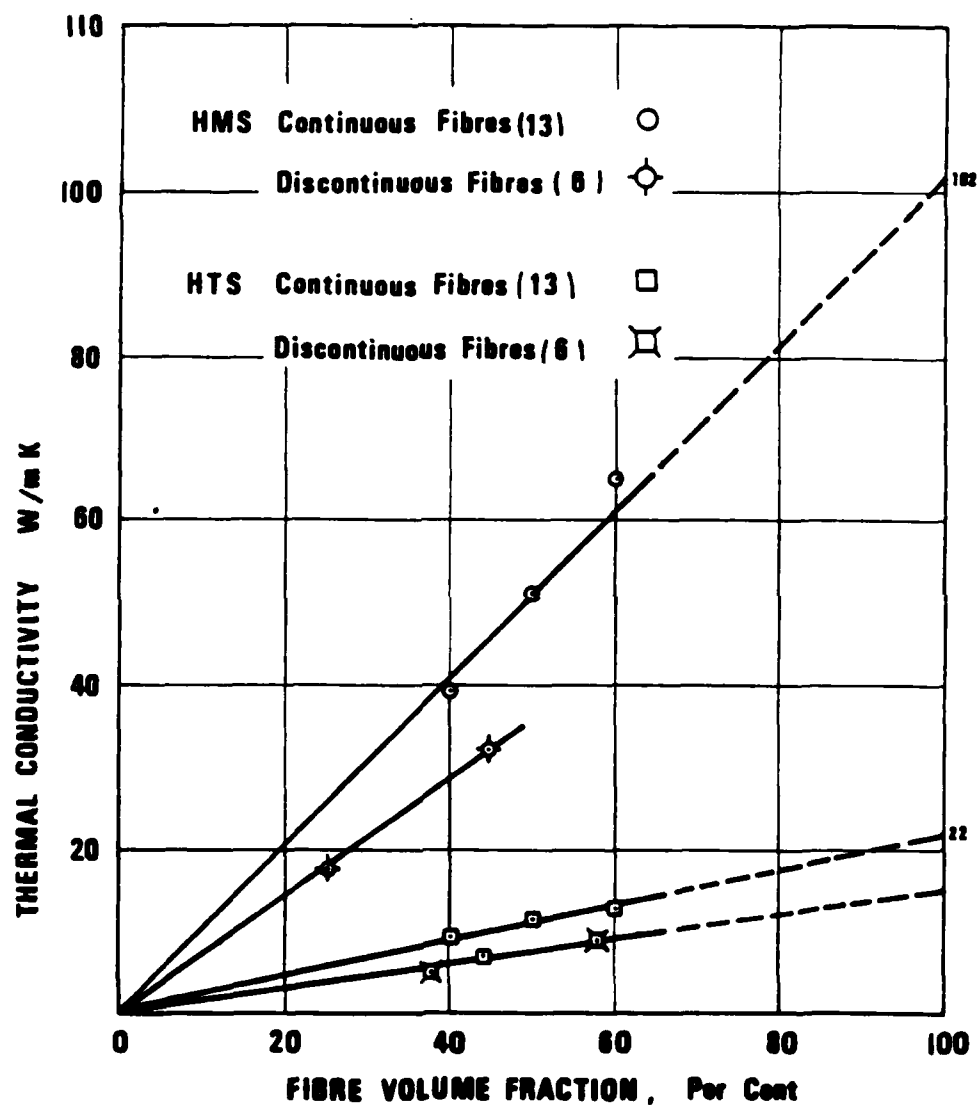


Figure 4.2-11. Longitudinal Thermal Conductivity of Uniaxially Aligned, Continuous and Discontinuous Carbon Fiber-Epoxy Composites at 20 °C as a Function of Fiber Volume Fraction (Reference 4-14)

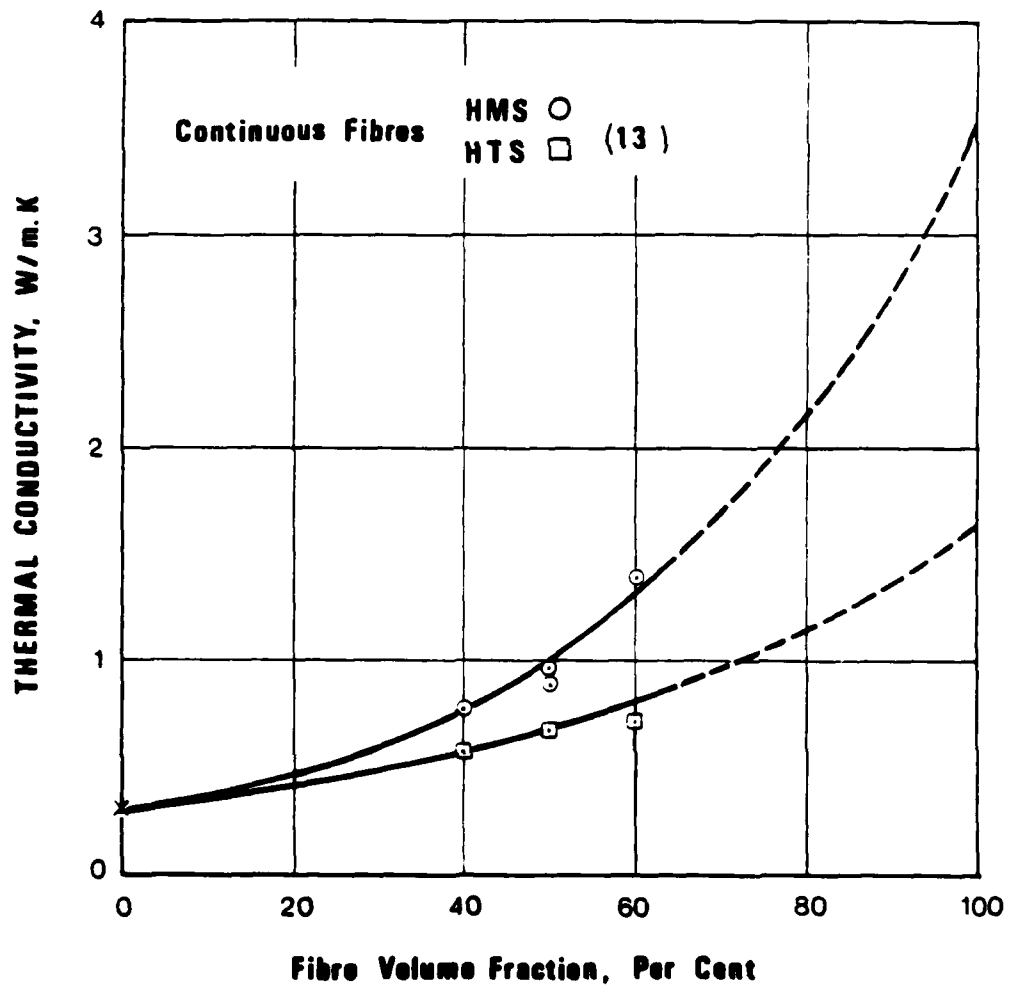


Figure 4.2-12. Transverse Thermal Conductivity of Uniaxially Aligned, Continuous Carbon Fiber-Epoxy Composites at 20 °C as a Function of Fiber Volume Fraction (Reference 4-15)

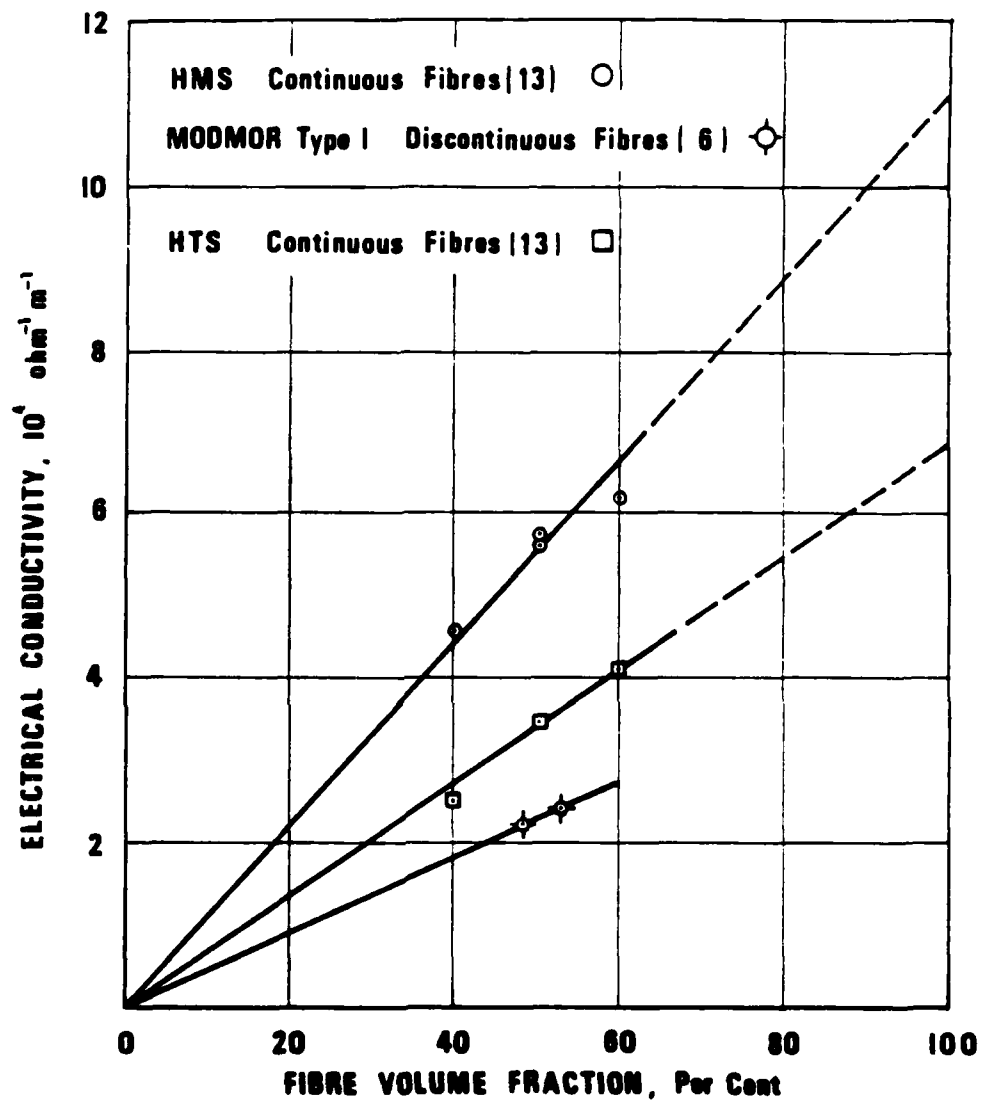


Figure 4.2-13. Longitudinal Electrical Conductivity of Uniaxially Aligned, Continuous and Discontinuous Carbon Fiber-Epoxy Composites at 20 °C as a Function of Fiber Volume Fraction
(Reference 4-16)

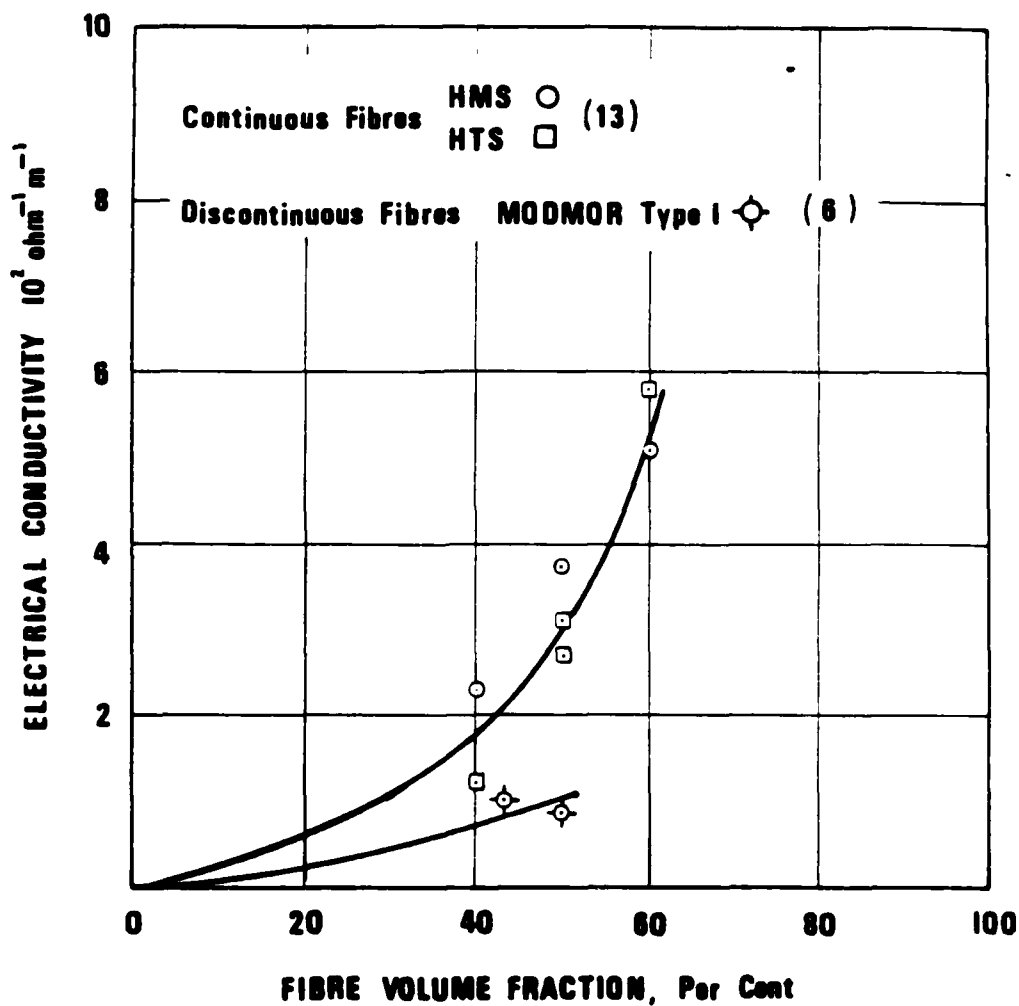


Figure 4.2-14. Transverse Electrical Conductivity of Uniaxially Aligned, Continuous and Discontinuous Carbon Fiber-Epoxy Composites at 20 °C as a Function of Fiber Volume Fraction (Reference 4-17)

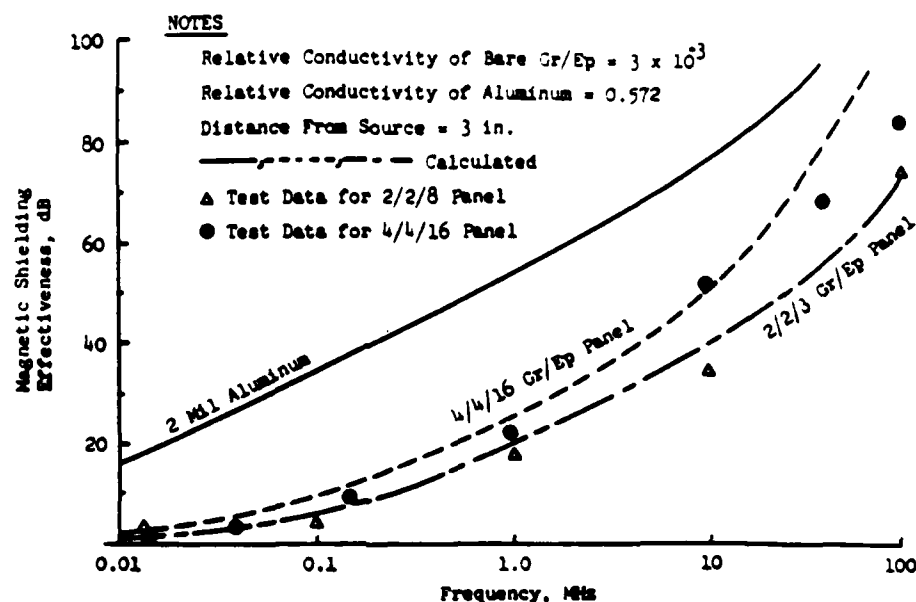


Figure 4.2-15. Magnetic Shielding Effectiveness for 2/2/8 and 4/4/16 Unprotected Graphite/Epoxy Panels and a 2 Mil Aluminum Panel (Reference 4-18)

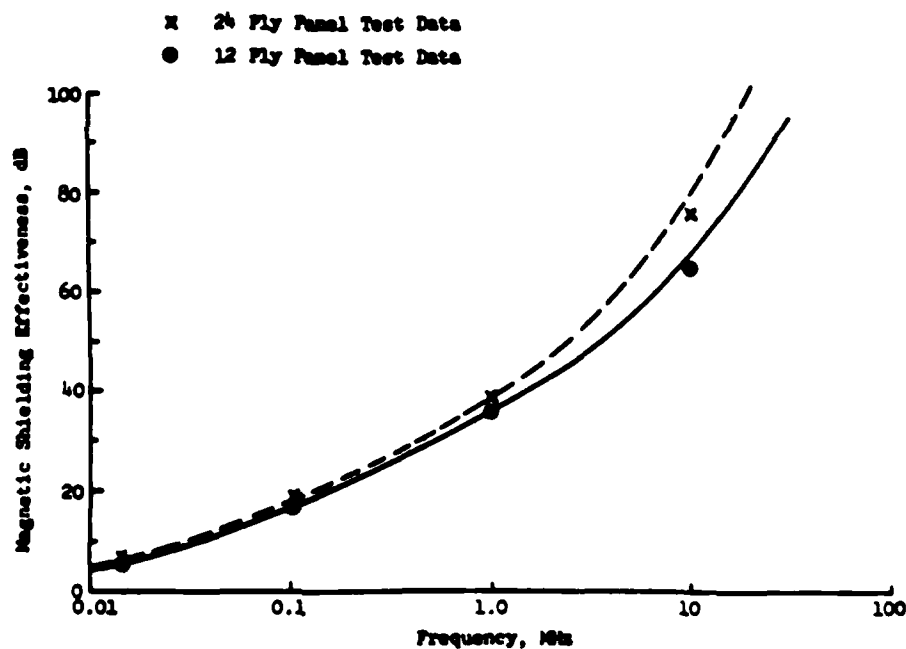


Figure 4.2-16. Magnetic Shielding Effectiveness for 2/2/8 and 4/4/16 Graphite/Epoxy Panel Protected with 6 Mil Aluminum Flame Spray (Reference 4-19)

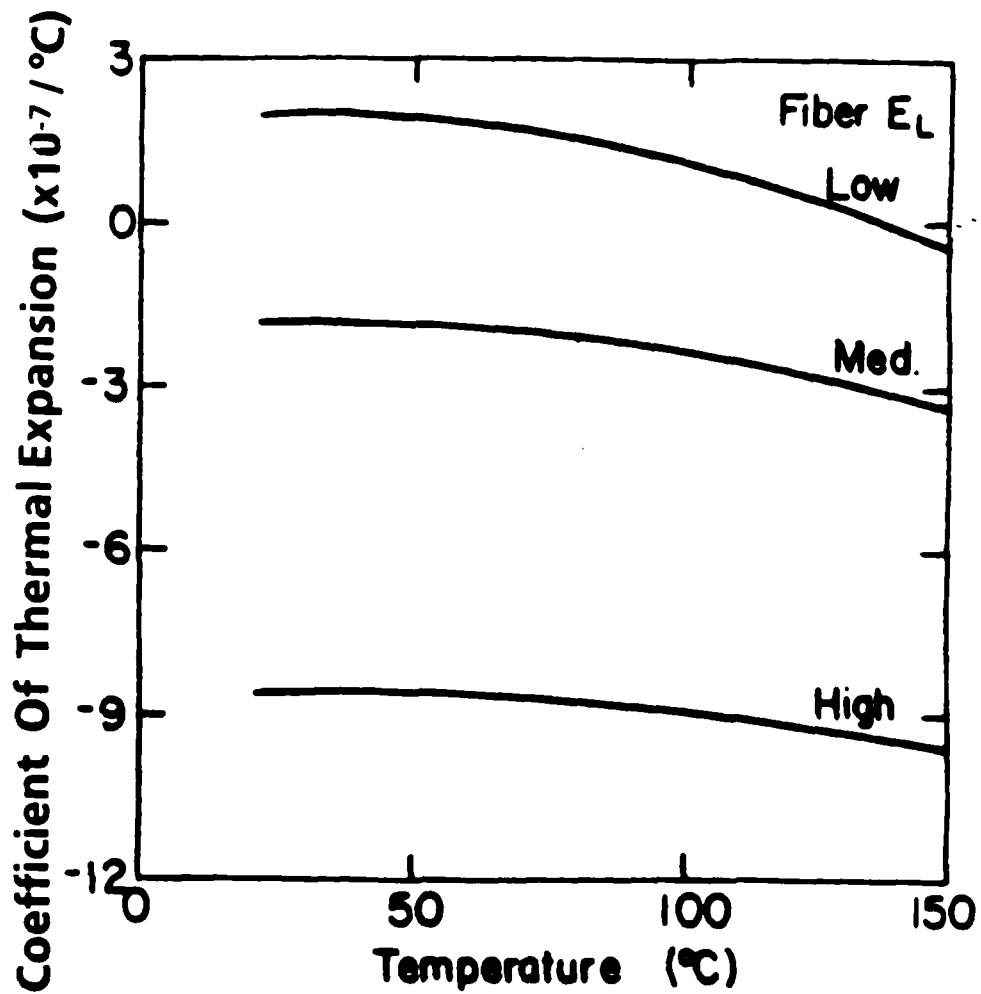


Figure 4.2-17. Composite Longitudinal Coefficient of Thermal Expansion Versus Temperature for Three Graphite Fibers
(Reference 4-20)

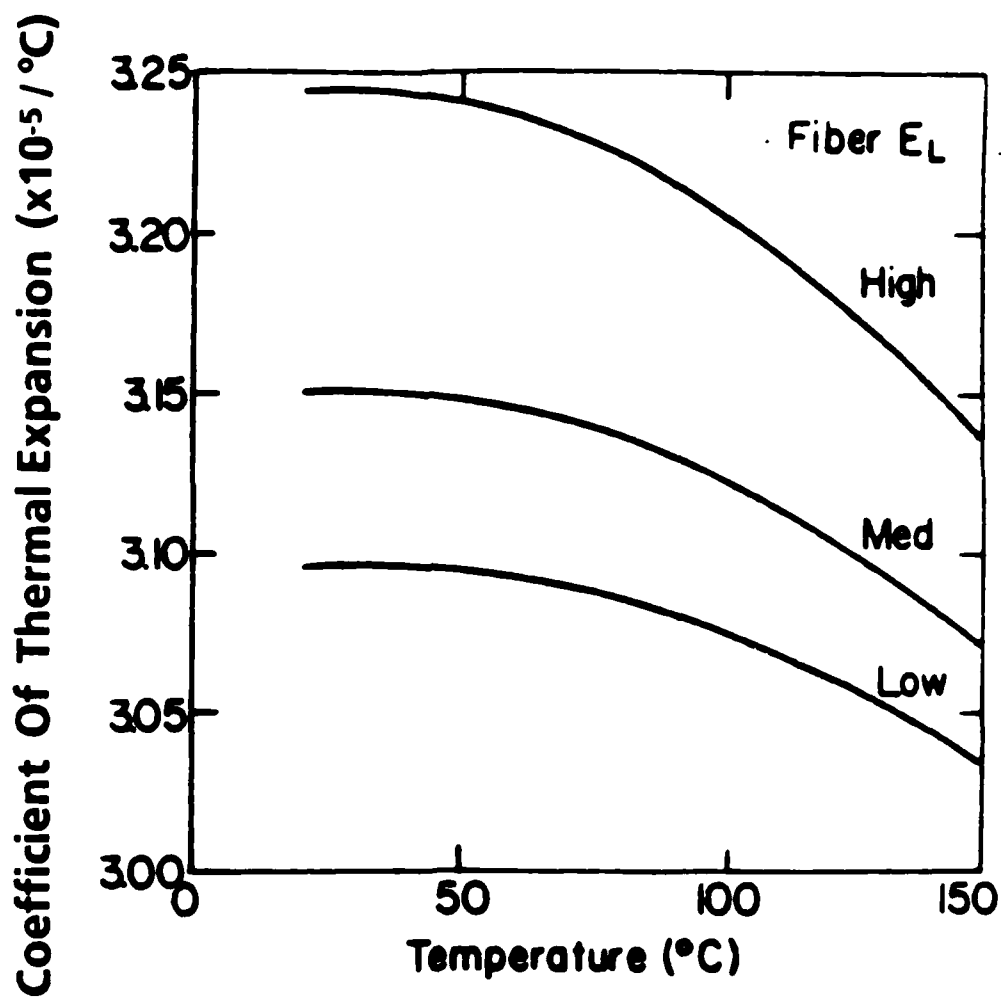


Figure 4.2-18. Composite Transverse Coefficient of Thermal Expansion Versus Temperature for Three Graphite Fibers
(Reference 4-21)

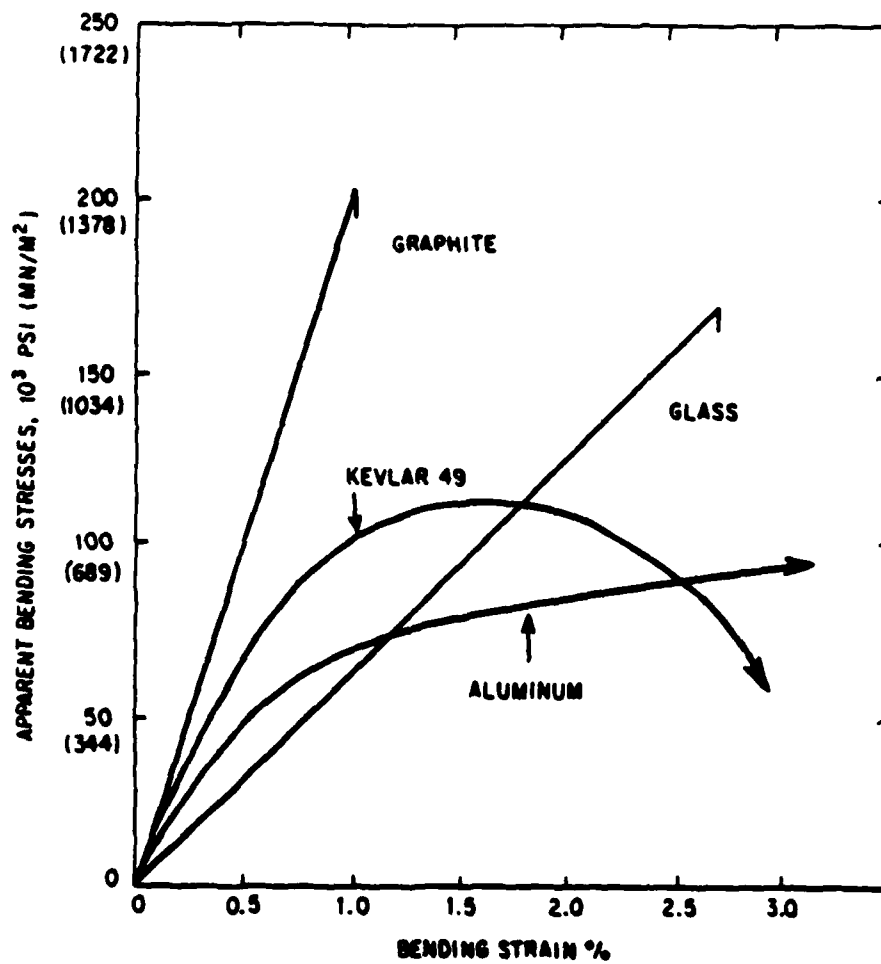


Figure 4.2-19. Unidirectional Composite Bending Stress/Strain Curves in Epoxy Resin (Reference 4-22)

TABLE 4.2-3. Basic Properties of Graphite/Epoxy Composites ($0 \pm 60^\circ$)
(Reference 4-23)

				INTERMEDIATE STRENGTH GRAPHITE/EPOXY		HIGH STRENGTH GRAPHITE/EPOXY		HIGH MODULUS GRAPHITE/EPOXY	
				R.T.	350°F	R.T.	350°F	R.T.	350°F
Design strengths (typical)	Longitudinal tensile, ultimate	(ksi)	F_x^{tu}	60.0	45.0	65.0	62.0	42.0	35.0
	Transverse tensile, ultimate	(ksi)	F_y^{tu}	48.0	36.0	52.0	43.0	36.0	24.0
	Longitudinal compression, ultimate	(ksi)	F_x^{cu}	64.0	24.0	69.0	26.0	38.0	22.0
	Transverse compression, ultimate	(ksi)	F_y^{cu}	55.0	21.0	59.0	22.0	33.0	19.0
	In-plane shear, ultimate	(ksi)	F_{xy}^{su}	31.0	23.0	40.0	33.0	26.0	24.0
	Interlaminar shear, ultimate	(ksi)	F^{isu}	—	—	—	—	—	—
	Ultimate longitudinal strain	(μ in./in.)	ϵ_x^{tu}	8,840.0	7,800.0	7,900.0	9,150.0	4,410.0	3,980.0
	Ultimate transverse strain	(μ in./in.)	ϵ_y^{tu}	7,060.0	6,360.0	6,430.0	6,590.0	3,820.0	2,750.0
Elastic properties (typical)	Longitudinal tension modulus	(msi)	E_x^t	6.75	5.95	8.09	6.78	9.42	8.73
	Transverse tension modulus	(msi)	E_y^t	6.75	5.95	8.09	6.78	9.42	8.73
	Longitudinal compression modulus	(msi)	E_x^c	6.75	5.95	8.09	6.78	9.42	8.73

TABLE 4.2-3. (continued)

				INTERMEDIATE STRENGTH GRAPHITE/EPOXY		HIGH STRENGTH GRAPHITE/EPOXY		HIGH MODULUS GRAPHITE/EPOXY	
				R.T.	350°F	R.T.	350°F	R.T.	350°F
Physical constants (typical)	Transverse compression modulus	(msi)	E_y^c	6.75	5.95	8.09	6.78	9.42	8.73
	In-plane shear modulus	(msi)	G_{xy}	2.58	2.26	3.03	2.57	3.56	3.31
	Longitudinal Poisson's ratio		ν_{xy}	0.307	0.318	0.312	0.322	0.324	0.317
	Transverse Poisson's ratio		ν_{yx}	0.307	0.318	0.312	0.322	0.324	0.317
	Density	(lb/in. ³)	ρ	0.055	0.055	0.056	0.056	0.058	0.058
	Longitudinal coefficient of thermal expansion	(μ in./in./°F)	α_x	1.79	1.90	1.21	1.10	1.27	0.984
	Transverse coefficient of thermal expansion	(μ in./in./°F)	α_y	1.79	1.90	1.21	1.10	1.27	0.984

TABLE 4.2-4. Typical Properties of Various Graphite Epoxy Composites
(Reference 4-24)

	Ultimate Properties			
	Tensile		Compression	
	Ultimate, psi	E, psi	Ultimate, psi	E, psi
Chopped fiber				
molding compound	51 000	15 700 000	68 000	...
Unidirectional (nonwoven)				
high strength fiber (0°)	236 000	20 000 000	144 000	16 400 000
high strength fiber (0°/±45°)	72 000	8 300 000	73 000	7 300 000
medium strength fiber (0°)	211 000	21 300 000	204 000	19 000 000
medium strength fiber (0°/±45°)	73 000	9 400 000	73 000	9 300 000
high modulus fiber (0°)	180 000	31 200 000	110 000	25 600 000
Fabric (woven)				
medium strength fiber	74 000	10 200 000	74 000	9 200 000

Conversion factor—

10³ psi = 6.9 MPa, and
10⁶ psi = 6.9 GPa.

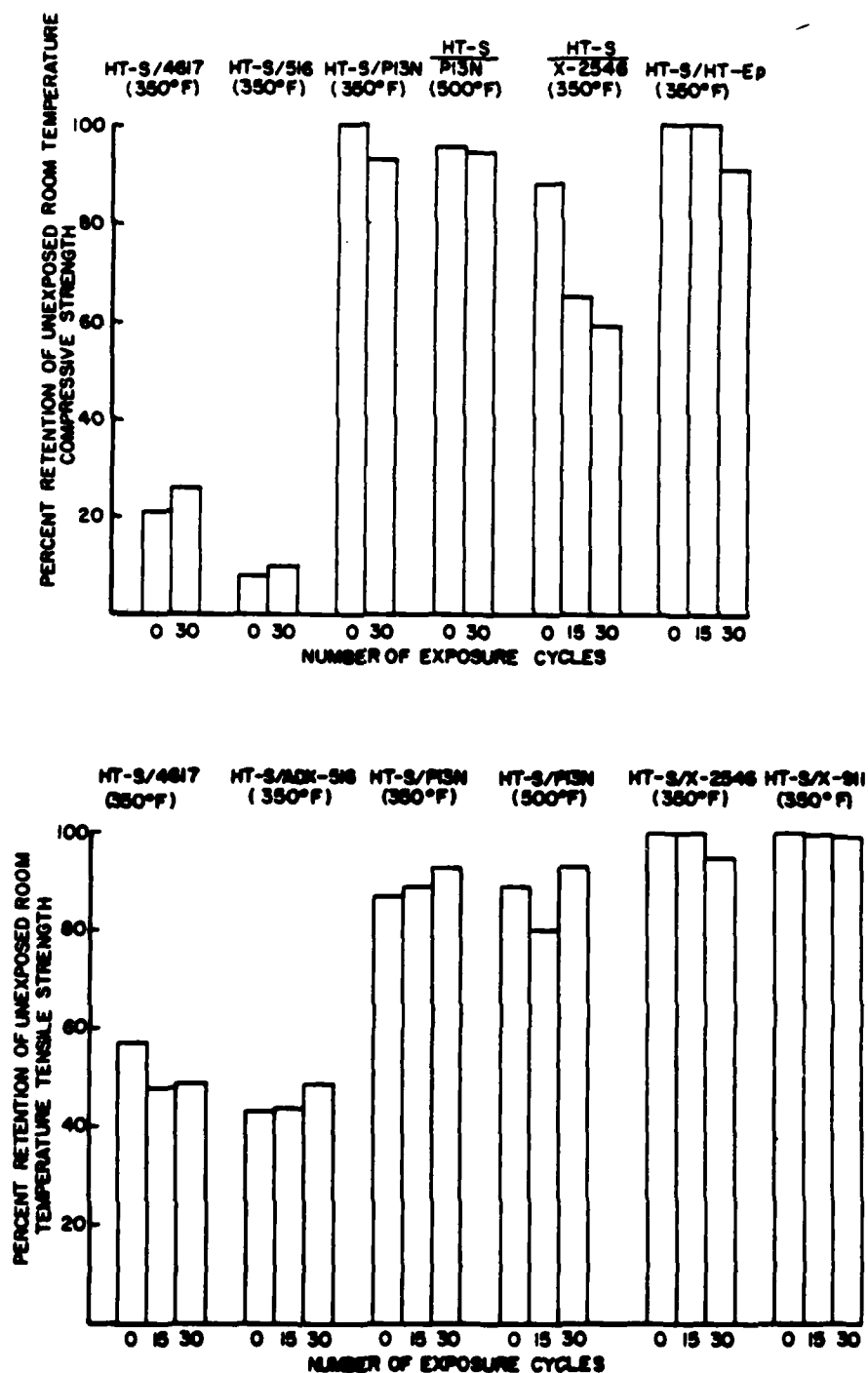


Figure 4.2-20. Effect of Cyclic Exposures on the Tensile Strengths and Compressive Strengths of Quasi-Isotropic Graphite/Epoxy Composites (Reference 4-25)

TABLE 4.2-5. Typical Impact Energy Values for Graphite/Epoxy and for Various Materials--Standard Charpy V--Notched Impact Tests (Reference 4-26)

Material description	Impact energy	
	kJ/m^2	ft-lb/in.^2
Modmor II graphite-epoxy ($V_f = 55\%$)	114	54
Kevlar-epoxy ($V_f = 65\%$)	604	330
S-Glass-epoxy ($V_f = 72\%$)	694	330
Nomex nylon-epoxy ($V_f = 70\%$)	116	55
Boron-epoxy ($V_f = 60\%$)	78	37
4130 Steel alloy (UTS = 100-160 ksi)	593	282
4340 Steel alloy [Rockwell (43-46)]	214	102
431 Stainless steel (annealed)	509	242
2024-T3 Aluminum alloy	84	40
6061-T6 Aluminum alloy (solution treated and precipitation hardened)	153	73
7075-T6 Aluminum alloy (solution treated and precipitation hardened)	67	32

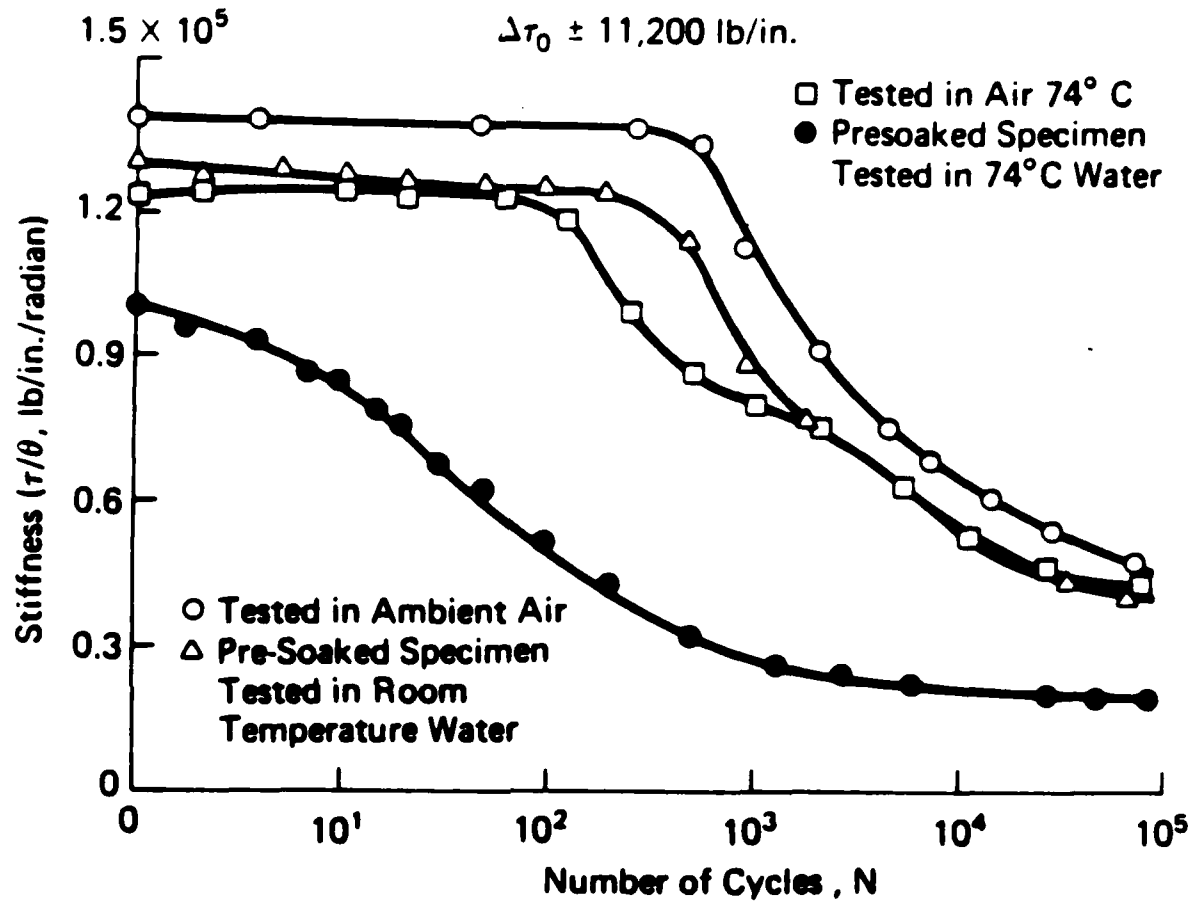
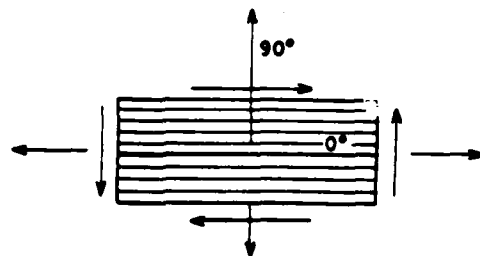


Figure 4.2-21. Torsion Fatigue of $\pm 45^\circ$ Fiber-Oriented Graphite-Epoxy Composite. Decrease in Stiffness (τ/θ) with Number of Cycles ($\log N$) as a Function of Environment (Reference 4-27)

4.2.3.2 Kevlar-Reinforced Epoxy. Low density Kevlar fibers used for composite materials provide a typical weight savings of 10 to 30 percent over fiberglass and graphite reinforced materials. Table 4.2-6 compares epoxy matrix composites reinforced with Kevlar 49, E glass, and graphite. Kevlar 49 shows a greater tensile strength and tensile stiffness, but a lower compressive strength. Composites reinforced with Kevlar 49 also show excellent fatigue behavior, as shown in Figure 4.2-22. Other physical and mechanical properties are shown in Figures 4.2-23 through 4.2-26 and in Tables 4.2-6 through 4.2-8.

TABLE 4.2-6. Comparison of Kevlar/Epoxy Properties with Different Types of Composites (Reference 4-28)



	Kevlar 49	E-Glass	Graphite
Density, lb/in. ³ (g/cm ³)	0.050 (1.38)	0.075 (2.08)	0.055 (1.52)
Tensile strength 0°, 10 ³ psi (MN/m ²)	200 (1 378)	160 (1 102)	180 (1 240)
Compressive strength 0°, 10 ³ psi (MN/m ²)	40 (276)	85 (586)	160 (1 102)
Tensile strength 90°, 10 ³ psi (MN/m ²)	4.0 (27.6)	5.0 (34.4)	6.0 (41.3)
Compressive strength 90°, 10 ³ psi (MN/m ²)	20 (138)	20 (138)	20 (138)
In-plane shear strength 10 ³ psi (MN/m ²)	6.4 (44.1)	9.0 (62.0)	9.0 (62.0)
Interlaminar shear strength, 10 ³ psi (MN/m ²)	7-10 (48.2-68.9)	12 (82.7)	14 (96.5)
Poisson's ratio	0.34	0.30	0.25
Tensile and compression modulus 0°, 10 ⁶ psi (MN/m ²)	11 (75 790)	5.7 (39 270)	19 (130 900)
Tensile and compression modulus 90°, 10 ⁶ psi (MN/m ²)	0.8 (5 512)	1.3 (8 960)	0.9 (6 200)
In-plane shear modulus, 10 ⁶ psi (MN/m ²)	0.3 (2 070)	0.5 (3 445)	0.7 (4 820)

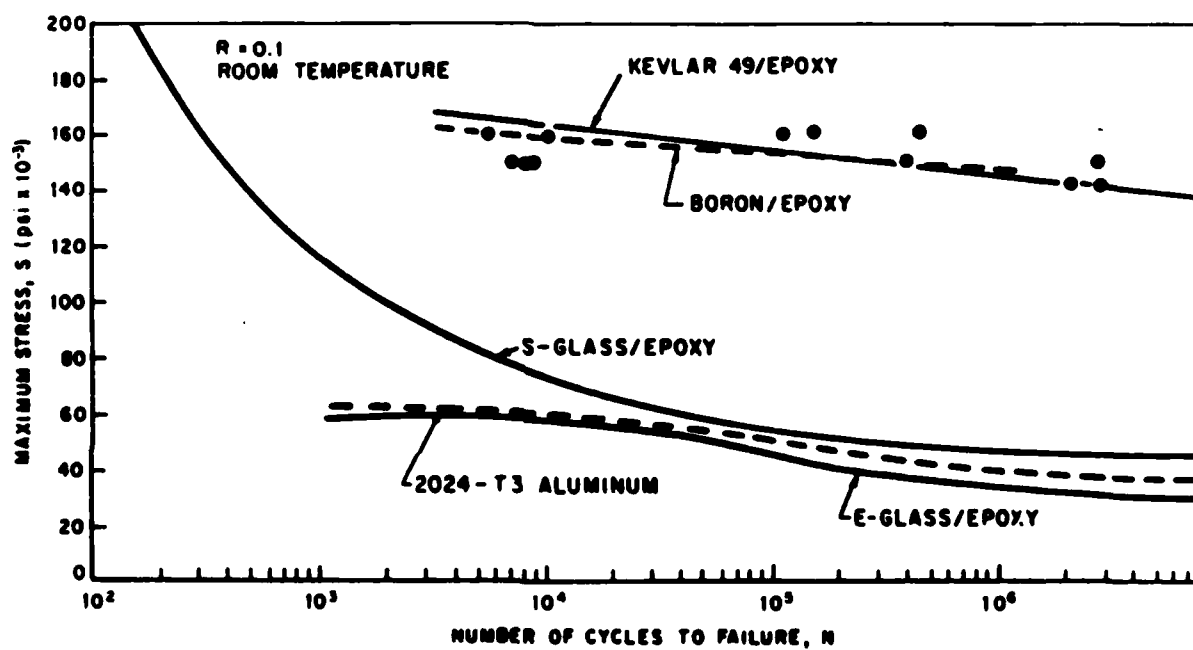


Figure 4.2-22. Tension-Tension Fatigue Behavior of Unidirectional Kevlar/Epoxy Composites and Aluminum (Reference 4-29)

TABLE 4.2-7. Attenuation of Free Vibrations in Kevlar/Epoxy and in Other Various Materials (Reference 4-30)

Material	Loss Factor $\times 10^4$
1020 steel	> 20
Ductile cast iron	30
Graphite/epoxy	30
Fiberglass/epoxy	47
Kevlar 49/epoxy	160
Cured polyester resin	400

loss factor $\sim \frac{A_n}{A_{n+1}}$

Amplitude Decay

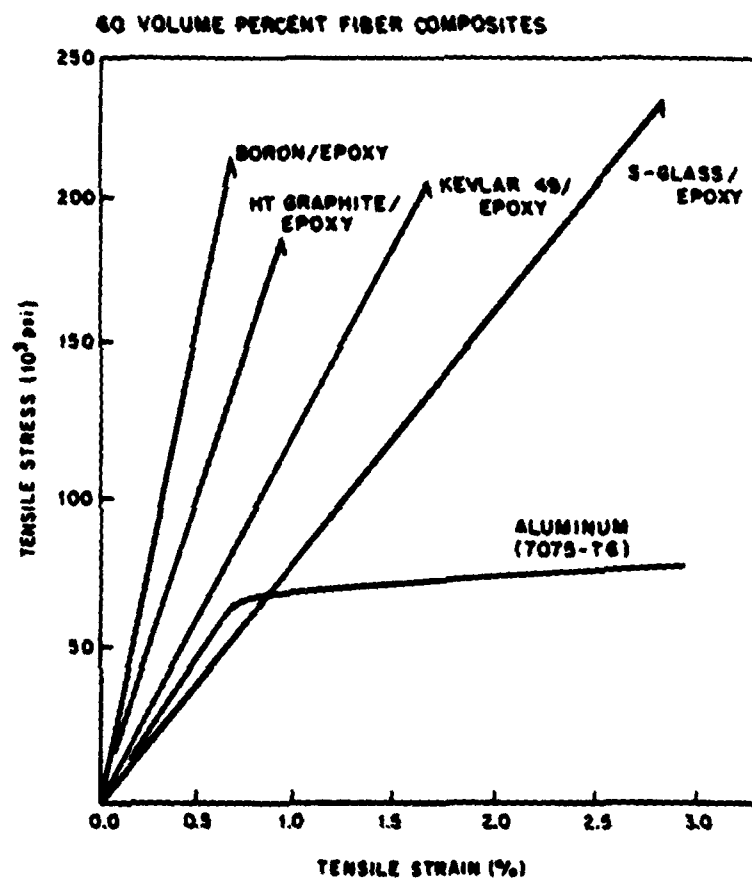


Figure 4.2-23. Creep and Recovery Behavior of Kevlar 49 Compared to Other Unidirectional Composites (Reference 4-31)

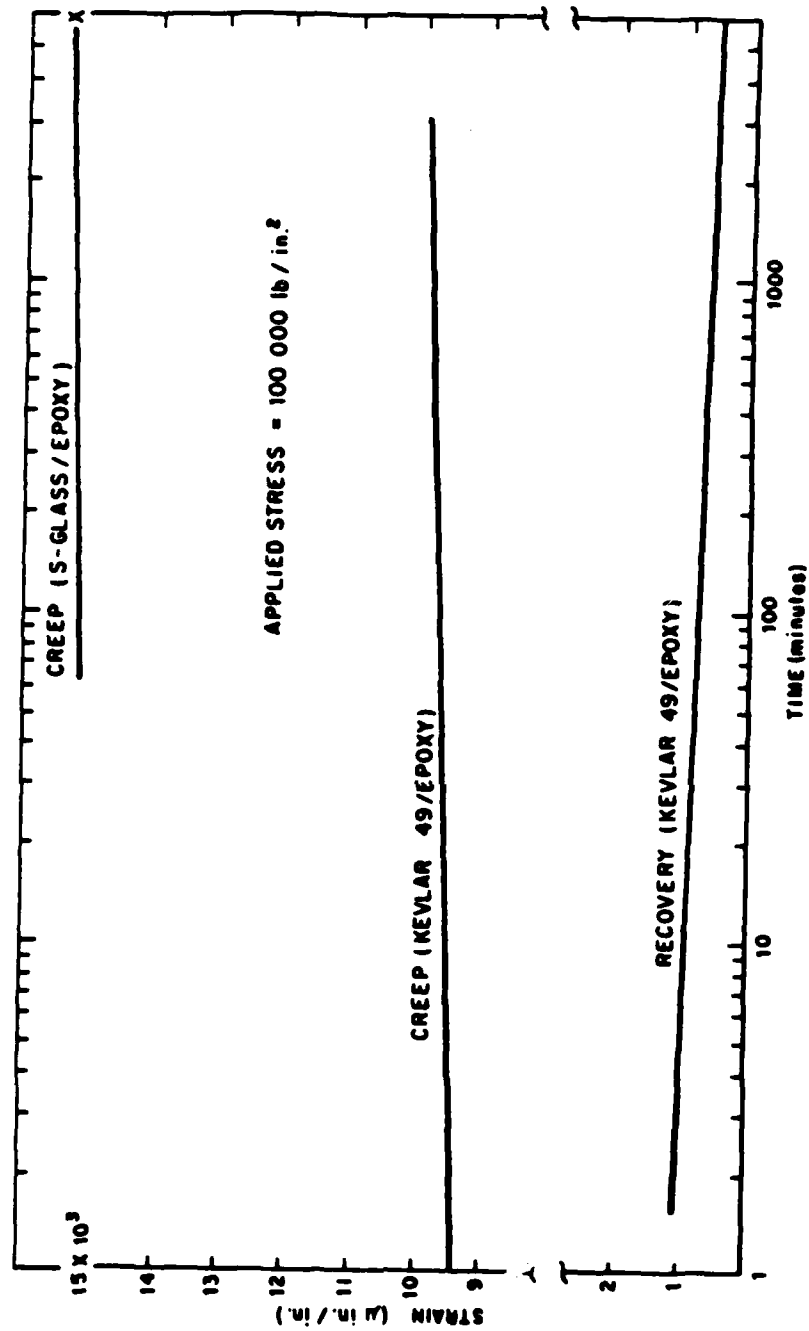
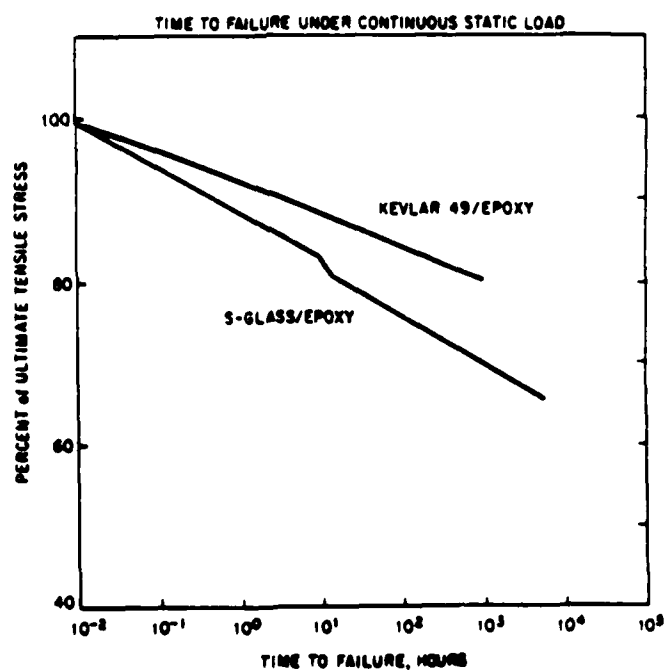


Figure 4.2-24. Creep and Recovery Behavior of Kevlar 49 and S-Glass Unidirectional Composites (Reference 4-32)

TABLE 4.2-8. Effect of Form of Reinforcement on Engineering Properties of Composites of Kevlar 49 Aramid (Reference 4-33)

Orientation	Form of Reinforcement of Kevlar 49						
	Unidirectional		Bidirectional		Fabric		Chopped Fiber
	All 0°		0°/90°		0°/90°		Random
Measurement direction	0°	90°	0°	45°	0°	45°	All
Tensile modulus, 10^6 psi	11.0	0.8	5.6	0.95	4.5	1.1	3.0
Tensile strength, 10^3 psi	200.0	4.0	92.0	14.1	75.0	30.0	28.5
Compressive modulus, 10^6 psi	11.0	0.8	5.6	1.0	4.5	1.0	...
Compressive strength, 10^3 psi	40.0	20.0	29.0	18.3	25.0	18.0	...
Flexural modulus, 10^6 psi	11.0	...	...	...	4.0	...	2.7
Flexural strength, 10^3 psi	90.0	...	...	...	50.0	...	35.5

Figure 4.2-25. Stress-Rupture Behavior of Kevlar 49 and S-Glass Unidirectional Composites (Reference 4-34)

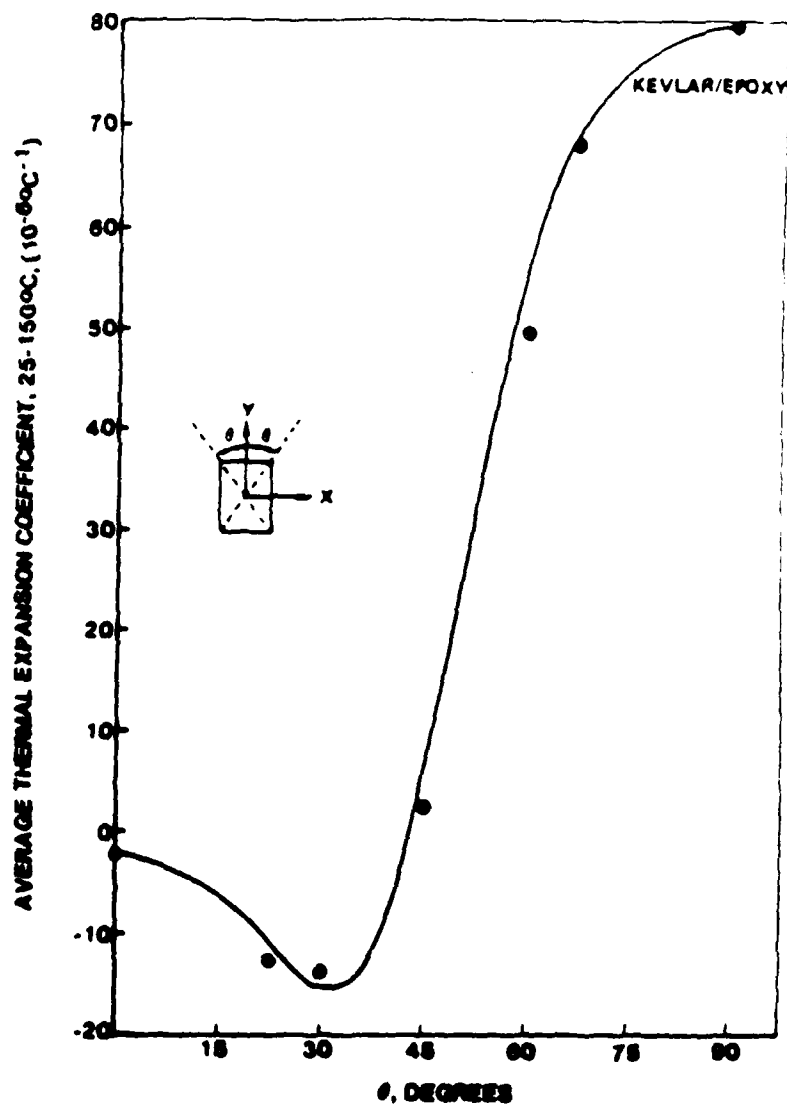


Figure 4.2-26. The Average Thermal Expansion Coefficient, α_y , Over the Temperature Range 25-150 °C for Bidirectional Kevlar/Epoxy Composites Reinforced in Directions Defined by θ in the Figure. The Solid Curve is a Plot of the Calculated Values of α_y for a Fiber Volume Fraction of 50% (Reference 4-35)

4.2.3.3 Boron-Reinforced Epoxy. Boron-reinforced epoxy systems have exceptional strength at elevated temperatures. They are capable of continuous service at 175 °C (350 °F) and up to 215 °C (420 °F) intermittently.

The boron-epoxy composite material "Narmco 5505" has some interesting results as shown in Table 4.2-9. This material is available as a tape 3 inches (7.62cm) wide and 100 to 250 feet (30 to 76m) long and containing

about 620 boron filaments across the width. The thickness of the layers is about .0051 inches (.0130cm). Directional properties make this material an ideal candidate for laminates. Load-carrying capacity and structural weight can be optimized by efficient arrangement and alignment of reinforcing materials.

Comparison of boron-epoxy composites to aluminum alloys, titanium, and fiberglass epoxy composites is shown in Figure 4.2-27. Other unique physical and mechanical properties of boron-reinforced epoxy can be found in Figures 4.2-28 through 4.2-30 and Table 4.2-10.

TABLE 4.2-9. Properties of "Narmco 5505" Boron-Epoxy Composite
(Reference 4-36)

<i>Property</i>	<i>Room temperature</i>		<i>260°F</i>		<i>350°F</i>	
Strength ksi (10⁶ N/m²)						
longitudinal tension	198.0	(13.65)	174.0	(12)	149.0	(10.27)
transverse tension	6.5	(0.45)	5.9	(0.4)	4.9	(0.34)
longitudinal compression	230.0	(15.86)	176.0	(12.13)	159.0	(10.96)
transverse compression	30.9	(2.13)	19.4	(1.38)	14.5	(1.0)
in-plane shear	9.0	(0.62)	5.0	(0.35)	3.0	(0.21)
Modulus 10⁶ psi (10¹⁰ N/m²)						
longitudinal tension	30.6	(21.1)	30.3	(20.9)	25.6	(17.65)
transverse tension	3.5	(2.41)	2.1	(1.45)	1.0	(0.69)
longitudinal compression	34.0	(23.4)	33.0	(22.75)	32.0	(22.06)
transverse compression	3.7	(2.55)	2.35	(1.62)	1.5	(1.0)
in-plane shear	1.00	(0.69)	0.80	(0.55)	0.22	(0.15)
major Poisson's ratio	0.36		0.35		0.30	
minor Poisson's ratio	0.033		0.025		0.017	
Coefficient of thermal expansion 10⁻⁶ in./in. °F (10⁻⁶ cm/cm °C)						
longitudinal	2.5	(4.5)	2.5	(4.5)	2.5	(4.5)
transverse	13.1	(23.6)	17.7	(31.9)	20.2	(36.4)

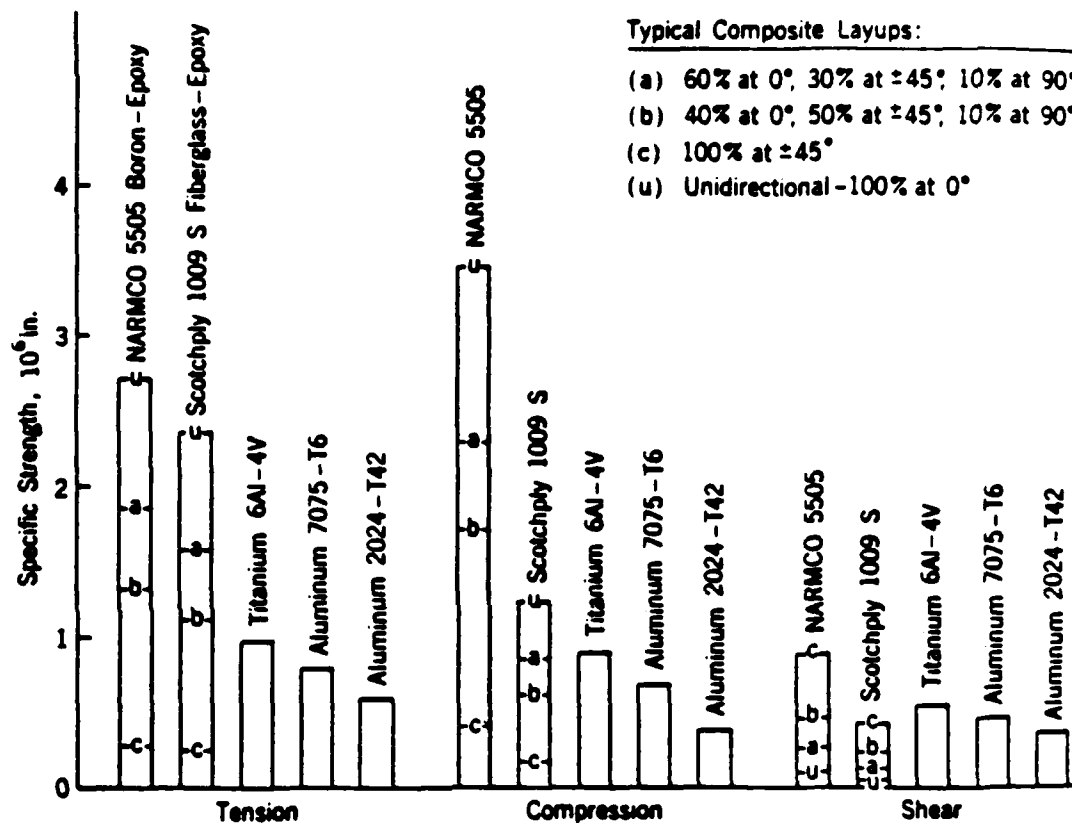


Figure 4.2-27. Specific Strength of Boron/Epoxy Composite Materials and Metals at Room Temperature (Reference 4-37)

TABLE 4.2-10. Allowable Strengths of a Unidirectional Boron Epoxy Laminate (Reference 4-38)

	Room Temperature	350°F
0° tensile strength (10^3 psi)	230	180
0° tensile modulus (10^6 psi)	32	28
90° tensile strength (10^3 psi)	10	5
90° tensile modulus (10^6 psi)	3.0	1.4
0° compression strength (10^3 psi)	360	110
Interlaminar shear (10^3 psi)	16	8

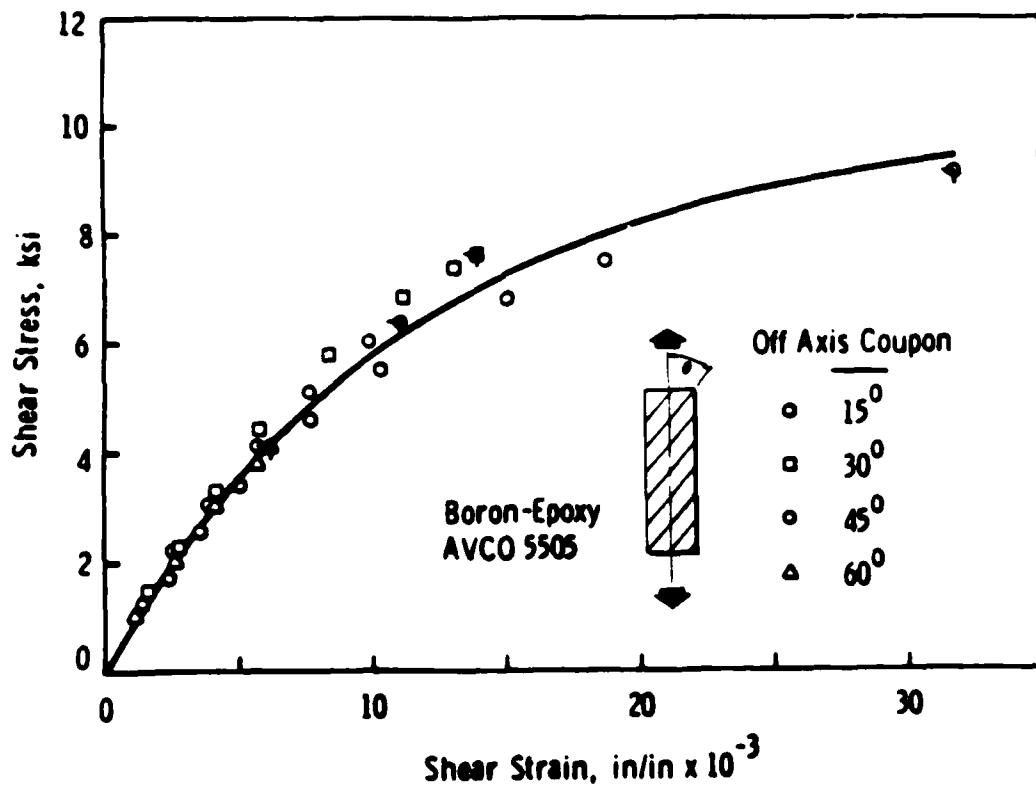


Figure 4.2-28. Boron/Epoxy Composite Shear Stress-Strain (Reference 4-39)

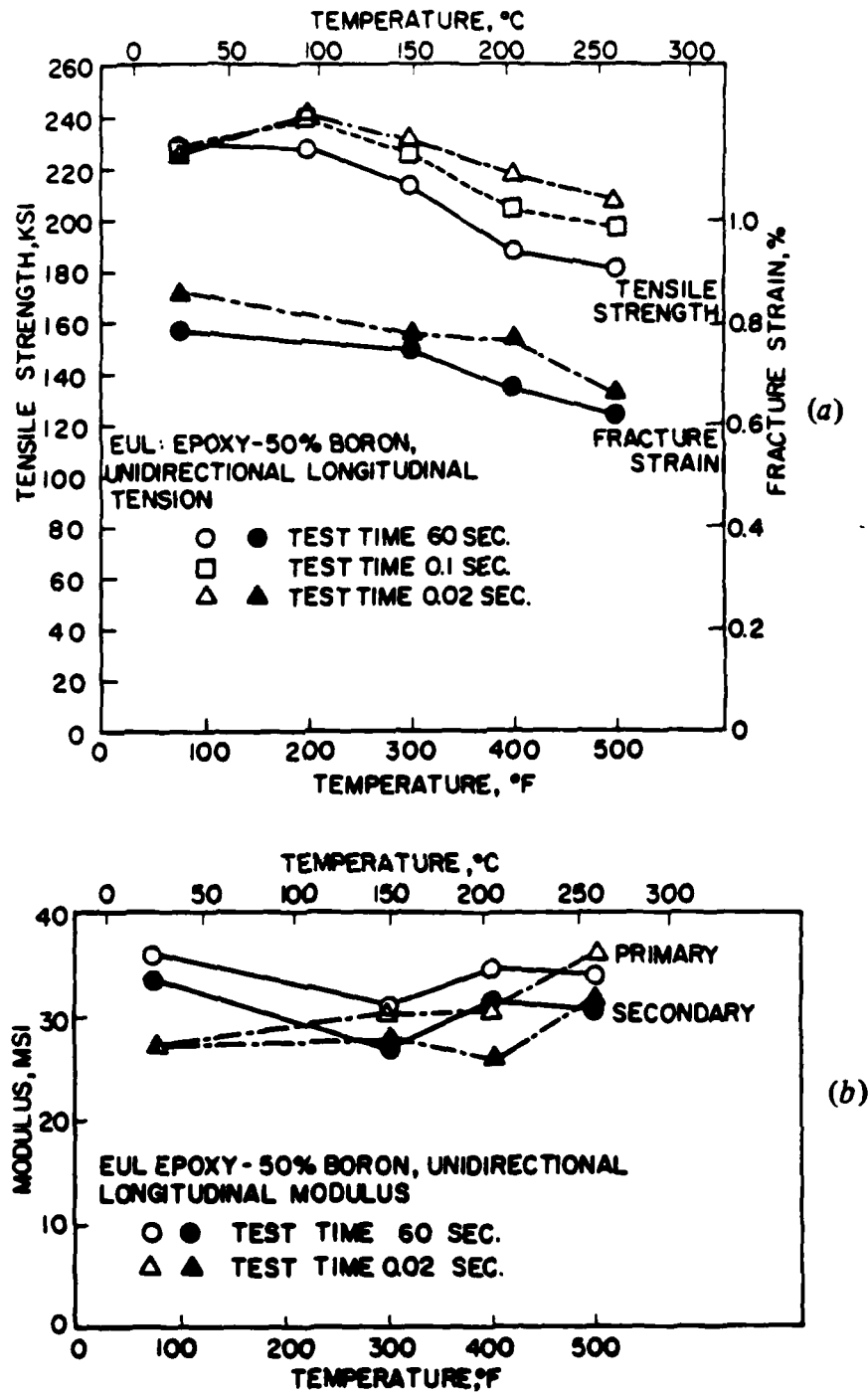


Figure 4.2-29. Tensile Properties of Epoxy-50 Percent Boron Unidirectional Composite at Several Temperatures and Strain Rates. (a) Longitudinal Ultimate Strength and Fracture Strain; (b) Longitudinal Young's Moduli (Reference 4-40)

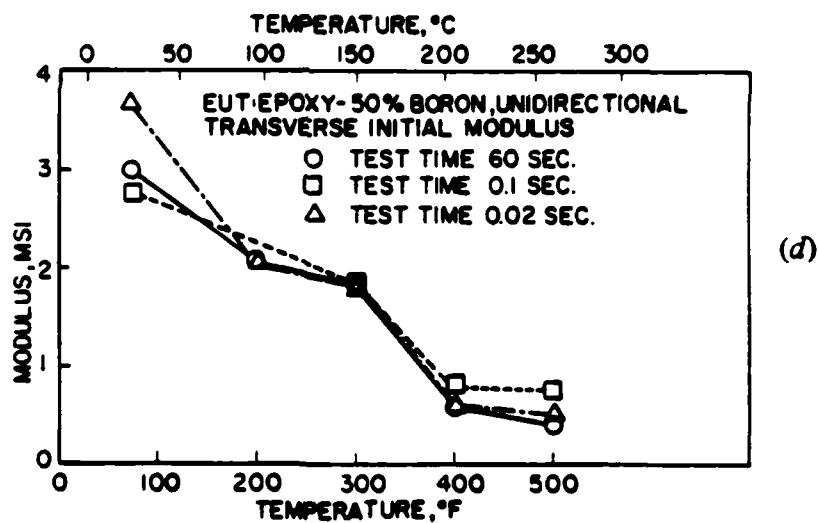
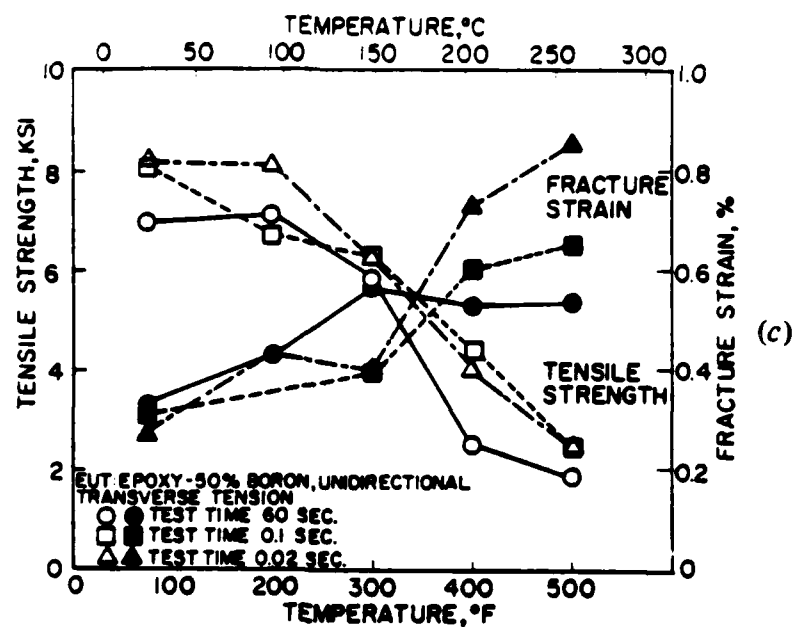


Figure 4.2-29. (continued) (c) Transverse Ultimate Strength and Fracture Strain; (d) Transverse Young's Moduli

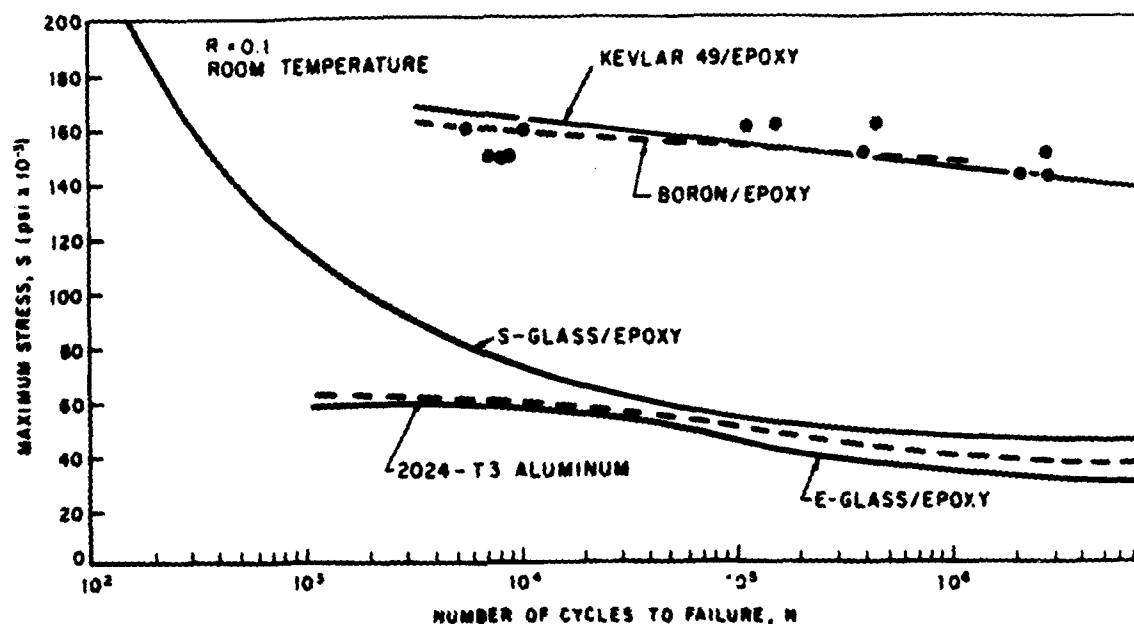


Figure 4.2-30. Tension-Tension Fatigue Behavior of Unidirectional Boron/Epoxy Composite and Aluminum (Reference 4-41)

4.2.3.4 Glass-Reinforced Epoxy. In the aerospace industry, more advanced composite parts are manufactured with fiberglass reinforcement than with any type of advanced fiber. Fiberglass reinforced composites are of great interest to structural designers because of the fiber long-term aging and strength retention properties, high tensile and impact strengths composites, and high chemical resistance. Table 4.2-11 shows the fiberglass and quartz-reinforced composite properties with 50 percent fiber volume fraction. The disadvantages of using fiberglass are low modulus, self-abrasiveness of fibers, relatively low fatigue resistance, and poor adhesion to matrix resins.

TABLE 4.2-11. Typical Properties of Glass/Epoxy and Quartz/Epoxy Composites (Reference 4-42)

Type of Fiber	E-Glass	S-Glass	Quartz
Density, g/cm ³	0.065	0.060	0.065
Tensile strength, unidirectional, psi	160 000	200 000	...
Tensile strength, fabric, psi	60 000	85 000	70 000
Tensile modulus, unidirectional, psi	6 000 000	8 000 000	...
Tensile modulus, fabric, psi	3 400 000	4 000 000	3 000 000
Compressive strength, fabric, psi	50 000	60 000	40 000
Dielectric constant	4.3	3.8	3.2
Loss factor	0.19 to 0.24	0.25	0.01
Coefficient of thermal expansion			
in./in./°F	4.8×10^6	3.5×10^6	2.2×10^6
cm/cm/°C	8.6×10^6	6.3×10^6	4.0×10^6

Conversion factor—

10³ psi = 6.9 MPa, and
in./in./°F = 0.556 cm/cm/°C.

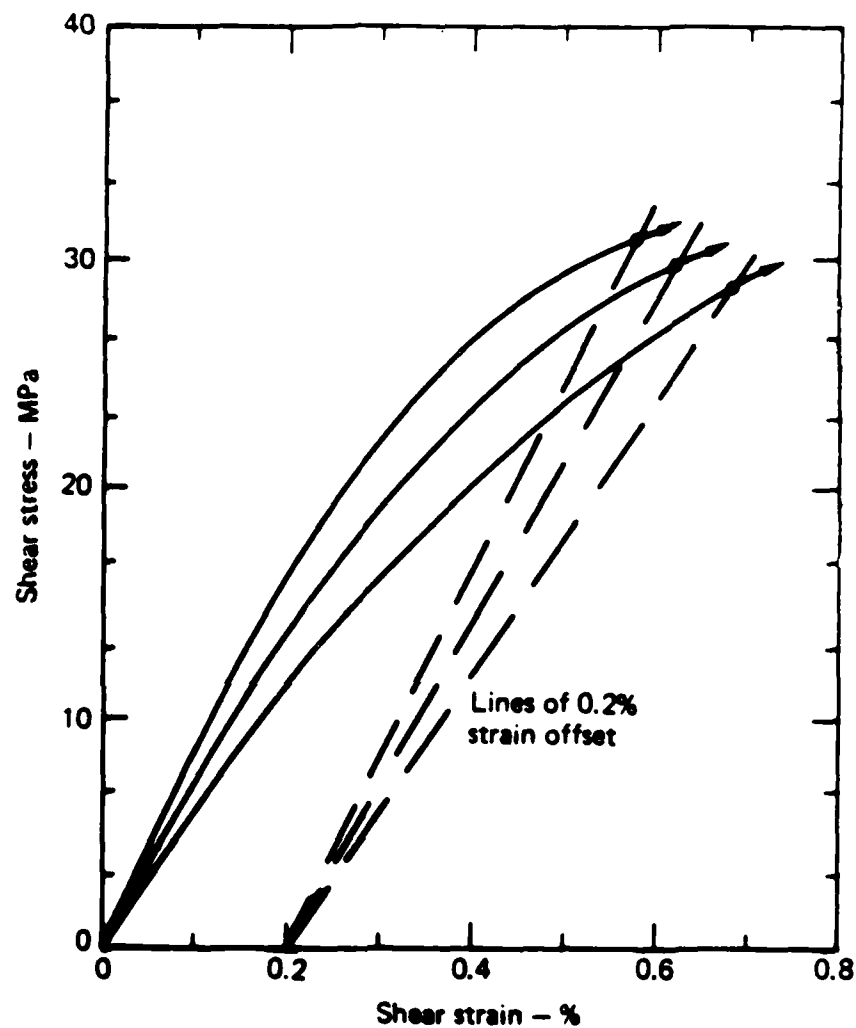


Figure 4.2-31. Average $\pm 45^\circ$ Tensile Shear Stress-Strain Curves for Three-Volume Percentages of S-2 Glass Fiber in a Room-Temperature-Curable Epoxy Matrix (Reference 4-43)

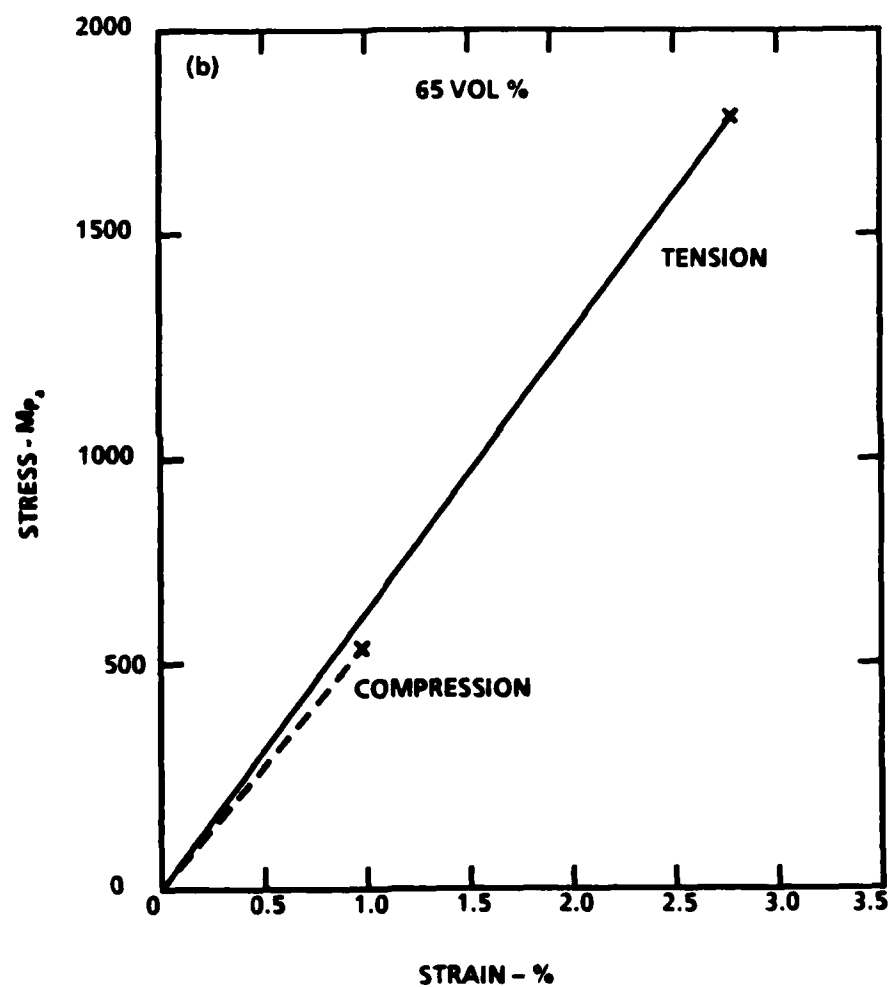


Figure 4.2-32. Average Longitudinal Tensile and Compressive Curves for 65% Fiber Volume (Reference 4-44)

TABLE 4.2-12. Comparison of Mechanical Properties for Five S-2 Glass-Epoxy Composites (Reference 4-45)

MECHANICAL PROPERTY	COMPOSITE (FIBER CONTENT)				
	50 VOL %	55 VOL %	60 VOL %	65 VOL %	70 VOL %
ELASTIC CONSTANTS					
LONGITUDINAL MODULUS, GPa	45.23 ± 0.89 ^a (31)	49.75 ± 0.98 ^a (31)	54.28 ± 1.05 ^a (31)	58.80 ± 1.16 ^a (31)	63.32 ± 1.25 ^a (31)
TRANSVERSE MODULUS, GPa	12.73 ± 0.24 ^b (34)	14.28 ± 0.24 ^b (34)	15.85 ± 0.24 ^b (34)	17.46 ± 0.24 ^b (34)	19.09 ± 0.24 ^b (34)
SHEAR MODULUS, GPa	~4.18 ^c (20)	~5.11 ^c (20)	6.14 ± 0.19 ^c (20)	7.28 ± 0.19 ^c (20)	8.52 ± 0.19 ^c (20)
MAJOR POISSON'S RATIO	0.2653 ± 0.0057 ^a (31)	0.2651 ± 0.0057 ^a (31)	0.2653 ± 0.0057 ^a (31)	0.2651 ± 0.0057 ^a (31)	0.2655 ± 0.0057 ^a (31)
MINOR POISSON'S RATIO	0.0749 ± 0.0020 ^b (34)	0.0763 ± 0.0021 ^b (34)	0.0777 ± 0.0022 ^b (34)	0.0789 ± 0.0023 ^b (34)	0.0802 ± 0.0024 ^b (34)
ULTIMATES					
LONGITUDINAL TENSION					
STRESS, MPa	1346 ± 52 ^a (29)	1480 ± 57 ^a (29)	1615 ± 62 ^a (29)	1749 ± 67 ^a (29)	1884 ± 72 ^a (29)
STRAIN, %	2.93 ± 0.14 (6)	3.07 ± 0.02 (6)	3.12 ± 0.09 (9)	2.87 ± 0.27 (10)	2.57 ± 0.32 (5)
LONGITUDINAL COMPRESSION					
STRESS, MPa	380 ± 50 ^d (4)	420 ± 50 ^d (4)	460 ± 60 ^d (4)	500 ± 60 ^d (4)	540 ± 70 ^d (4)
STRAIN, %	-	-	-	0.93 ± 0.07 (4)	-
TRANSVERSE TENSION					
STRESS, MPa	35.62 ± 0.95 ^b (29)	37.76 ± 0.95 ^b (29)	39.82 ± 0.95 ^b (29)	41.81 ± 0.95 ^b (29)	43.75 ± 0.95 ^b (29)
STRAIN, %	0.314 ± 0.010 ^b (29)	0.294 ± 0.010 ^b (29)	0.277 ± 0.010 ^b (29)	0.263 ± 0.010 ^b (29)	0.250 ± 0.010 ^b (29)
TRANSVERSE COMPRESSION					
STRESS, MPa	-	-	-	111.6 ± 2.3 (5)	-
STRAIN, %	-	-	-	3.89 ± 0.47 (5)	-
± 45° -TENSILE SHEAR, AT 0.2% OFFSET					
STRESS, MPa	~26.7 ^c (20)	~27.9 ^c (20)	29.04 ± 0.39 ^c (20)	30.12 ± 0.39 ^c (20)	31.16 ± 0.39 ^c (20)
STRAIN, %	~0.82 ^c (20)	~0.74 ^c (20)	0.676 ± 0.014 ^c (20)	0.620 ± 0.014 ^c (20)	0.573 ± 0.014 ^c (20)

^aBY RULE OF MIXTURES FROM SPECIMENS RANGING FROM 41 TO 65 VOL % FIBER.^bINTERPOLATED FROM TESTS OF SPECIMENS RANGING FROM 44 TO 68 VOL % FIBER.^cEXTRAPOLATED OR INTERPOLATED FROM TESTS OF SPECIMENS RANGING FROM 62 TO 69 VOL % FIBER.^dBY RULE OF MIXTURES FROM RESULTS AT 63.4 VOL % FIBER.

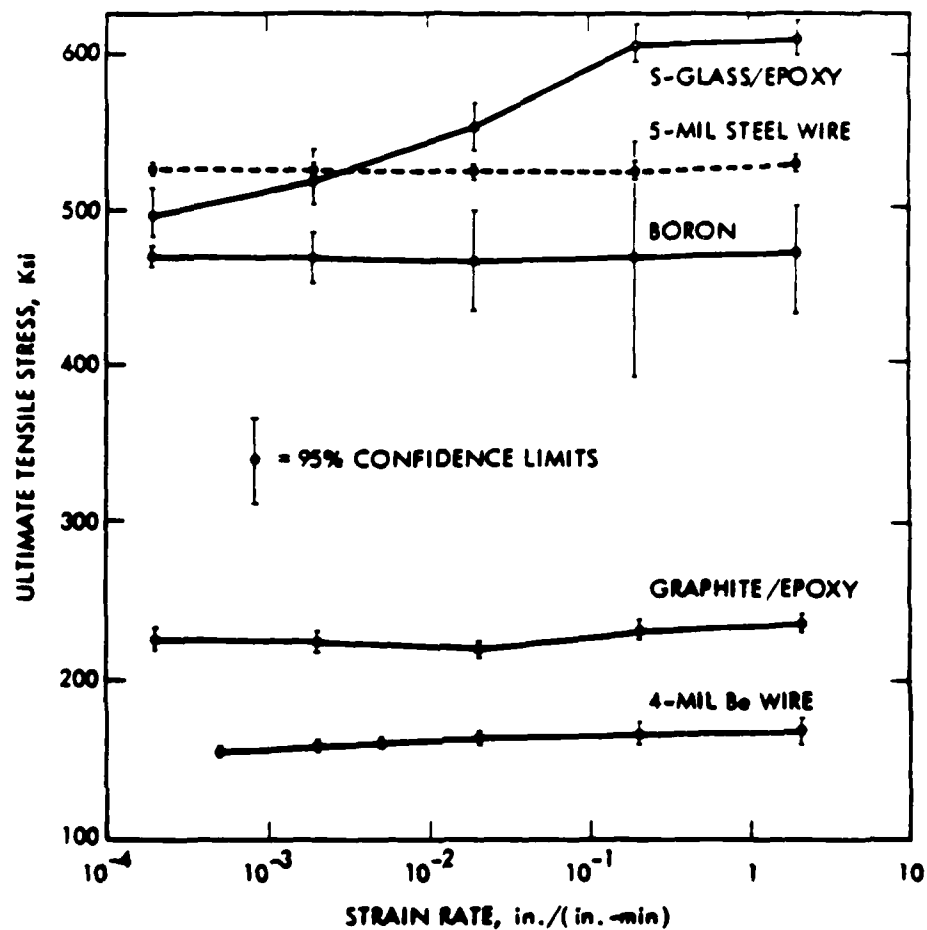


Figure 4.2-33. Strain Rate Effect on the Ultimate Tensile Stress of Glass Fiber/Epoxy Strands (Reference 4-46)

TABLE 4.2-13. Comparison of Thermal Property Data for Three S-2 Glass/Epoxy Composites (Reference 4-47)

THERMAL PROPERTY	COMPOSITE (FIBER CONTENT)		
	60 VOL %	65 VOL%	70 VOL
LINEAR COEFFICIENT OF THERMAL EXPANSION, $10^{-6}/^{\circ}\text{C}$ LONGITUDINAL (-50 to +75°C)	3.523 ± 0.038	3.523 ± 0.038	3.379 ± 0.38
TRANSVERSE -50°C -25°C 0°C 25°C 50°C 75°C	23.5 ± 0.8 24.3 ± 0.8 26.3 ± 0.8 28.9 ± 0.8 32.7 ± 3.4 98 ± 21	19.9 ± 0.8 21.3 ± 0.8 23.2 ± 0.8 25.1 ± 0.8 27.6 ± 3.4 77 ± 21	21.3 ± 0.8 23.4 ± 0.8 24.9 ± 0.8 27.6 ± 0.8 29.6 ± 3.4 86 ± 21
THERMAL CONDUCTIVITY, W/m °C LONGITUDINAL 0°C 25°C 50°C 75°C	1.50 ± 0.26 1.58 ± 0.26 1.67 ± 0.26 1.75 ± 0.26	1.62 ± 0.26 1.70 ± 0.26 1.80 ± 0.26 1.88 ± 0.26	1.74 ± 0.26 1.82 ± 0.26 1.92 ± 0.26 2.00 ± 0.26
TRANSVERSE -50°C -25°C 0°C 25°C 50°C 75°C	0.477 0.509 0.540 0.571 0.603 0.634	-	-

6027

4.3 Phenolic Polymer Matrix Composite.

4.3.1 Background. Although phenol formaldehyde resins (phenolic resins) have not found as widespread use as epoxy resins, they are still used in many applications. Epoxy has advantages of better adhesion, lower cure shrinkage, and the absence of voids; but these advantages may be overlooked for the unique char strength of phenolic matrix composites. The physical integrity of the charred structure makes phenolics desirable for such applications as ablative shields for reentry vehicles and rocket nozzles. Phenolic resins may be used as binders for carbon fiber structures. They may also be used as curing agents for some epoxies because of their

hydroxyl group. The rate of reaction of epoxy resin polymerization is accelerated by the presence of phenol or thio-phenol. Epoxidized phenolic-novolacs are candidates for advanced composite matrix material. Flammability and smoke evolution have recently been minimized in phenolics, making them excellent candidates for applications where these properties are important.

4.3.2 Phenolic Resin Preparation. Compared with other thermosetting materials, phenolic resins are very inexpensive. The production of phenolic resins involves a condensation reaction between phenol or phenol mixture and an aldehyde, such as formaldehyde, in the presence of a catalyst. The ratio of the reactants and the type of catalyst can be manipulated to form either a linear or a network structure. The structure is usually in the form of phenol molecules linked together by methylene and ether bridges. Many production methods make use of a partially cured powdered resin that allows fusion and cross-linking to form a final continuous structure by the application of heat and pressure. Impact strength and shrinkage are controlled by the addition of fillers. An idealized phenolic structure is shown below (Figure 4.3-1) where $n = 0-2$, $w = 0-3$, $x = 0-2$, $y = 0-1$. Other unique properties of phenolic resin can be found in Table 4.3-1 and Figure 4.3-2.

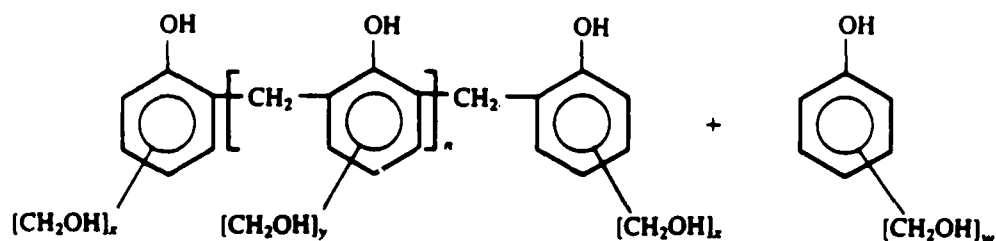


Figure 4.3-1. Formation of Phenolic Resin (Reference 4-48)

TABLE 4.3-1. Thermal Conductivity of Phenolic and Typical Thermosetting Resins at 35 °C (Reference 4-49)

Material	Density g cm^{-3}	Thermal conductivity $\text{W m}^{-1} \text{K}^{-1}$
Phenolic	1.36	0.27
	1.25	0.29
Epoxy	1.22	0.20
	1.18	0.29
Polyester	1.22	0.26
	1.21	0.18

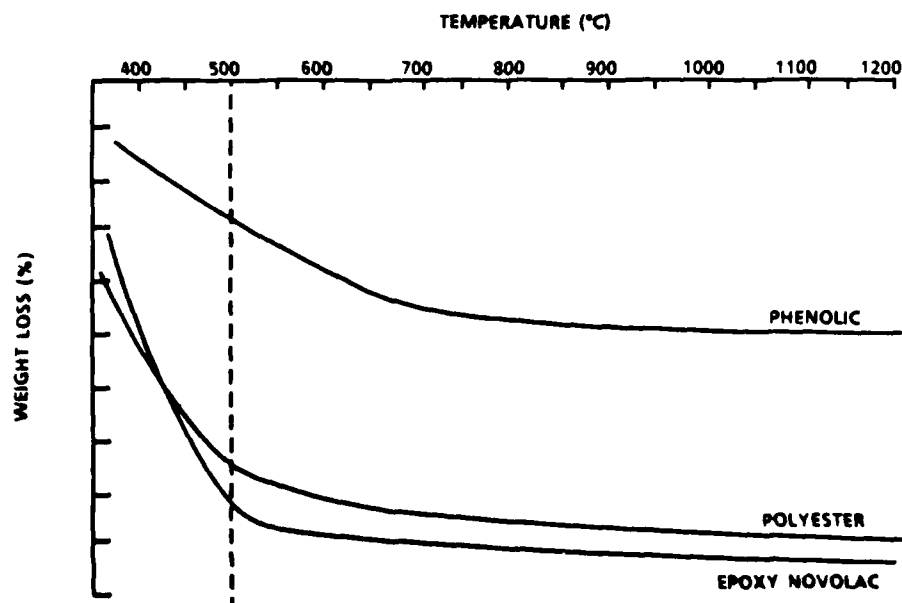


Figure 4.3-2. Comparison of Thermal Stabilities of Polyester, Phenolic, and Epoxy Novolac Resins. (Based on weight loss after 30 minutes at temperature up to 500 °C and 5 minutes at temperature thereafter) (Reference 4-50)

Phenolic fibers are available commercially under the trade name Kynol. These fibers will not melt or burn, and when exposed to flame, they give off 60 percent carbon residue with major volatiles of carbon dioxide and water (Figure 4.3-3). Blends with other fibers are often used to decrease flammability. Weight loss of Kynol fibers at 150, 200, and 250 °C is shown in Figure 4.3-4. It should be noted that temperatures above 150° cause oxidative degradation, and 150 °C should be the maximum temperature for long term use. Addition of compounds preventing peroxide formation will cause some improvement. Fiber properties after exposure to high temperatures are given in Table 4.3-2. In inert atmospheres, the tensile strength and modulus are not significantly changed by long exposures at high temperatures, but elongation at break is substantially reduced.

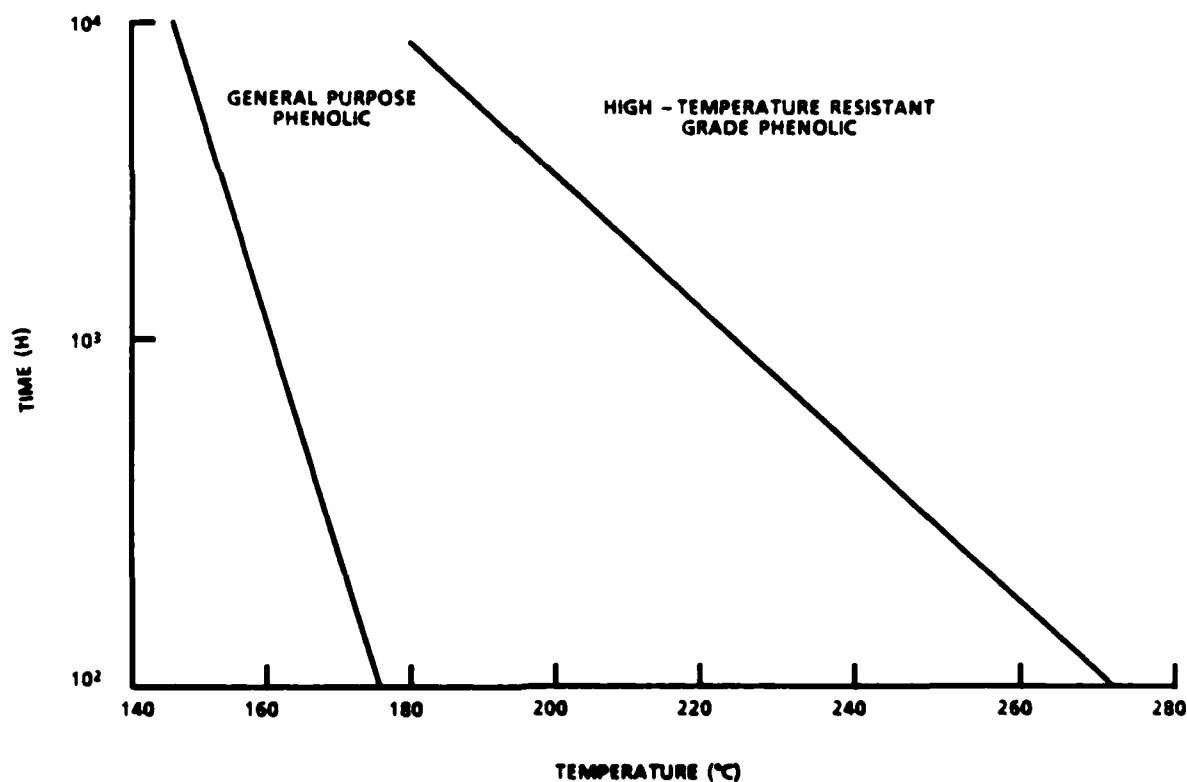


Figure 4.3-3. Lifetime at Temperature Plots for Phenolic Moldings Based Upon 70 Percent Retention of Flexural Strength
(Reference 4-51)

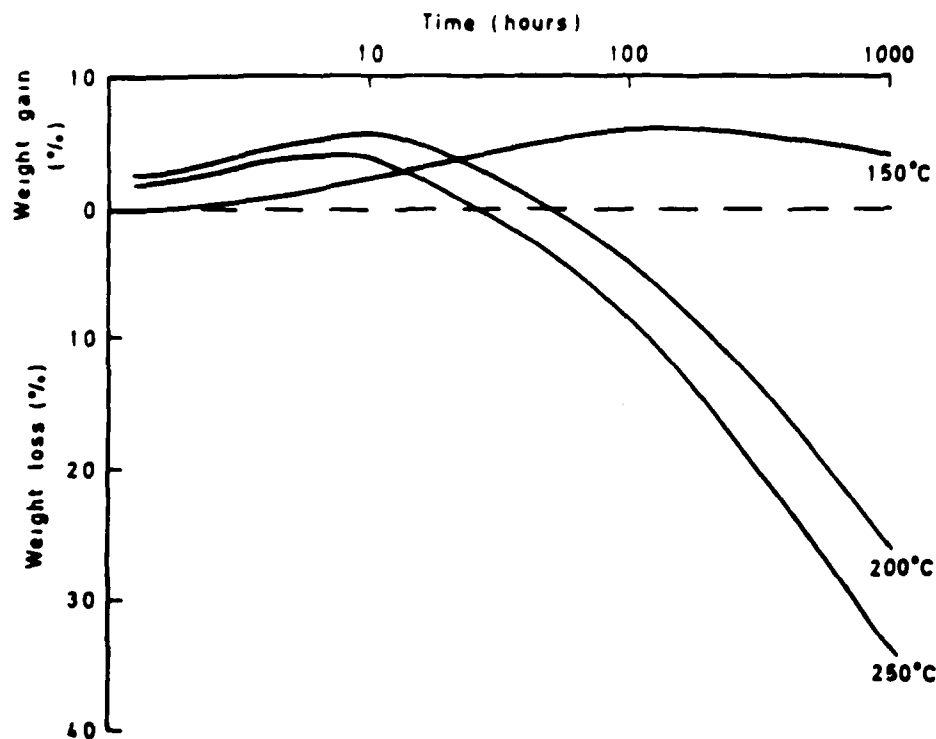


Figure 4.3-4. Isothermal Weight Loss of Phenolic Kynol Fibers in Air at Different Temperatures (Reference 4-52)

TABLE 4.3-2. Properties of Phenolic Kynol Fibers after Aging at Elevated Temperatures (Reference 4-53)

Aging condition	Atmosphere	Tenacity (g/den)	Modulus (g/den)	Elongation at break (%)
Unaged		1.9	48	33.6
350 hours at 250°C	Nitrogen	1.9	44	7.3
500 hours at 250°C	Nitrogen	1.9	42	9.2
1000 hours at 250°C	Nitrogen	1.9	46	8.3
100 hours at 350°C	Nitrogen	1.8	43	6.8
500 hours at 150°C	Air	0.9	47	4.2
1200 hours at 150°C	Air	0.6	37	1.6
350 hours at 250°C	Air	0.7	35	2.9
500 hours at 250°C	Air	0.7	49	2.6
1000 hours at 250°C	Air	0.4	30	1.2

4.3.3 Properties of Phenolic Matrix Composites. The aerospace industry has extensively used phenolic matrix composites. They are primarily reinforced with glass fabric and have been successfully used at temperatures of 500 °F for up to 200 hours. Other reinforcements have been used in thermal protection applications including nylon, high-silica, quartz, and graphite textile reinforcements.

Phenolics release large amounts of volatiles during the condensation reaction, thus presenting much difficulty in the use of reinforcements other than glass. Phenolic composites are not as sound as polyimides and do not have as great heat resistance. Thermal degradation of phenolics can be characterized by either the amount of volatiles given off or by weight loss. Figure 4.3-5 describes the weight loss of a glass-phenolic system at various high temperatures as a function of time. Decomposition is accelerated uniformly with increasing temperatures above 300 °F. Figure 4.3-6 shows mechanical properties of carbon reinforced phenolics as a function of temperature. Flexural strength tends to have an accelerated decrease above 120 °C, but torsional modulus changes very little, even at 240 °C. Various properties of glass fiber reinforced phenolic matrix composite are listed in Table 4.3-3. With the exception of flexural strength and modulus, there is relatively little change in properties. In fact, tensile and compressive rupture strengths are retained very well at 260 °C for over 1000 hours. This is superior to aluminum alloys commonly used for structural materials in aircraft. Figure 4.3-7 shows changes in flexural, compressive, tensile strength, and modulus of silane-modified phenolic/glass fiber composite relative to temperatures up to 535 °C. Seen from this representation, phenolic resins seem to have excellent retention of properties at high temperatures, but a difference is significant when held at these temperatures for extended periods of time. Other unique properties of phenolic matrix composites can be found in Table 4.3-4 through 4.3-8 and Figures 4.3-8 and 4.3-9.

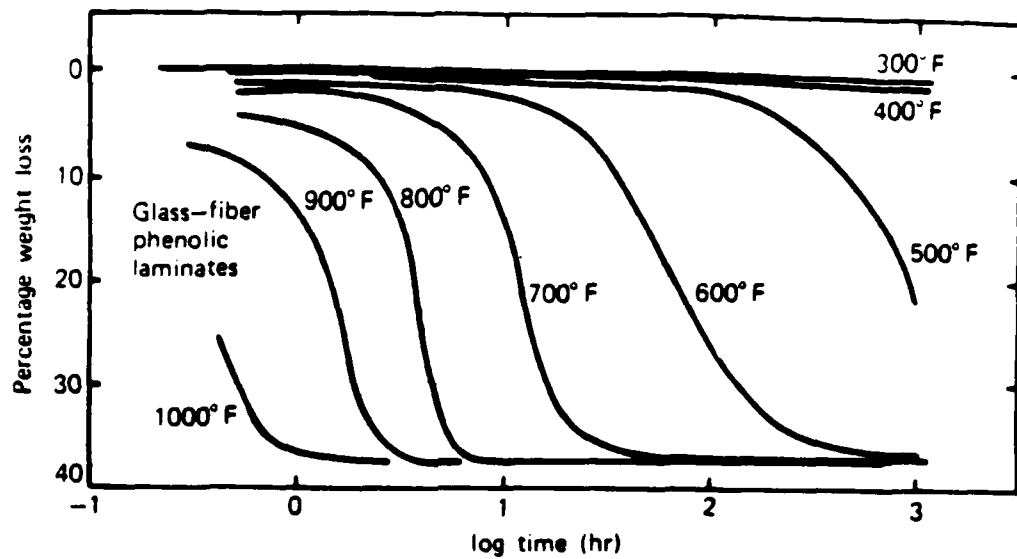


Figure 4.3-5. Thermal Degradation of Glass-Phenolic System
(Reference 4-54)

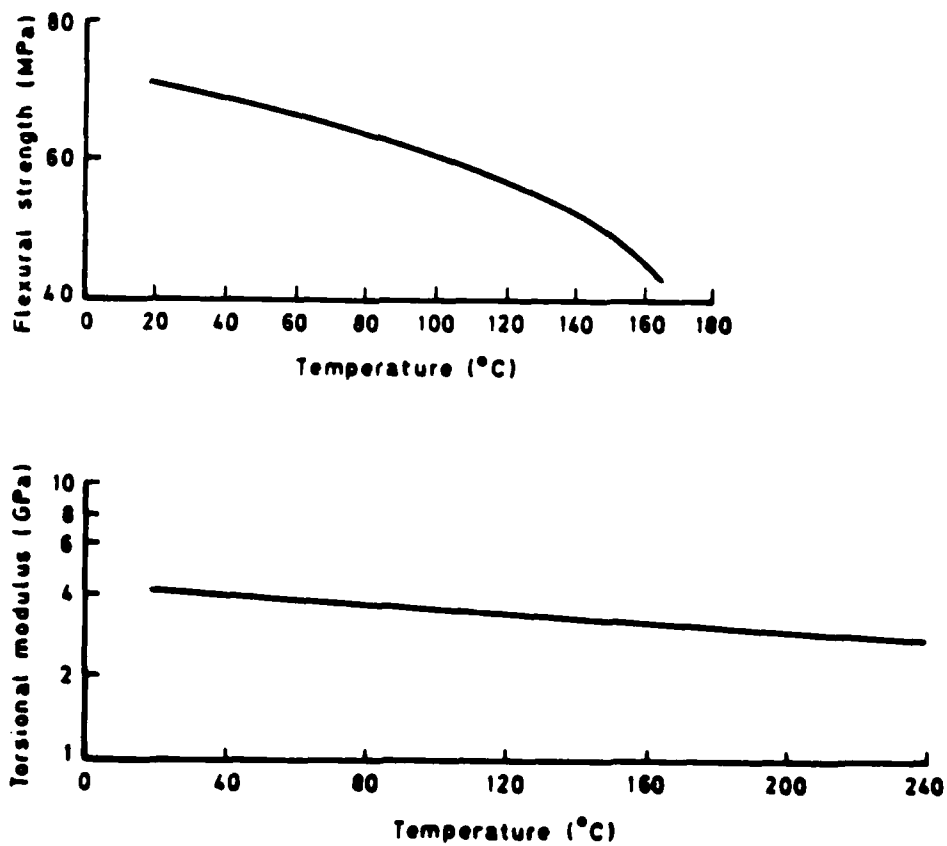


Figure 4.3-6. Mechanical Properties as a Function of Temperature of Carbon-Filled Phenolic Moldings (Reference 4-55)

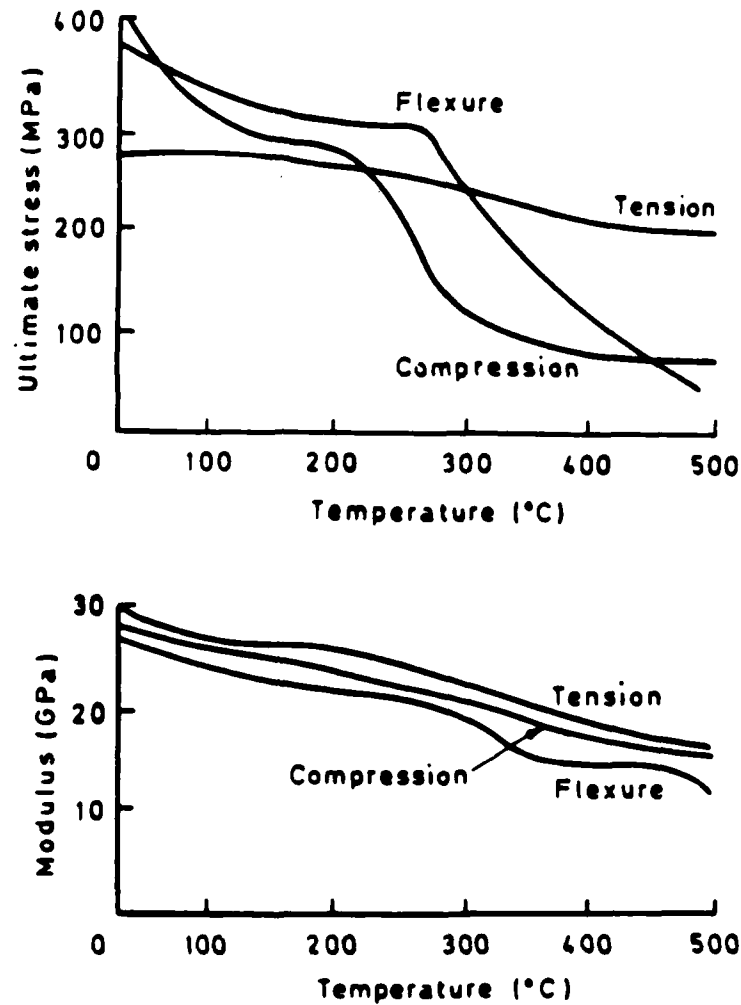


Figure 4.3-7. Change in Mechanical Properties of a Silane-Modified Phenolic Resin/Glass Fiber (181 Volan A) Laminate with Temperature. Tested at Temperature After 30 Minutes at Temperature (Reference 4-56)

TABLE 4.3-3. Properties of a CTL 91-LD Phenolic Resin/181 Glass Fiber Laminate (Reference 4-57)

Property	Room temperature	Value at 260°C after 30 minutes at 260°C	Property retention (%)
Flexural strength (MPa)	600	449	75
Flexural modulus (GPa)	33	26	79
Tensile strength (MPa)	400	359	90
Tensile modulus (GPa)	23	21	91
Compressive strength (MPa)	345	319	92
Shear strength (MPa)	286	266	93
Izod impact strength (J/mm notch)	0.8	0.8	100
Dielectric constant at 1 MHz	4.0	3.98	—
at 10 MHz	3.57	4.16	—
Power factor at 1 MHz	0.0098	0.0055	—
at 10 MHz	0.010	0.0126	—

TABLE 4.3-4. Transverse and Longitudinal Thermal Conductivity of a Glass Fiber Reinforced Phenolic Resin ($V_f = 0.54 \pm 0.02$) (Reference 4-58)

Temperature <i>K</i>	Thermal conductivity $W m^{-1} K^{-1}$		k_{CL}/k_{CT}	Density $g cm^{-3}$
	k_{CT}	k_{CL}		
300	0.508	0.60	1.18	2.18
250	0.472	0.548	1.16	—
200	0.428	0.490	1.14	—
150	0.374	0.423	1.13	—
100	0.320	0.357	1.12	—
50	0.27	0.285	1.06	—

TABLE 4.3-5. Vibration Data for Carbon-Phenolic (warp direction)
(Reference 4-59)

<i>Mode</i> <i>n</i>	<i>Frequency</i> f_n (Hz)	<i>Modulus</i> $E_1 \times 10^{-6}$ (psi)	<i>Loss Factor</i> $\tan \delta$
1	77	3.18	0.0054
2	480	3.21	0.0083
3	1,335	3.23	0.0077
4	2,585	3.24	0.0095
5	4,230	3.19	0.0107
6	6,230	3.17	0.0123
7	8,600	3.25	0.0140
8	11,200	3.22	0.0150

TABLE 4.3-6. Vibration Data for Silica-Phenolic (warp direction)
(Reference 4-60)

<i>Mode</i> <i>n</i>	<i>Frequency</i> f_n (Hz)	<i>Modulus</i> $E_1 \times 10^{-6}$ (psi)	<i>Loss Factor</i> $\tan \delta$
1	118	3.32	0.0051
2	741	3.35	0.0079
3	2060	3.33	0.0092
4	3983	3.35	0.0124
5	6426	3.30	0.0146
6	9426	3.32	0.0179

TABLE 4.3-7. High-Temperature Flexural Properties of Carbon-Based Plastic Laminates (Reference 4-61)

MATERIAL	DENSITY (lb/in ³)	FLEXURAL STRENGTH (lb/in ²)				FLEXURAL MODULUS (10 ⁶ lb/in ²)			
		75°F	400°F	700°F	75°F	400°F	700°F	75°F	700°F
Phenolic ^a 40% Carbon fabric ^b 60%	89.8	26,500	26,500	21,200	2.27	1.49	1.31		
Phenolic ^a 35% Carbon fabric ^c 65%	82.0	18,300	17,500	13,600	0.92	1.06	0.82		
Phenyl silane ^d 32% Carbon fabric ^e 68%	83.5	18,600	19,600	14,600	1.19	1.10	0.89		
Phenolic ^a 30% Graphite fabric ^e 70%	82.6	20,200	17,600	8160	1.64	1.40	0.65		
Phenyl silane ^d 30% Graphite fabric ^e 70%	83.2	19,900	17,200	10,600	1.58	1.51	1.04		

^aMontanto "SC 1008."^b"CCA-1."^c"VCA."^dC.T.L. "37.9X."^e"WCB."

TABLE 4.3-8. Strength Properties of Carbon-Based Fabric Reinforced Plastics (Reference 4-62)

MATERIAL	DENSITY (lb/ft ³)	TENSILE STRENGTH (lb/in ²)	FLEXURAL STRENGTH (lb/in ²)	FLEXURAL MODULUS (10 ⁶ lb/in ²)	COMPRESSIVE STRENGTH (lb/in ²)	COMPRESSIVE MODULUS (10 ⁶ lb/in ²)
Phenolic ^a 40% Carbon fabric ^b 60%	89.8	16,600	26,500	2.27	40,200	2.47
Phenolic ^a 35% Carbon fabric ^c 65%	82.0	9160	18,300	0.92	23,800	1.50
Phenolic ^a 46% Carbon fabric ^c 54%	85.2	7250	14,800	1.01	27,100	1.22
Epoxy novolac ^d 27% Carbon fabric ^c 73%	78.7	9310	16,000	0.93	16,700	1.19
Phenolic ^e 27% Graphite fabric ^f 73%	82.6	11,600	20,100	1.69	13,200	2.13
Phenolic ^e 37% Graphite fabric ^f 63%	86.7	9970	17,900	1.17	10,900	1.75
Phenyl silane ^g 30% Graphite fabric ^f 70%	83.2	11,200	19,900	1.58	11,500	1.95

^aMonsanto "SC 1008."^bCCA I."^cVCA."^dDow Chemical "D.F.N. 438."^eC.T.L. "91LD."^fWCB."^gC.T.L. "37-9X."

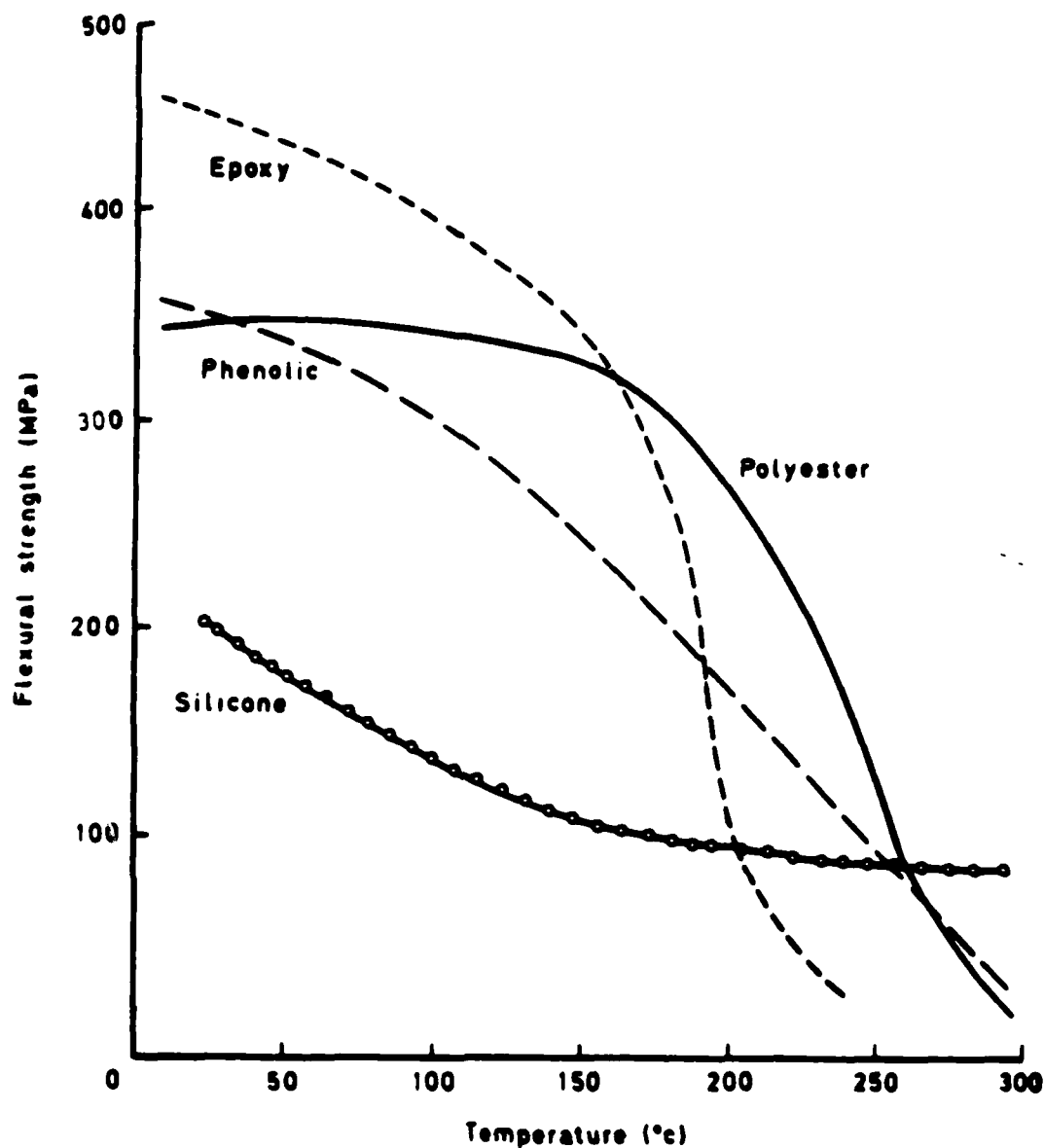


Figure 4.3-8. Flexural Strength of Various Glass-Cloth Laminates after 100 Hours at Temperature. (All heat-cleaned Y227 cloth. Polyester resin-PDL-7-669. Epoxy resin-Epikote 828. Phenolic resin-VI7085. Silicone resin MS 2106.)
(Reference 4-63)

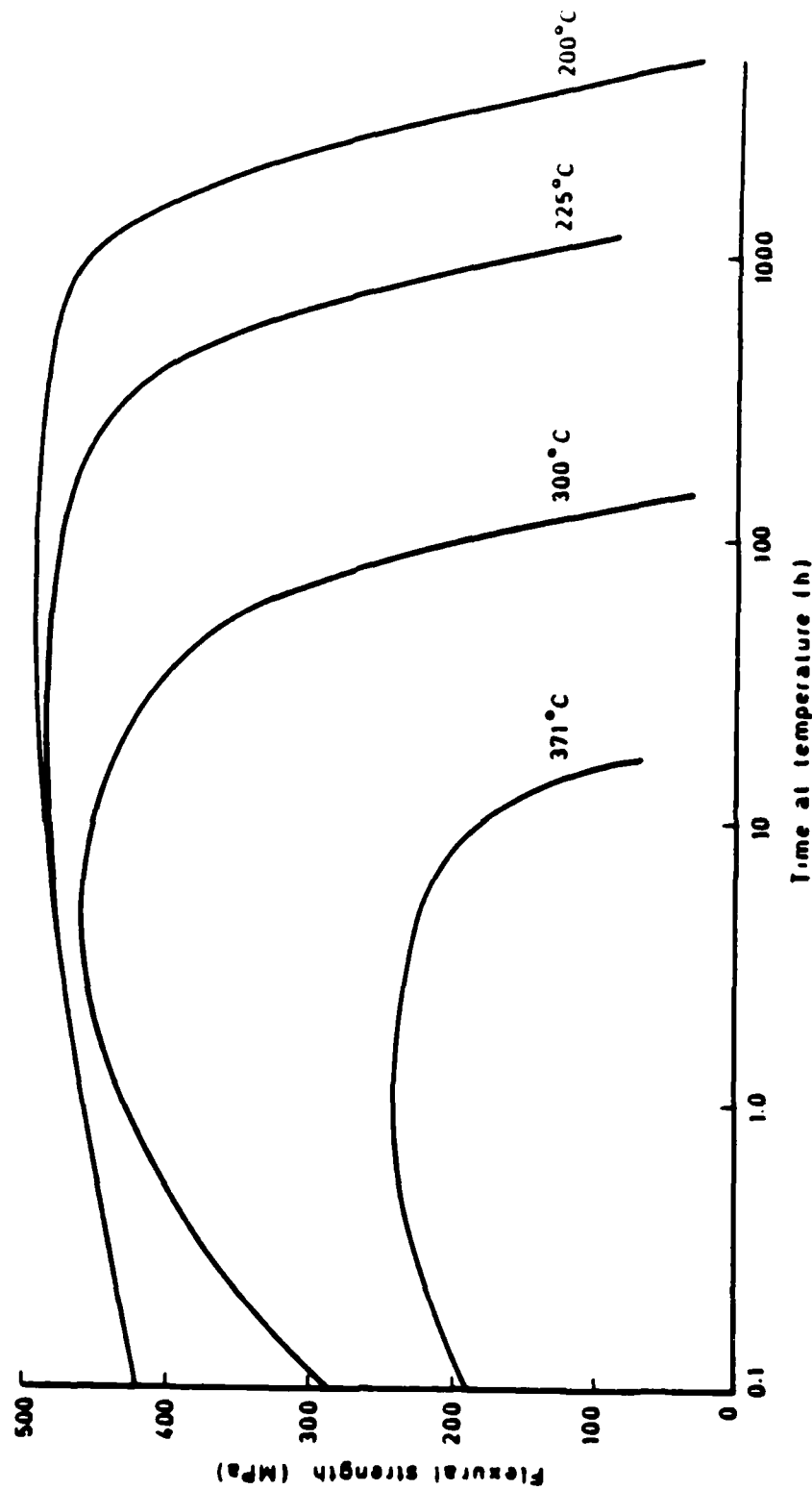


Figure 4.3-9. Effect of Aging at Temperature on Flexural Strength of a Phenolic Resin/Glass Fiber Laminate. (H-5834 phenolic resin, 181/Al100 glass cloth) (Reference 4-64)

4.4 Polyimide Polymer Matrix Composites.

4.4.1 Background. Polyimide resins are candidate materials for use with graphite reinforcements to form composite systems capable of use at 600 °F (316 °C). Polyimides cost more than epoxies, but this difference can be overlooked because of other more significant properties.

Polyimides are synthesized by a reaction between an aromatic tetracarboxylic dianhydride, such as PMDA or BTDA, and an aromatic diamine. This reaction forms a polyamic acid, which is soluble in dimethyl acetimide or a similar solvent. The prepolymer is cured at a high temperature, forming an aromatic linear resin (Figure 4.4-1). Polyimides are currently the prime candidate for high temperature advanced resin composite applications.

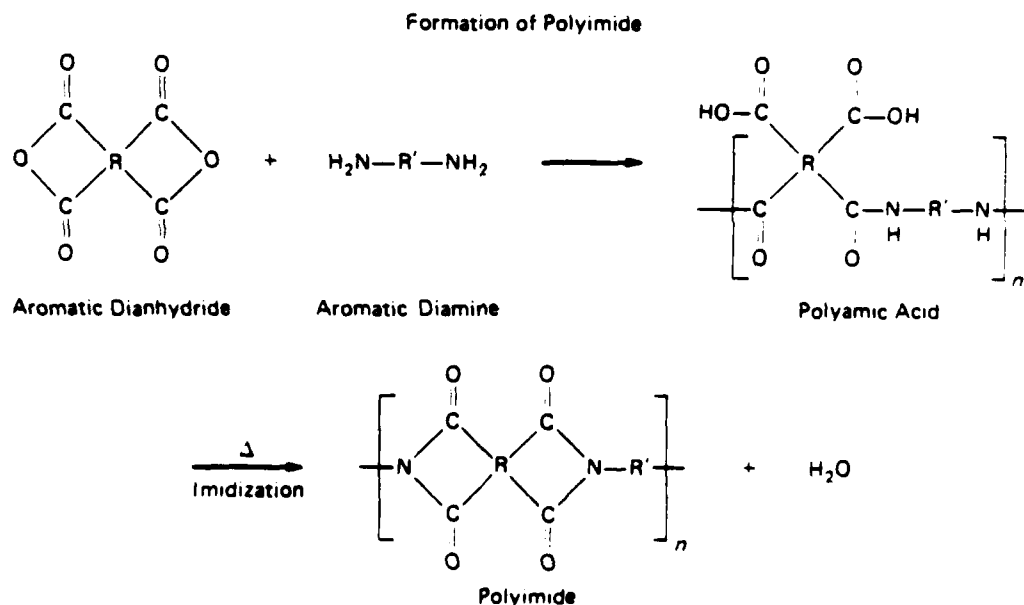


Figure 4.4-1. Formation of Polyimide (Reference 4-65)

4.4.2 Polyimide Resin Preparation. Early work in polyimides focused on the production of condensation type polyimides. These are produced by the reaction of an aryldianhydride with an aryldiamine, producing a polyamide acid through chain extension. Polymerization takes a long time, and the products are unstable, even in solution, and must be refrigerated.

More recently, partial esters of polyanhydrides have been used, eliminating the evolution of water and other volatiles. This process involves a higher curing temperature and a higher thermal stability which are due to reactive end groups capable of cross-linking. Thermoplastic polyimides are classified as linear polymers with thermoplastic processing qualities. They do not need a post-cure cycle, but do require high press temperatures and possibly high pressures. Vacuum bag/autoclave processing has not been developed for all of these systems. Some mechanical properties of polyimide resins are given in Tables 4.4-1 and 4.4-2.

TABLE 4.4-1. Comparison of Unreinforced Polyimide Matrix Properties
(Reference 4-66)

Property	Temperature (°C)	Condensation	Thermoplastic	
			Type 1 (NR150)	Type 2 (2080)
Tensile strength (MPa)	25	76-100	110	118
	260	—	—	30
	288	—	—	28
	300	33-43	—	—
	316	—	31	—
Tensile modulus (GPa)	25	3.10-3.35	4.00-4.66	1.30
	260	—	—	—
	288	—	—	0.67
	300	1.90-2.07	—	—
	316	—	1.04	—
Compressive strength (MPa)	25	253-310	—	206
	300	128-133	—	—
Compressive modulus (GPa)	25	3.93	—	2.04
	300	1.90	—	—
Flexural strength (MPa)	25	107-128	117	119
	200	—	—	124
	250	—	—	55
	288	—	—	35
	300	58-72	—	—
Flexural modulus (GPa)	25	3.03-3.17	3.80-4.17	3.32
	200	—	2.42	2.00
	250	—	1.93	1.59
	288	—	1.66	1.11
	300	1.79-1.89	—	—
Impact strength (J/cm) Izod notched	—	0.38-0.76	0.43	0.38
Elongation at break (%)	25	5-8	6	10
	300	3	[316°C] 65	—
Heat distortion temperature (°C)	—	357	—	270-280
Water pick-up (% in 24 hours)	—	0.32	—	0.6

TABLE 4.4-2. Comparison of Unreinforced Polyimide Properties
(Reference 4-67)

Property	Temperature (°C)	Addition		
		Norbornene/PMR	Bismaleimide	Acetylenic
Tensile strength (MPa)	25	48-83	48-59	83
	260	39	—	—
Tensile modulus (GPa)	25	3.80	—	3.93
	260	2.39	—	—
Compressive strength (MPa)	25	255	197	173
Compressive modulus (GPa)	25	2.89	—	—
Flexural strength (MPa)	25	76	128	131
	200	—	83	—
	250	48	57	—
	260	41-55	—	—
	288	35-41	—	—
	316	—	—	29
Flexural modulus (GPa)	25	3.17-3.38	3.80	4.49
	200	—	3.17	—
	250	2.17	2.76	—
	260	2.07-2.28	—	—
	288	1.93-2.07	—	—
Elongation at break (%)	25	1.4-2.5	<1	2
	260	1.8	—	—
Heat distortion temperature (°C)		>300	—	195-210
Water pick-up (% in 24 hours)		0.4	—	[1000 hours] <1

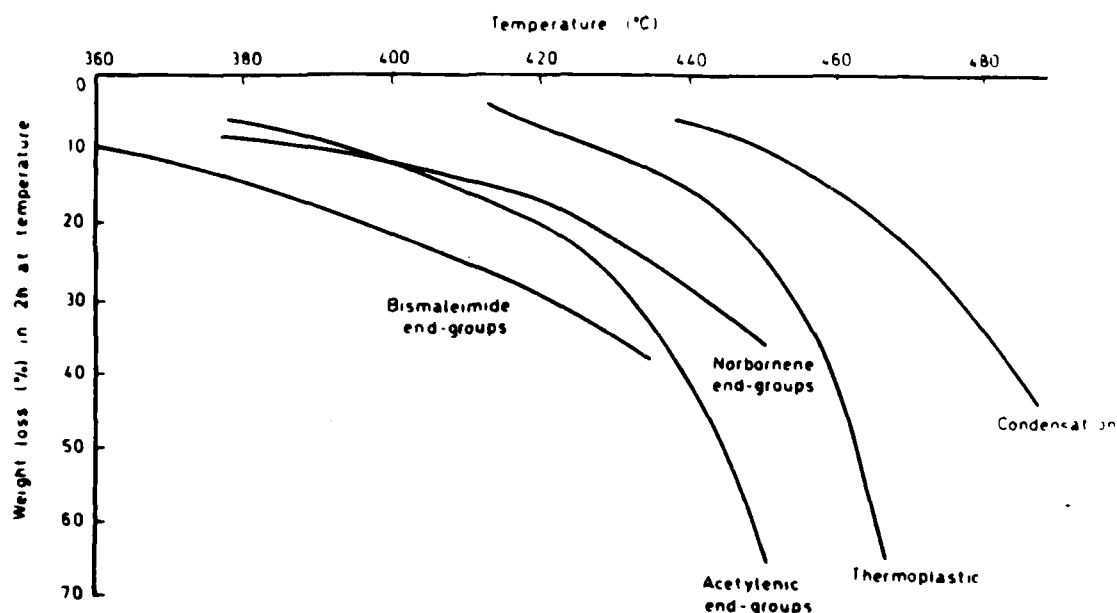


Figure 4.4-2. Comparison of Thermal Stability in Air of Different Types of Polyimide (Reference 4-68)

4.4.3 Properties of Polyimide Matrix Composites. PMR polyimides were the first high-temperature polymer matrix systems that met with any degree of success. These polymer matrix composites provided heat resistance nearly double that of existing epoxy systems. Unfilled polyimides have low wear resistance, but with 10 percent graphite, wear resistance becomes good and is retained well in high temperatures. Mechanical properties of different polyimides and carbon reinforcements are given in Table 4.4-3. Differences in resin properties do not significantly affect properties in their composites. Table 4.4-4 shows interlaminar shear strength as a function of time and temperature. As technology improves, minor advances in these areas may occur, but major developments are not expected. The development of boron-reinforced polyimides has proved difficult because the resin tends to flow out during curing. Processing polyimides is in general more complex than epoxy resins. Careful steps must be followed to keep void content low by eliminating volatiles and avoiding loss of resin. Other unique properties of polyimide matrix composites can be found in Figure 4.4-2 through 4.4-5 and Tables 4.4-5 and 4.4-6.

TABLE 4.4-3. Comparison of Properties of Carbon Fiber/Polyimide Resin Unidirectional Laminates (Reference 4-69)

Polyimide type	Carbon fiber type	Interlaminar shear strength (MPa)	Flexural strength (MPa)	Flexural modulus (GPa)
Condensation	High modulus	49	710	163
	High strength	72	1340	115
	Type III or A	66	1420	108
Addition—norbornene	High modulus	52	—	—
	High strength	78	1430	100
Addition—bismaleimide	High strength	85	1410	120
Addition—acetylenic	High strength	83	1350	104
	Type III or A	116	1190	108
Thermoplastic type I (NR 150)	High modulus	51	870	145
	High strength	61	1240	108
	Type III or A	88	1390	104

TABLE 4.4-4. Currently Achievable Levels of Performance with Polyimide/Carbon Fiber Composites (Reference 4-70)

Polyimide type	Interlaminar shear strength (MPa)	Temperature (°C)	Time (h)
Condensation	83	260	1000
Addition—PMR	83	260	1000
Addition—bismaleimide	83	230	1000
Condensation	55	350	10
Condensation	55	320	1000
Thermoplastic	55	320	1000
Addition—PMR	55	320	500
Addition—PMR	55	290	1000
Thermoplastic	55	260	50000
Addition—PMR	55	260	10000
Addition—bismaleimide	55	260	1000
Thermoplastic	28	350	10
Addition—PMR	28	350	10
Addition—PMR	28	320	1000
Condensation	28	290	10000
Thermoplastic	28	290	10000
Addition—PMR	28	290	10000
Thermoplastic	28	230	50000
Addition—PMR	28	230	50000
Addition—bismaleimide	28	230	10000

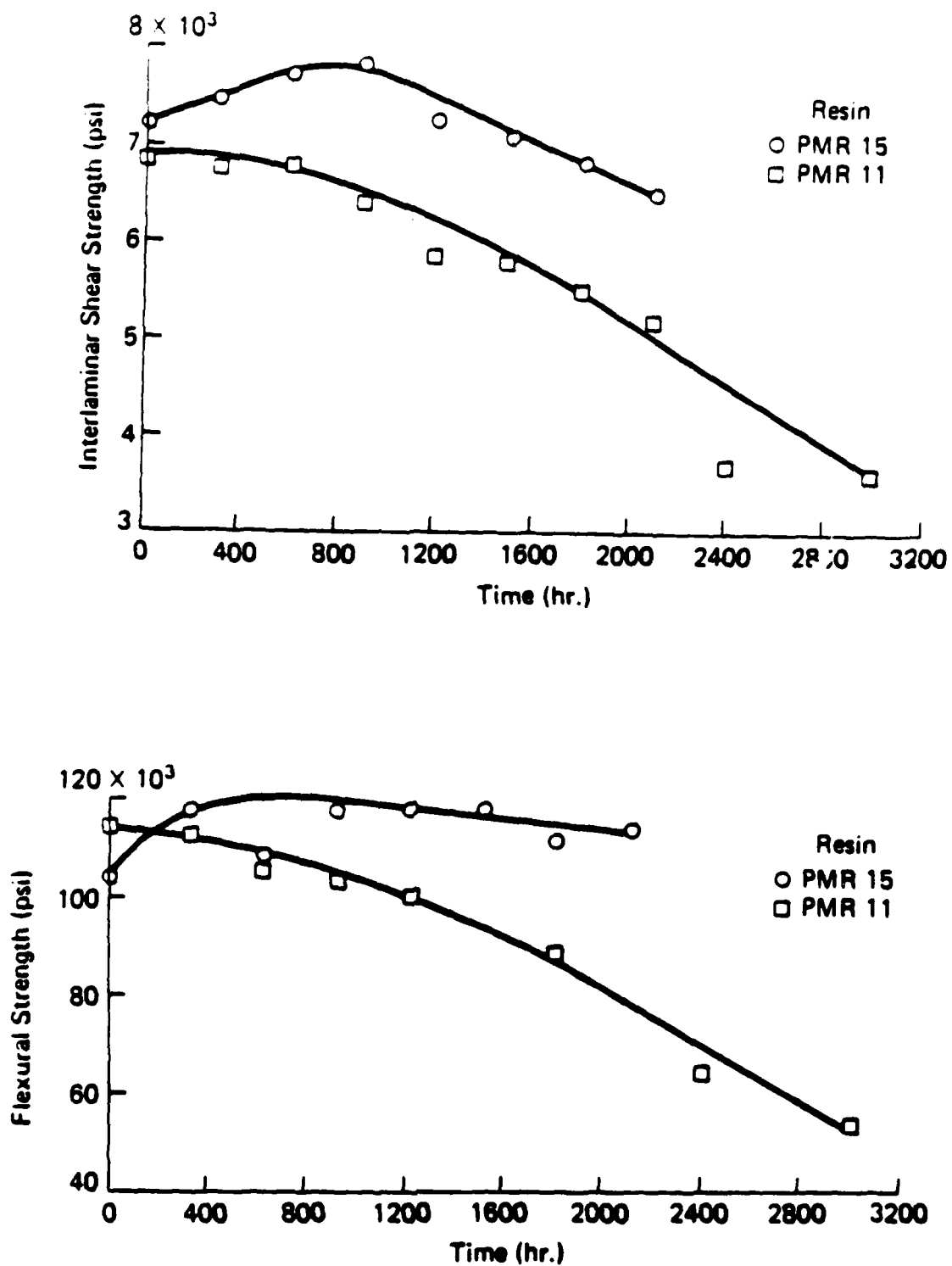


Figure 4.4-3. Flexural Strength Stability of Graphite/Polyimide Composites at 600 °F (Reference 4-71)

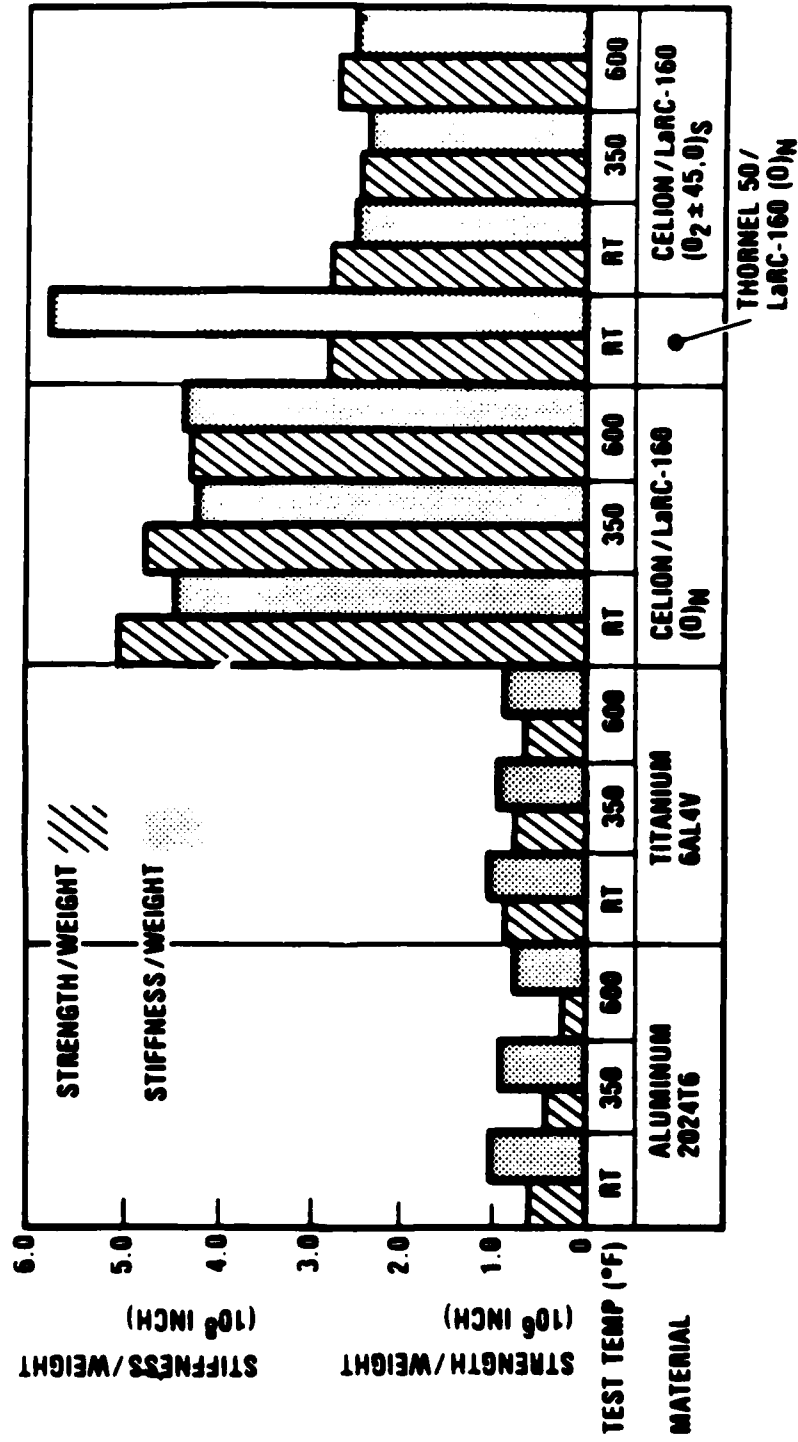


Figure 4.4-4. Graphite/Polyimide Composite System Capable of 600 °F Service Temperature Could Replace Baseline Aluminum Structural Material. (Reference 4-72)

TABLE 4.4-5. Graphite/Polyimide Composite Properties (Reference 4-73)

Composite System		Manufacturer		T _g , °C (°F)	ΔT, °C (°F)	Fiber Content, vol %	Void Content, vol %
Resin	Fiber	Prepreg/Composite					
NR-150B2	Δ C-6000	Fiberite Corp./United Technologies Corp. (Hamilton Standard Div.)		337 (638)	291 to 343 (556 to 649)	60.1 ± 2.2	3.1 ± 0.5
	▲ GY-70 (i)	Fiberite Corp./United Technologies Corp. (Hamilton Standard Div.)		365 (689)	322 to 386 (612 to 727)	61.8 ± 1.4	3.9 ± 0.2
	▼ GY-70 (ii)	Composites Horizons/Composites Horizons		346 (654)	294 to 361 (561 to 682)	55.0 ± 0.2	~0
PMR-15	○ C-6000	Composites Horizons/Composites Horizons		380 (717)	269 to 405 (516 to 761)	59.2 ± 1.4	4.5 ± 0.8
	⊙ F-5A	Composites Horizons/Composites Horizons		379 (714)	279 to 401 (534 to 754)	55.8 ± 2.0	3.7 ± 1.0
	● GY-70	Composites Horizons/Composites Horizons		371 (700)	294 to 397 (561 to 747)	56.1 ± 0.3	3.7 ± 0.4
CPI-2237	□ C-6000	Ferro Corp./Ferro Corp.		376 (708)	283 to 385 (542 to 725)	63.7 ± 1.3	4.8 ± 0.6
	■ GY-70	Ferro Corp./Ferro Corp.		379 (715)	296 to 386 (565 to 727)	57.3 ± 1.0	1.9 ± 0.6

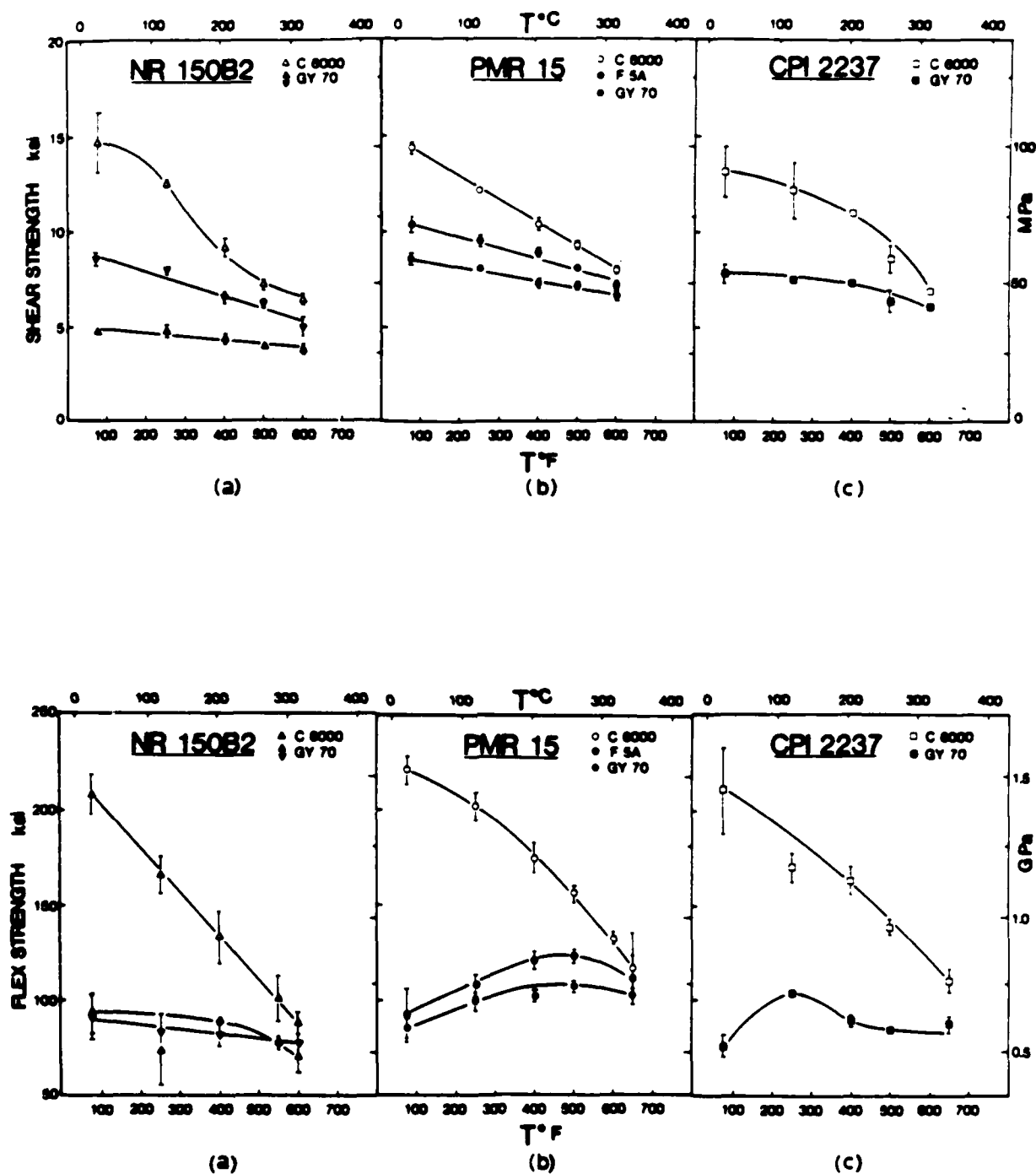


Figure 4.4-5. Strength Dependence on Temperature of Graphite/Polyimide Composites, Shown According to Matrix Resin Type
(Reference 4-74)

TABLE 4.4-6. Test Matrix, Test Panel Properties and Test Results for Different Types of Graphite/Polyimide Matrix Composites (Reference 4-75)

Layup	Thermal Conductivity			Thermal Expansion			Specific Heat	Emittance
	X	Y	Z	X	Y	Z	...	...
UNI	1	1	...	2	2	...	...	...
ISO	1	...	1	2	...	2	2	2

NOTE—A similar set was tested for both HTS/PMR 15 and HTS/NR 150B2. Numbers indicate specimen quantities. Temperature extremes are: 116 and 588 K.

Material	Layup	Total Plies	Nominal Thickness, mm	Resin Content, wt %	Tensile Strength, MN/m ²
HTS/PMR 15	(UNI) [0] ₁₈	18	3.2	35.1	1 263.0
HTS/PMR 15	(ISO) [0,45,90,135] ₂₈	16	2.8	32.9	460.0
HTS/NR 150B2	(UNI) [0] ₂₄	24	3.2	22.2	1 551.0
HTS/NR 150B2	(ISO) [0,45,90,135] ₈₂	24	3.2	23.1	548.0

Material	Layup/Direction	Thermal Conductivity, w/mk			Thermal Expansion* 10 ⁻⁶ m/m/K	Specific Heat		
		170 K	300 K	540 K		180 K	300 K	590 K
HTS/PMR 15	UNI X	13	22	42	-0.2/0	...	...	...
HTS/NR 150B2	UNI X	4.6	7.6	14	-0.4/0.6	...	...	...
HTS/PMR 15	UNI Y	0.85	0.93	1.4	-0.5/0.5	...	...	...
HTS/NR 150B2	UNI Y	0.60	0.86	1.3	-0.4/0.2	...	...	...
HTS/PMR 15	ISO X	6.6	9.9	15	24.0	...	...	...
HTS/NR 150B2	ISO X	2.2	4.8	9.6	24.0	...	...	...
HTS/PMR 15	ISO Z	0.33	0.57	0.85	16.0	...	...	...
HTS/NR 150B2	ISO Z	0.33	0.55	0.87	16.0	...	...	...
HTS/PMR 15	UNI X	...	...	...	0.8/1.7	...	...	...
HTS/NR 150B2	UNI X	...	...	...	0.8/1.5	0.440	0.808	1.36
HTS/PMR 15	UNI Y	...	...	...	0.3/1.0	...	...	...
HTS/NR 150B2	UNI Y	...	...	...	0.4/1.2	0.419	0.775	1.24
HTS/PMR 15	ISO X	...	...	...	30.0	...	...	...
HTS/NR 150B2	ISO X	...	...	...	-4/20	...	...	...
HTS/PMR 15	ISO Z	...	...	...	17.0	...	...	...
HTS/NR 150B2	ISO Z	...	...	...	23.0	...	...	...

* Where there were significant differences between slopes above and below ambient temperature two values are listed.

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GLOSSARY

1. Aramid (Kevlar) Fiber. Kevlar is a type of polymer fiber such as nylon, rayon, and Nomex. However, the Kevlar fibers possess very high specific strength combined with an attractive specific modulus or stiffness due to the low density of these materials. Kevlar materials have excellent inherent toughness which contributes to the high impact strength. The specific modulus is the highest of the polymer reinforcing fibers and is exceeded in value only by the moduli of advanced ceramic type materials such as graphite, boron, silicon carbide and alumina. The Kevlar materials (Kevlar 29, Kevlar 49) have a negative coefficient of thermal expansion in the longitudinal direction which must be considered in the design and fabrication of composite structures. Kevlar is available in the following reinforcement forms: continuous yarns, rovings, staples, and fabrics.

2. Autoclave Molding. A process that is used primarily for molding thermoset preimpregnated materials.

Process. Prepreg laminates are laid up on a mold duplicating the part surface to be fabricated; the laminate is covered with flexible sheets and vacuum sealed; the assembly is cured under vacuum, heat and pressure according to a specified heating-pressure cycle; as the laminate cures, the material becomes an integrated part duplicating the shape of the mold.

Advantages. (1) Molds are made from inexpensive materials and have minimum wear. (2) Premolded composite and metallic inserts are easily incorporated in the molding process as well as different types of prepreg materials including cloth, mat, and fibers such as glass and graphite in mixed materials. (3) Extremely large parts can be produced in one lay up.

Disadvantages. (1) Autoclave molding is labor intensive because of the hand work involved in laying up the preform and vacuum bagging. (2) The process is slow because of the time required to lay up the part and the time for curing in the autoclave. (3) Only one side of the part is molded since the back is free-formed by bag pressure, and controllability of the tolerance of one face of the part may be unacceptable.

3. Boron Fiber. Synthesized by chemical vapor deposition (CVD) from the reduction of Boron Trichloride (BCl_3) with hydrogen on a tungsten or carbon monofilament substrate. The substrate is resistively heated to a temperature of about 2,300 °F and continuously pulled through the reactor to obtain the desired boron coating thickness. Current development of boron filament technology is directed at cost reductions for future markets and increased strengths for specialized applications. One area of development directed at lowering filament cost is to replace the tungsten wire precursor with a carbon monofilament. Use of the carbon core offers the potential of reducing the cost of boron filament significantly.

4. Chemical Vapor Deposition (CVD). A manufacturing process used in coating fibers or parts. Method involves placing the fiber or part to be

coated in a chemical vapor environment. The vapor deposits on the fiber in a thin layer. This method is used to make Borsic filaments. Boron filaments are made, and then by the CVD process, a SiC coating is deposited onto the boron fiber.

5. Composite. A compound material which differs from alloys by retaining the characteristics of individual components which are so incorporated into the composite as to take advantage of their attributes, not their shortcomings. A material which consists of a strengthening phase in the form of particulates, whiskers, short, discontinuous or continuous fibers embedded in another phase called a matrix. Composite materials are usually divided into three broad groups identified by the matrix material: resin, metal and ceramic.

6. Compression Molding. A manufacturing process for fabricating a composite structure. Materials containing the fiber and resin are placed in a metal cavity and compressed under the pressure from a metal punch descending from above. The resulting fluid material is forced into the cavity or mold. After the material has set or cured, the mold is opened and the part is removed.

7. Creep. A slow deformation by stresses below the normal yield strength commonly occurring at elevated temperatures. Creep rate is the creep strain per unit of time.

8. Fatigue. The tendency to fracture under cyclic stresses.

9. Fiberglass Reinforcement. The most common reinforcing fibers for resin matrix composite structures. The two most common are structural glasses and quartz. The tensile strength of "S" glass is higher than that of any other high performance fiber including both boron and graphite fibers.

Two forms of fiberglass can be produced: continuous fiber and staple (discontinuous) fiber. Both forms are made by the same production method up to the fiber drawing stage. Continuous fibers are produced by introducing molten glass consisting of sand, limestone, and boric acid into a fiber drawing furnace. A platinum alloy tank called a bushing allows the molten glass to be gravity-fed through the multiple holes located at the base of the bushing. The droplets of molten glass are gathered together and mechanically attenuated to the proper dimensions, passed through a light water spray, and then traversed over a belt which applies a protective and lubricating binder or size to the individual fibers or filaments.

Staple fibers are produced by passing a jet of air across the holes in the base of the bushing, thus pulling individual fibers eight to fifteen inches long from the molten glass extruding from each opening. These fibers are collected on a rotating drum, sprayed with binder, and gathered into a strand.

10. Filament Winding. Technique which consists of mechanically winding single or multiple continuous fiber strands on a mandrel in a pattern specified by the designer for the required strength or stiffness in the final product. The process consists first of selecting a mandrel, the dimensions of which conform to the inside of the part being formed. The selection of a mandrel depends on the complexity of the part being formed. Typical mandrels are metal cores, inflatable sections, or soluble hard salts. Multiple passes are employed to obtain a desired wall thickness.

Advantages. (1) Ability to place large quantities of composite in a precise position without large expenditure of manpower, (2) Low capital investment, (3) Easy alignment of fibers to carry torsional or circumferential loads efficiently, and (4) Highly automated process.

Disadvantages. (1) Addition of preformed composite or steel inserts may complicate the filament winding process, (2) Longitudinal strength and stiffness properties are low unless angle winding or hand lay up is employed, and (3) Mandrel design fabrication is expensive for complex designs.

11. Graphite Fibers. Fibers consist principally of carbon, which is amorphous, and a lesser amount of graphite, which has a hexagonal crystalline structure. The percentage of graphite in the fibers depends essentially on the final processing temperature. As the final processing temperature is increased, the percentage of graphite is increased. The three most popular precursors are polyacrylonitrile (PAN), pitch, and staple rayon fibers.

12. Injection Molding. A manufacturing technique which produces more thermoplastic products than any other process. Raw material is fed from a hopper into a pressure chamber ahead of a plunger. The plunger forces the plastic into a heating chamber, where it is melted, and its flow is regulated. The plastic then flows through a nozzle seated against the mold and into the die cavity. The die cavity is cooler than the molten plastic so the plastic solidifies as soon as the mold is filled.

Advantages. (1) Parts can be produced at extremely high production rates and at low labor costs, (2) Dimensional tolerances are very precise, and (3) Scrap material is reusable.

Disadvantages. (1) The process is limited to very short fiber reinforcements; therefore, the very high tensile strength and stiffness capabilities of long fiber reinforcement can't be obtained, and (2) Mold costs are high.

13. Matrix. One of the two component materials which makes up a composite. The other is commonly referred to as the reinforcement. It can be a metal, resin, or ceramic material. It holds the reinforcements together to enable the transfer of stresses and loads to the reinforcements.

14. Modulus of Elasticity. The ratio of the change in stress to the change in elastic strain. If the stress-strain relationship is linear, the parameter is called Young's modulus. If the relationship is nonlinear, an instantaneous value of modulus of elasticity can be computed for a specific value of applied stress.

15. Poisson's Ratio. The ratio of material lateral strain to axial strain.

16. Pultrusion. A continuous manufacturing process where resin-coated fiber material is pulled through a heat forming die which results in fully or partially cured parts. The fiber is coated either in a resin dip bath before entering the back end of the die or within the die where the resin has been pressure fed. The resin sets during passage through the die.

Advantages. (1) Capital investment in equipment is low compared to the volume of parts which can be produced, (2) Pultruded parts have high strength and stiffness in the direction of fiber alignment, (3) Labor costs are low, and (4) No scrap loss is incurred.

Disadvantages. (1) Constant cross-section parts are required, and (2) Partially cured pultrusions are more complex and costly.

17. Reinforcement. One of the two component materials which make up a composite. The other is commonly referred to as the matrix. Reinforcement materials come in forms of continuous and discontinuous fibers, whiskers, particulates and wires. Principal reinforcement materials are graphite, boron, glass, and silicon carbide. The material that carries the major stresses and loads.

18. Shear Modulus. The shear stress per unit shear strain.

19. Silicon Carbide Reinforcement. A potential low cost/high performance filament suitable for advanced metal matrix applications. The SiC filament is produced in a manner similar to the boron filament using chemical vapor deposition (CVD) onto continuous substrates. The substrate is resistively heated to incandescent temperatures in a hydrogen/silane gaseous environment to deposit silicon carbide on either a tungsten or carbon substrate. The SiC filament retains strength properties at temperatures well above 1,200 °F with usable strengths at 1,800 to 2,000 °F. Other types of SiC reinforcement are being developed to reduce cost and increase the composite mechanical properties. The development of flat, ribbon shaped filaments and whiskers are alternative forms of SiC. Significant cost reductions and production increases have been seen with the flat, ribbon shape compared to the standard and substrate.

20. Specific Modulus. Defined as E/ρ , where E is the elastic modulus, and ρ is the density.

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21. Specific Strength. Defined as σ/ρ , where σ is the tensile strength, and ρ is the density.

22. Thermal Expansion Coefficient. Change in dimensions per change in temperature.