CHAPTER 9

COMPOSITE MATERIALS AND MECHANICAL DESIGN

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9.1 INTRODUCTION

The development of composite materials and related design and manufacturing technologies is one of the most important advances in the history of materials. Composites are multifunctional materials having unprecedented mechanical and physical properties that can be tailored to meet the requirements of a particular application. Many composites also exhibit great resistance to high-temperature corrosion and oxidation and wear. These unique characteristics provide the mechanical engineer with design opportunities not possible with conventional monolithic (unreinforced) materials. Composites technology also makes possible the use of an entire class of solid materials, ceramics, in applications for which monolithic versions are unsuited because of their great strength scatter and poor resistance to mechanical and thermal shock. Further, many manufacturing processes for composites are well adapted to the fabrication of large, complex structures, which allows consolidation of parts, reducing manufacturing costs.

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Composites are important materials that are now used widely, not only in the aerospace industry, but also in a large and increasing number of commercial mechanical engineering applications, such as internal combustion engines; machine components; thermal control and electronic packaging; automobile, train, and aircraft structures and mechanical components, such as brakes, drive shafts, flywheels, tanks, and pressure vessels; dimensionally stable components; process industries equipment requiring resistance to high-temperature corrosion, oxidation, and wear; offshore and onshore oil exploration and production; marine structures; sports and leisure equipment; and biomedical devices.

It should be noted that biological structural materials occurring in nature are typically some type of composite. Common examples are wood, bamboo, bone, teeth, and shell. Further, use of artificial composite materials is not new. Straw-reinforced mud bricks were employed in biblical times. Using modern terminology, discussed later, this material would be classified as an organic fiber-reinforced ceramic matrix composite.

In this chapter, we consider the properties of reinforcements and matrix materials (Section 9.2), properties of composites (Section 9.3), how they are made (Section 9.4), their use in mechanical engineering applications (Section 9.5), and special design considerations for composites (Section 9.6).

9.1.1 Classes and Characteristics of Composite Materials

There is no universally accepted definition of a composite material. For the purpose of this work, we consider a composite to be a material consisting of two or more distinct phases, bonded together.[1]

Solid materials can be divided into four categories: polymers, metals, ceramics, and carbon, which we consider as a separate class because of its unique characteristics. We find both reinforcements and matrix materials in all four categories. This gives us the ability to create a limitless number of new material systems with unique properties that cannot be obtained with any single monolithic material. Table 9.1 shows the types of material combinations now in use.

Composites are usually classified by the type of material used for the matrix. The four primary categories of composites are polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon/carbon composites (CCCs). At this time, PMCs are the most widely used class of composites. However, there are important applications of the other types, which are indicative of their great potential in mechanical engineering applications.

Figure 9.1 shows the main types of reinforcements used in composite materials: aligned continuous fibers, discontinuous fibers, whiskers (elongated single crystals), particles, and numerous forms of fibrous architectures produced by textile technology, such as fabrics and braids. Increasingly, designers are using hybrid composites that combine different types of reinforcements to achieve more efficiency and to reduce cost.

A common way to represent fiber-reinforced composites is to show the fiber and matrix separated by a slash. For example, carbon fiber-reinforced epoxy is typically written "carbon/epoxy," or, "C/Ep." We represent particle reinforcements by enclosing them in parentheses followed by "p"; thus, silicon carbide (SiC) particle-reinforced aluminum appears as "(SiC)p/Al."

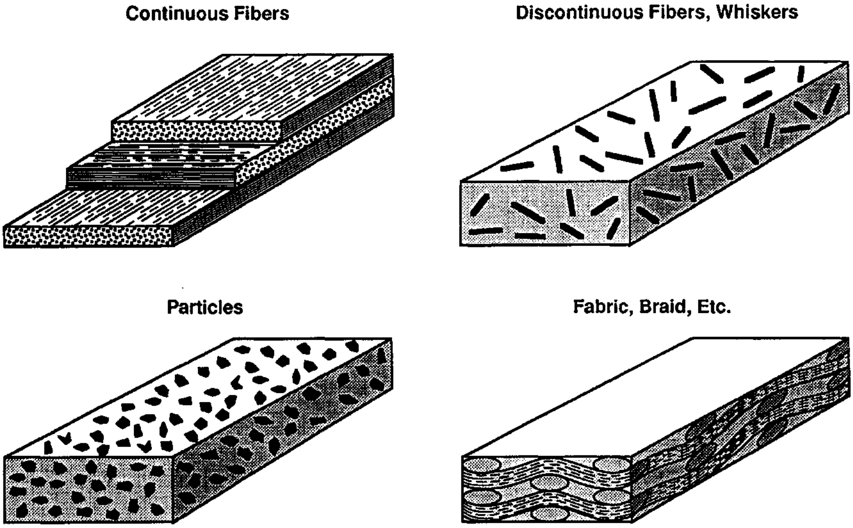
Composites are strongly heterogeneous materials; that is, the properties of a composite vary considerably from point to point in the material, depending on which material phase the point is located in. Monolithic ceramics and metallic alloys are usually considered to be homogeneous materials, to a first approximation.

Many artificial composites, especially those reinforced with fibers, are anisotropic, which means their properties vary with direction (the properties of isotropic materials are the same in every direction). This is a characteristic they share with a widely used natural fibrous composite, wood. As for wood, when structures made from artificial fibrous composites are required to carry load in more than one direction, they are used in laminated form.

Many fiber-reinforced composites, especially PMCs, MMCs, and CCCs, do not display plastic behavior as metals do, which makes them more sensitive to stress concentrations. However, the absence of plastic deformation does not mean that composites are brittle materials like monolithic ceramics. The heterogeneous nature of composites results in complex failure mechanisms that impart toughness. Fiber-reinforced materials have been found to produce durable, reliable structural components in countless applications. The unique characteristics of composite materials, especially anisotropy, require the use of special design methods, which are discussed in Section 9.6.

Table 9.1 Types of Composite Materials

	Matrix			
Reinforcement	Polymer	Metal	Ceramic	Carbon
Polymer	X	X	X	X
Metal	X	X	X	X
Ceramic	X	X	X	X
Carbon	X	X	X	X



Continuous Fibers

Discontinuous Fibers, Whiskers

Particles

Fabric, Braid, Etc.

Fig. 9.1 Reinforcement forms.

9.1.2 Comparative Properties of Composite Materials

There are a large and increasing number of materials that fall in each of the four types of composites, making generalization difficult. However, as a class of materials, composites tend to have the following characteristics: high strength; high modulus; low density; excellent resistance to fatigue, creep, creep rupture, corrosion, and wear; and low coefficient of thermal expansion (CTE). As for monolithic materials, each of the four classes of composites has its own particular attributes. For example, CMCs tend to have particularly good resistance to corrosion, oxidation, and wear, along with high-temperature capability.

For applications in which both mechanical properties and low weight are important, useful figures of merit are specific strength (strength divided by specific gravity or density) and specific stiffness (stiffness divided by specific gravity or density). Figure 9.2 presents specific stiffness and specific tensile strength of conventional structural metals (steel, titanium, aluminum, magnesium, and beryllium), two engineering ceramics (silicon nitride and alumina), and selected composite materials. The composites are PMCs reinforced with selected continuous fibers—carbon, aramid, E-glass, and boron—and an MMC, aluminum containing silicon carbide particles. Also shown is beryllium–aluminum, which can be considered a type of metal matrix composite, rather than an alloy, because the mutual solubility of the constituents at room temperature is low.

The carbon fibers represented in Figure 9.2 are made from several types of precursor materials: polyacrilonitrile (PAN), petroleum pitch, and coal tar pitch. Characteristics of the two types of pitch-based fibers tend to be similar but very different from those made from PAN. Several types of carbon fibers are represented: standard-modulus (SM) PAN, ultrahigh-strength (UHS) PAN, ultrahigh-modulus (UHM) PAN, and ultrahigh-modulus (UHM) pitch. These fibers are discussed in Section 9.2. It should be noted that there are dozens of different kinds of commercial carbon fibers, and new ones are continually being developed.

Because the properties of fiber-reinforced composites depend strongly on fiber orientation, fiber-reinforced polymers are represented by lines. The upper end corresponds to the axial properties of a unidirectional laminate, in which all the fibers are aligned in one direction. The lower end represents a quasi-isotropic laminate having equal stiffness and approximately equal strength characteristics in all directions in the plane of the fibers.

As Figure 9.2 shows, composites offer order-of-magnitude improvements over metals in both specific strength and stiffness. It has been observed that order-of-magnitude improvements in key properties typically produce revolutionary effects in a technology. Consequently, it is not surprising that composites are having such a dramatic influence in engineering applications.

In addition to their exceptional static strength properties, fiber-reinforced polymers also have excellent resistance to fatigue loading. Figure 9.3 shows how the number of cycles to failure (N) varies with maximum stress (S) for aluminum and selected unidirectional PMCs subjected to tension-tension fatigue. The ratio of minimum stress to maximum stress (R) is 0.1. The composites consist of epoxy matrices reinforced with key fibers: aramid, boron, SM carbon, high-strength (HS) glass, and E-glass. Because of their excellent fatigue resistance, composites have largely replaced metals

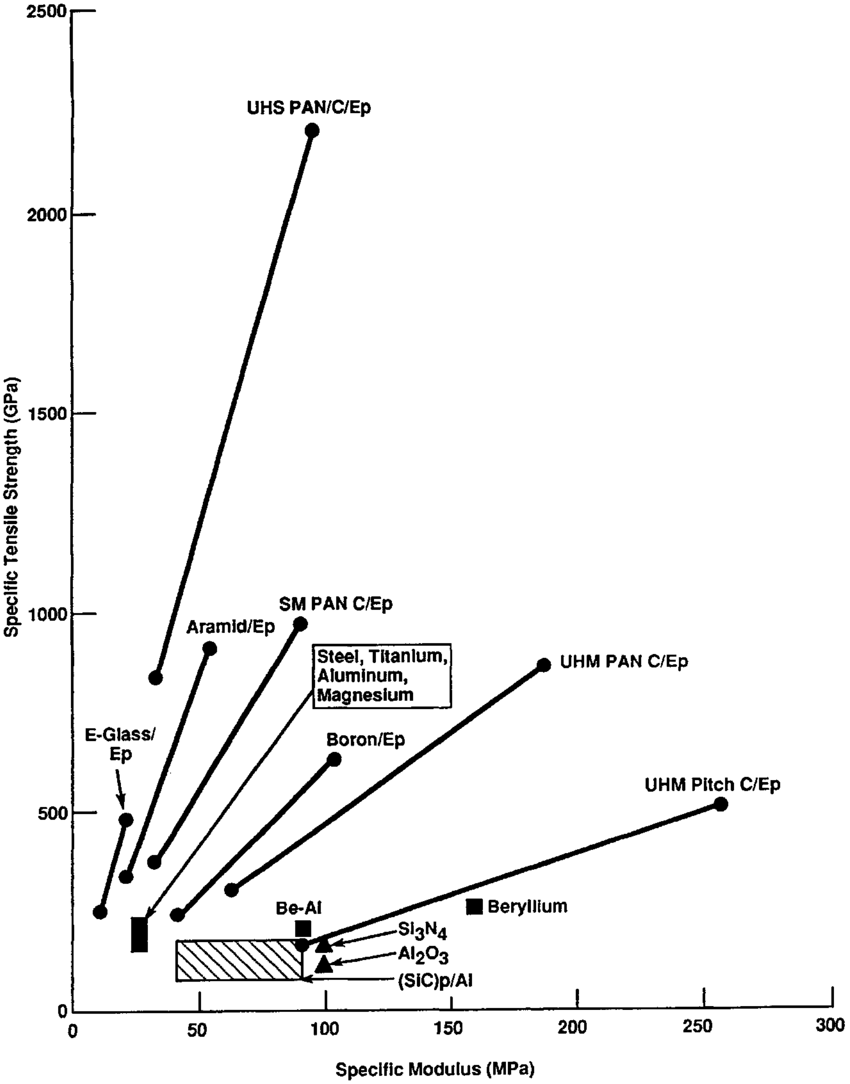


Fig. 9.2 Specific tensile strength (tensile strength divided by density) as a function of specific modulus (modulus divided by density) of composite materials and monolithic metals and ceramics.

in fatigue-critical aerospace applications, such as helicopter rotor blades. Composites also are being used in commercial fatigue-critical applications, such as automobile springs (see Section 9.5).

The outstanding mechanical properties of composite materials have been a key reason for their extensive use in structures. However, composites also have important physical properties, especially low, tailorable CTE and high-thermal conductivity, that are key reasons for their selection in an increasing number of applications.

Many composites, such as PMCs reinforced with carbon and aramid fibers, and silicon carbide particle-reinforced aluminum, have low CTEs, which are advantageous in applications requiring dimensional stability. By appropriate selection of reinforcements and matrix materials, it is possible to produce composites with near-zero CTEs.

Coefficient of thermal expansion tailorability provides a way to minimize thermal stresses and distortions that often arise when dissimilar materials are joined. For example, Figure 9.4 shows how the CTE of silicon carbide particle-reinforced aluminum varies with particle content. By varying the

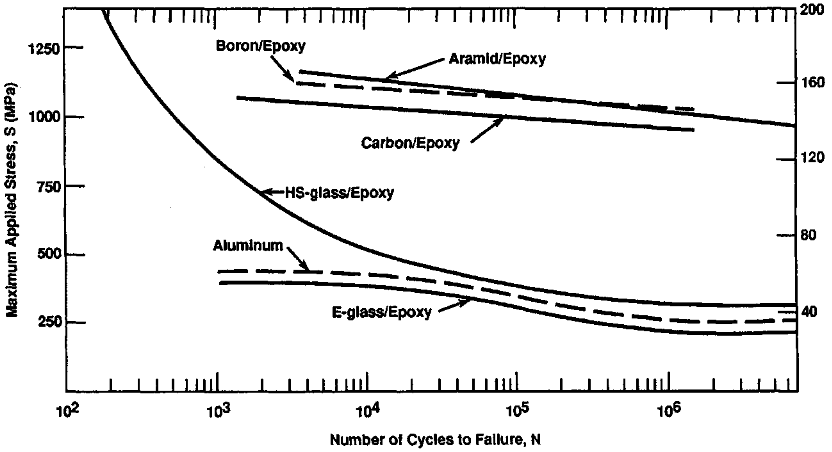


Fig. 9.3 Number of cycles to failure as a function of maximum stress for aluminum and unidirectional polymer matrix composites subjected to tension-tension fatigue with a stress ratio, R = 0.1 (from Ref. 2).

amount of reinforcement, it is possible to match the CTEs of a variety of key engineering materials, such as steel, titanium, and alumina (aluminum oxide).

The ability to tailor CTE is particularly important in applications such as electronic packaging, where thermal stresses can cause failure of ceramic substrates, semiconductors, and solder joints.

Another unique and increasingly important property of some composites is their exceptionally high-thermal conductivity. This is leading to increasing use of composites in applications for which heat dissipation is a key design consideration. In addition, the low densities of composites make them

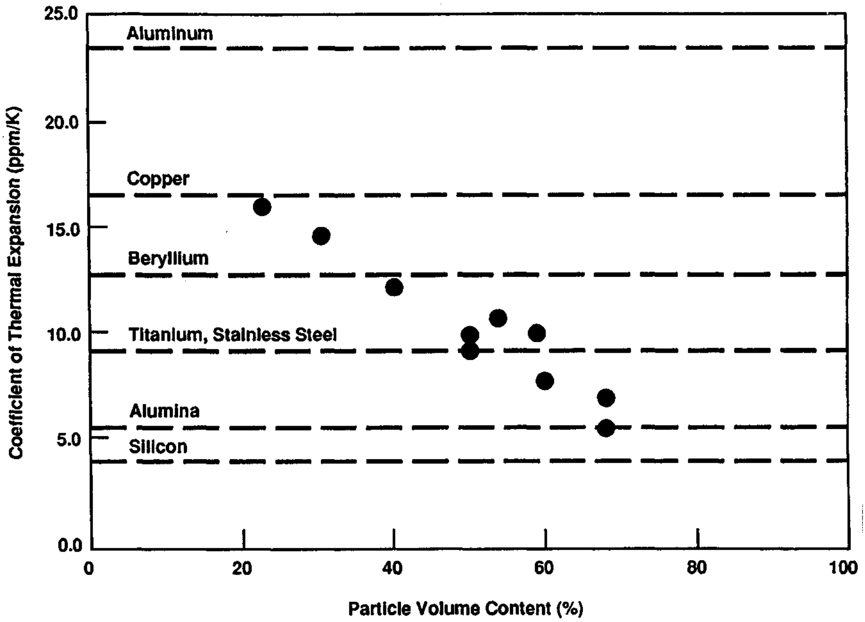


Fig. 9.4 Variation of coefficient of thermal expansion with particle volume fraction for silicon carbide particle-reinforced aluminum (from Ref. 3).

particularly advantageous in thermal control applications for which weight is important, such as laptop computers, avionics, and spacecraft components, such as radiators.

There are a large and increasing number of thermally conductive composites, which are discussed in Section 9.3. One of the most important types of reinforcements for these materials is pitch fibers. Figure 9.5 shows how thermal conductivity varies with electrical resistivity for conventional metals and carbon fibers. It can be seen that PAN-based fibers have relatively low thermal conductivities. However, pitch-based fibers with thermal conductivities more than twice that of copper are commercially available. These reinforcements also have very high-stiffnesses and low densities. At the upper end of the carbon fiber curve are fibers made by chemical vapor deposition (CVD). Fibers made from another form of carbon, diamond, also have the potential for thermal conductivities in the range of 2000 W/m K (1160 BTU/h · ft · F).

9.1.3 Manufacturing Considerations

Composites also offer a number of significant manufacturing advantages over monolithic metals and ceramics. For example, fiber-reinforced polymers and ceramics can be fabricated in large, complex shapes that would be difficult or impossible to make with other materials. The ability to fabricate complex shapes allows consolidation of parts, which reduces machining and assembly costs. Some processes allow fabrication of parts to their final shape (net shape) or close to their final shape (near-net shape), which also produces manufacturing cost savings. The relative ease with which smooth shapes can be made is a significant factor in the use of composites in aircraft and other applications for which aerodynamic considerations are important. Manufacturing processes for composites are covered in Section 9.4.

9.2 REINFORCEMENTS AND MATRIX MATERIALS

As discussed in Section 9.1, we divide solid materials into four classes: polymers, metals, ceramics, and carbon. There are reinforcements and matrix materials in each category. In this section, we consider the characteristics of key reinforcements and matrices.

There are important issues that must be discussed before we present constituent properties. The conventional materials used in mechanical engineering applications are primarily structural metals, for most of which there are industry and government specifications. The situation is very different for composites. Most reinforcements and matrices are proprietary materials for which there are no industry standards. This is similar to the current status of ceramics. The situation is further complicated by the fact that there are many test methods in use to measure mechanical and physical properties of reinforcements and matrix materials. As a result, there are often conflicting material property data in the usual sources, published papers, and manufacturers' literature. The data presented in this article represent a carefully evaluated distillation of information from many sources. The principal sources are listed in the bibliography and references. In view of the uncertainties discussed, the properties presented in this section should be considered approximate values.

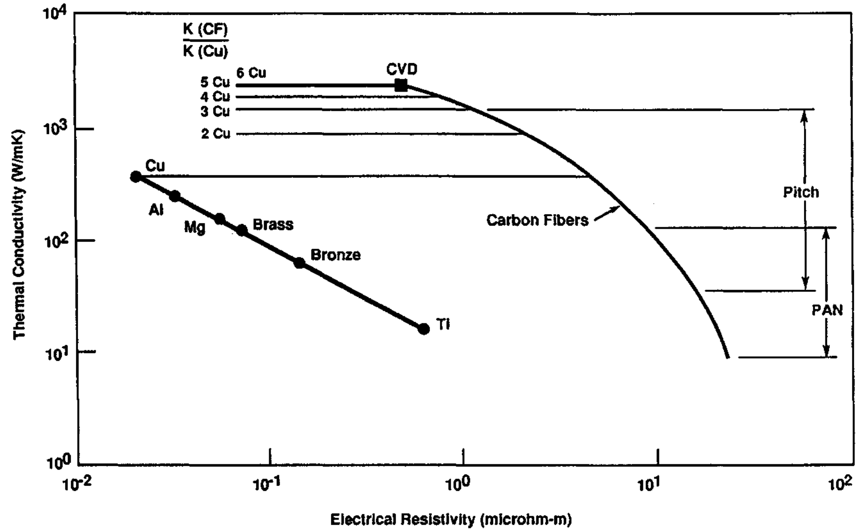


Fig. 9.5 Thermal conductivity as a function of electrical resistivity of metals and carbon fibers (adapted from one of Amoco Performance Products).

Because of the large number of matrix materials and reinforcements, we are forced to be selective. Further, space limitations prevent presentation of a complete set of properties. Consequently, properties cited are room temperature values, unless otherwise stated.

9.2.1 Reinforcements

The four key types of reinforcements used in composites are continuous fibers, discontinuous fibers, whiskers (elongated single crystals), and particles (Fig. 9.1). Continuous, aligned fibers are the most efficient reinforcement form and are widely used, especially in high-performance applications. However, for ease of fabrication and to achieve specific properties, such as improved through-thickness strength, continuous fibers are converted into a wide variety of reinforcement forms using textile technology. Key among them at this time are two-dimensional and three-dimensional fabrics and braids.

Fibers

The development of fibers with unprecedented properties has been largely responsible for the great importance of composites and the revolutionary improvements in properties compared to conventional materials that they offer. The key fibers for mechanical engineering applications are glasses, carbons (also called graphites), several types of ceramics, and high-modulus organics. Most fibers are produced in the form of multifilament bundles called strands or ends in their untwisted forms, and yarns when twisted. Some fibers are produced as monofilaments, which generally have much larger diameters than strand filaments. Table 9.2 presents properties of key fibers, which are discussed in the following subsections.

Fiber strength requires some discussion. Most of the key fibrous reinforcements are made of brittle ceramics or carbon. It is well known that the strengths of monolithic ceramics decrease with increasing material volume because of the increasing probability of finding strength-limiting flaws. This is called size effect. As a result of size effect, fiber strength typically decreases monotonically with increasing gage length (and diameter). Flaw sensitivity also results in considerable strength scatter at a fixed test length. Consequently, there is no single value that characterizes fiber strength. This is also true of key organic reinforcements, such as aramid fibers. Consequently, the values presented in Table 9.2 should be considered approximate values and are useful primarily for comparative purposes. Note that, because unsupported fibers buckle under very low stresses, it is very difficult to measure their inherent compression strength, and these properties are almost never reported. Instead, composite compression strength is measured directly.

Glass Fibers. Glass fibers are used primarily to reinforce polymers. The leading types of glass fibers for mechanical engineering applications are E-glass and high-strength (HS) glass. E-glass fibers, the first major composite reinforcement, were originally developed for electrical insulation applica-

Table 9.2 Properties of Key Reinforcing Fibers

Fiber	Density g/cm^3 (Pci)	Axial Modulus GPa (Msi)	Tensile Strength MPa (Ksi)	Axial Coefficient of Thermal Expansion ppm/K (ppm/F)	Axial Thermal Conductivity W/mK
E-glass	2.6 (0.094)	70 (10)	2000 (300)	5 (2.8)	0.9
HS glass	2.5 (0.090)	83 (12)	4200 (650)	4.1 (2.3)	0.9
Aramid	1.4 (0.052)	124 (18)	3200 (500)	−5.2 (−2.9)	0.04
Boron	2.6 (0.094)	400 (58)	3600 (520)	4.5 (2.5)	—
SM carbon (PAN)	1.7 (0.061)	235 (34)	3200 (500)	−0.5 (−0.3)	9
UHM carbon (PAN)	1.9 (0.069)	590 (86)	3800 (550)	−1 (−0.6)	18
UHS carbon (PAN)	1.8 (0.065)	290 (42)	7000 (1000)	−1.5 (−0.8)	160
UHM carbon (pitch)	2.2 (0.079)	895 (130)	2200 (320)	−1.6 (−0.9)	640
UHK carbon (pitch)	2.2 (0.079)	830 (120)	2200 (320)	−1.6 (−0.9)	1100
SiC monofilament	3.0 (0.11)	400 (58)	3600 (520)	4.9 (2.7)	—
SiC multifilament	3.0 (0.11)	400 (58)	3100 (450)	—	—
Si-C-O	2.6 (0.094)	190 (28)	2900 (430)	3.9 (2.2)	1.4
Si-Ti-C-O	2.4 (0.087)	190 (27)	3300 (470)	3.1 (1.7)	—
Aluminum oxide	3.9 (0.14)	370 (54)	1900 (280)	7.9 (4.4)	—
High-density Polyethylene	0.97 (0.035)	172 (25)	3000 (440)	—	—

tions (that is the origin of the "E"). E-glass is, by many orders of magnitude, the most widely used of all fibrous reinforcements. The primary reasons for this are its low cost and early development compared to other fibers. Glass fibers are produced as multifilament bundles. Filament diameters range from 3–20 micrometers (118–787 microinches). Table 9.2 presents representative properties of E-glass and HS glass fibers.

E-glass fibers have relatively low elastic moduli compared to other reinforcements. In addition, E-glass fibers are susceptible to creep and creep (stress) rupture. HS glass is stiffer and stronger than E-glass, and has better resistance to fatigue and creep.

The thermal and electrical conductivities of glass fibers are low, and glass fiber-reinforced PMCs are often used as thermal and electrical insulators. The CTE of glass fibers is also low compared to most metals.

Carbon (Graphite) Fibers. Carbon fibers, commonly called graphite fibers in the United States, are used as reinforcements for polymers, metals, ceramics, and carbon. There are dozens of commercial carbon fibers, with a wide range of strengths and moduli. As a class of reinforcements, carbon fibers are characterized by high-stiffness and strength, and low density and CTE. Fibers with tensile moduli as high as 895 GPa (130 Msi) and with tensile strengths of 7000 MPa (1000 Ksi) are commercially available. Carbon fibers have excellent resistance to creep, stress rupture, fatigue, and corrosive environments, although they oxidize at high-temperatures. Some carbon fibers also have extremely high-thermal conductivities—many times that of copper. This characteristic is of considerable interest in electronic packaging and other applications where thermal control is important. Carbon fibers are the workhorse reinforcements in high-performance aerospace and commercial PMCs and some CMCs. Of course, as the name suggests, carbon fibers are also the reinforcements in carbon/carbon composites.

Most carbon fibers are highly anisotropic. Axial stiffness, tension and compression strength, and thermal conductivity are typically much greater than the corresponding properties in the radial direction. Carbon fibers generally have small, negative axial CTEs (which means that they get shorter when heated) and positive radial CTEs. Diameters of common reinforcing fibers, which are produced in the form of multifilament bundles, range from 4–10 micrometers (160–390 microinches). Carbon fiber stress–strain curves tend to be nonlinear. Modulus increases under increasing tensile stress and decreases under increasing compressive stress.

Carbon fibers are made primarily from three key precursor materials: polyacrylonitrile (PAN), petroleum pitch, and coal tar pitch. Rayon-based fibers, once the primary CCC reinforcement, are far less common in new applications. Experimental fibers also have been made by chemical vapor deposition. Some of these have reported axial thermal conductivities as high as 2000 W/m K, five times that of copper.

PAN-based materials are the most widely used carbon fibers. There are dozens on the market. Fiber axial moduli range from 235 GPa (34 Msi) to 590 GPa (85 Msi). They generally provide composites with excellent tensile and compressive strength properties, although compressive strength tends to drop off as modulus increases. Fibers having tensile strengths as high as 7 GPa (1 Msi) are available. Table 9.2 presents properties of three types of PAN-based carbon fibers and two types of pitch-based carbon fibers. The PAN-based fibers are standard modulus (SM), ultrahigh-strength (UHS) and ultrahigh-modulus (UHM). SM PAN fibers are the most widely used type of carbon fiber reinforcement. They are one of the first types commercialized and tend to be the least expensive. UHS PAN carbon fibers are the strongest type of another widely used class of carbon fiber, usually called intermediate modulus (IM) because the axial modulus of these fibers falls between those of SM and modulus carbon fibers.

A key advantage of pitch-based fibers is that they can be produced with much higher axial moduli than those made from PAN precursors. For example, UHM pitch fibers with moduli as high as 895 GPa (130 Msi) are available. In addition, some pitch fibers, which we designate UHK, have extremely high-axial thermal conductivities. There are commercial UHK fibers with a nominal axial thermal conductivity of 1100 W/m K, almost three times that of copper. However, composites made from pitch-based carbon fibers generally are somewhat weaker in tension and shear, and much weaker in compression, than those using PAN-based reinforcements.

Boron Fibers. Boron fibers are primarily used to reinforce polymers and metals. Boron fibers are produced as monofilaments (single filaments) by chemical vapor deposition of boron on a tungsten wire or carbon filament, the former being the most widely used. They have relatively large diameters, 100–140 micrometers (4000–5600 microinches), compared to most other reinforcements. Table 9.2 presents representative properties of boron fibers having a tungsten core and diameter of 140 micrometers. The properties of boron fibers are influenced by the ratio of overall fiber diameter to that of the tungsten core. For example, fiber specific gravity is 2.57 for 100-micrometer fibers and 2.49 for 140-micrometer fibers.

Fibers Based on Silicon Carbide. Silicon carbide-based fibers are primarily used to reinforce metals and ceramics. There are a number of commercial fibers based on silicon carbide. One type, a monofilament, is produced by chemical vapor deposition of high-purity silicon carbide on a carbon monofilament core. Some versions use a carbon-rich surface layer that serves as a reaction barrier. There are a number of multifilament silicon carbide-based fibers which are made by pyrolysis of polymers. Some of these contain varying amounts of silicon, carbon and oxygen, titanium, nitrogen, zirconium, and hydrogen. Table 9.2 presents properties of selected silicon carbide-based fibers.

Fibers Based on Alumina. Alumina-based fibers are primarily used to reinforce metals and ceramics. Like silicon–carbide-based fibers, they have a number of different chemical formulations. The primary constituents, in addition to alumina, are boria, silica, and zirconia. Table 9.2 presents properties of high-purity alumina fibers.

Aramid Fibers. Aramid, or aromatic, polyamide fibers are high-modulus organic reinforcements primarily used to reinforce polymers and for ballistic protection. There are a number of commercial aramid fibers produced by several manufacturers. Like other reinforcements, they are proprietary materials with different properties. Table 9.2 presents properties of one of the most widely used aramid fibers.

High-Density Polyethylene Fibers. High-density polyethylene fibers are primarily used to reinforce polymers and for ballistic protection. Table 9.2 presents properties of a common reinforcing fiber. The properties of high-density polyethylene tend to decrease significantly with increasing temperature, and they tend to creep significantly under load, even at low temperatures.

9.2.2 Matrix Materials

The four classes of matrix materials are polymers, metals, ceramics, and carbon. Table 9.3 presents representative properties of selected matrix materials in each category. As the table shows, the properties of the four types differ substantially. These differences have profound effects on the properties of the composites using them. In this section, we examine characteristics of key materials in each class.

Polymer Matrix Materials

There are two major classes of polymers used as matrix materials: thermosets and thermoplastics. Thermosets are materials that undergo a curing process during part fabrication, after which they are rigid and cannot be reformed. Thermoplastics, on the other hand, can be repeatedly softened and reformed by application of heat. Thermoplastics are often subdivided into several types: amorphous, crystalline, and liquid crystal. There are numerous types of polymers in both classes. Thermosets tend to be more resistant to solvents and corrosive environments than thermoplastics, but there are exceptions to this rule. Resin selection is based on design requirements, as well as manufacturing and cost considerations. Table 9.4 presents representative properties of common matrix polymers.

Polymer matrices generally are relatively weak, low-stiffness, viscoelastic materials. The strength and stiffness of PMCs come primarily from the fiber phase. One of the key issues in matrix selection is maximum service temperature. The properties of polymers decrease with increasing temperature. A widely used measure of comparative temperature resistance of polymers is glass transition temperature (Tg), which is the approximate temperature at which a polymer transitions from a relatively rigid material to a rubbery one. Polymers typically suffer significant losses in both strength and stiffness above their glass transition temperatures. New polymers with increasing temperature capability are continually being developed, allowing them to compete with a wider range of metals. For example, carbon fiber-reinforced polyimides have replaced titanium in some aircraft gas turbine engine parts.

An important consideration in selection of polymer matrices is their moisture sensitivity. Resins tend to absorb water, which causes dimensional changes and reduction of elevated temperature strength and stiffness. The amount of moisture absorption, typically measured as percent weight gain, depends on the polymer and relative humidity. Resins also desorb moisture when placed in a drier atmosphere. The rate of absorption and desorption depends strongly on temperature. The moisture sensitivity of resins varies widely; some are very resistant.

In a vacuum, resins outgas water and organic and inorganic chemicals, which can condense on surfaces with which they come in contact. This can be a problem in optical systems and can affect surface properties critical for thermal control, such as absorptivity and emissivity. Outgassing can be controlled by resin selection and baking out the component.

Thermosetting Resins. The key types of thermosetting resins used in composites are epoxies, bismaleimides, thermosetting polyimides, cyanate esters, thermosetting polyesters, vinyl esters, and phenolics.

Epoxies are the workhorse materials for airframe structures and other aerospace applications, with decades of successful flight experience to their credit. They produce composites with excellent structural properties. Epoxies tend to be rather brittle materials, but toughened formulations with greatly improved impact resistance are available. The maximum service temperature is affected by reduced elevated temperature structural properties resulting from water absorption. A typical airframe limit is about 120°C (250°F).

Table 9.3 **Properties of Selected Matrix Materials**

Material	Class	Density g/cm^3 (Pci)	Modulus GPa (Msi)	Tensile Strength MPa (Ksi)	Tensile Failure Strain %	Thermal Conductivity W/mK (BTU/h · ft · F)	Coefficient of Thermal Expansion ppm/K (ppm/F)
Epoxy	Polymer	1.8 (0.065)	3.5 (0.5)	70 (10)	3	0.1 (0.06)	60 (33)
Aluminum (6061)	Metal	2.7 (0.098)	69 (10)	300 (43)	10	180 (104)	23 (13)
Titanium (6Al-4V)	Metal	4.4 (0.16)	105 (15.2)	1100 (160)	10	16 (9.5)	9.5 (5.3)
Silicon Carbide	Ceramic	2.9 (0.106)	520 (75)	—	< 0.1	81 (47)	4.9 (2.7)
Alumina	Ceramic	3.9 (0.141)	380 (55)	—	< 0.1	20 (120)	6.7 (3.7)
Glass (borosilicate)	Ceramic	2.2 (0.079)	63 (9)	—	< 0.1	2 (1)	5 (3)
Carbon	Carbon	1.8 (0.065)	20 (3)	—	< 0.1	5–90 (3–50)	2 (1)

Table 9.4 Properties of Selected Thermosetting and Thermoplastic Matrices

	Density g/cm^3 (Pci)	Modulus GPa (Msi)	Tensile Strength MPa (Ksi)	Elongation to Break (%)	Thermal Conductivity W/mK	Coefficient of Thermal Expansion ppm/K (ppm/F)
Epoxy (1)	1.1–1.4 (0.040–0.050)	3–6 (0.43–0.88)	35–100 (5–15)	1–6	0.1	60 (33)
Thermosetting polyester (1)	1.2–1.5 (0.043–0.054)	2–4.5 (0.29–0.65)	40–90 (6–13)	2	0.2	100–200 (56–110)
Polypropylene (2)	0.90 (0.032)	1–4 (0.15–0.58)	25–38 (4–6)	> 300	0.2	110 (61)
Nylon 6-6 (2)	1.14 (0.041)	1.4–2.8 (0.20–0.41)	60–75 (9–11)	40–80	0.2	90 (50)
Polycarbonate (2)	1.06–1.20 (0.038–0.043)	2.2–2.4 (0.32–0.35)	45–70 (7–10)	50–100	0.2	70 (39)
Polysulfone (2)	1.25 (0.045)	2.2 (0.32)	76 (11)	50–100	—	56 (31)
Polyetherimide (2)	1.27 (0.046)	3.3 (0.48)	110 (16)	60	—	62 (34)
Polyamideimide (2)	1.4 (0.050)	4.8 (0.7)	190 (28)	17	—	63 (35)
Polyphenylene sulfide (2)	1.36 (0.049)	3.8 (0.55)	65 (10)	4	—	54 (30)
Polyether etherketone (2)	1.26–1.32 (0.046–0.048)	3.6 (0.52)	93 (13)	50	—	47 (26)

(1) Thermoset, (2) Thermoplastic.

Bismaleimide resins are used for aerospace applications requiring higher temperature capabilities than can be achieved by epoxies. They are employed for temperatures of up to about 200°C (390°F).

Thermosetting polyimides are used for applications with temperatures as high as 250°C to 290°C (500°F to 550°F).

Cyanate ester resins are not as moisture sensitive as epoxies and tend to outgas much less. Formulations with operating temperatures as high as 205°C (400°F) are available.

Thermosetting polyesters are the workhorse resins in commercial applications. They are relatively inexpensive, easy to process, and corrosion resistant.

Vinyl esters are also widely used in commercial applications. They have better corrosion resistance than polyesters, but are somewhat more expensive.

Phenolic resins have good high-temperature resistance and produce less smoke and toxic products than most resins when burned. They are used in applications such as aircraft interiors and offshore oil platform structures, for which fire resistance is a key design requirement.

Thermoplastic Resins. Thermoplastics are divided into three main classes: amorphous, crystalline, and liquid crystal. Polycarbonate, acrylonitrile–butadiene–styrene (ABS), polystyrene, polysulfone, and polyetherimide are amorphous materials. Crystalline thermoplastics include nylon, polyethylene, polyphenylene sulfide, polypropylene, acetal, polyethersulfone, and polyether etherketone (PEEK). Amorphous thermoplastics tend to have poor solvent resistance. Crystalline materials tend to be better in this respect. Relatively inexpensive thermoplastics such as nylon are extensively used with chopped E-glass fiber reinforcements in countless injection-molded parts. There are an increasing number of applications using continuous fiber-reinforced thermoplastics.

Metals

The metals initially used for MMC matrix materials generally were conventional alloys. Over time, however, many special matrix materials tailored for use in composites have been developed. The key metallic matrix materials used for structural MMCs are alloys of aluminum, titanium, iron, and intermetallic compounds, such as titanium aluminides. However, many other metals have been used as matrix materials, such as copper, lead, magnesium, cobalt, silver, and superalloys. The *in situ* properties of metals in a composite depend on the manufacturing process and, because metals are elastic–plastic materials, the history of mechanical stresses and temperature changes to which they are subjected.

Ceramic Matrix Materials

The key ceramics used as CMC matrices are silicon carbide, alumina, silicon nitride, mullite, and various cements. The properties of ceramics, especially strength, are even more process-sensitive than those of metals. In practice, it is very difficult to determine the *in situ* properties of ceramic matrix materials in a composite.

As discussed earlier, in the section on fiber properties, ceramics are very flaw-sensitive, resulting in a decrease in strength with increasing material volume, a phenomenon called "size effect." As a result, there is no single value that describes the tensile strength of ceramics. In fact, because of the very brittle nature of ceramics, it is difficult to measure tensile strength, and flexural strength (often called modulus of rupture) is typically reported. It should be noted that flexural strength is also dependent on specimen size and is generally much higher than that of a tensile coupon of the same dimensions. In view of the great difficulty in measuring a simple property like tensile strength, which arises from their flaw sensitivity, it is not surprising that monolithic ceramics have had limited success in applications where they are subjected to significant tensile stresses.

The fracture toughness of ceramics is typically in the range of 3–6 $\mathrm{MPa \cdot m^{1/2}}$. Those of transformation-toughened materials are somewhat higher. For comparison, the fracture toughnesses of structural metals are generally greater than 20 $\mathrm{MPa \cdot m^{1/2}}$.

Carbon Matrix Materials

Carbon is a remarkable material. It includes materials ranging from lubricants to diamonds and structural fibers. The forms of carbon matrices resulting from the various carbon/carbon manufacturing processes tend to be rather weak, brittle materials. Some forms have very high-thermal conductivities. As for ceramics, *in situ* matrix properties are difficult to measure.

9.3 PROPERTIES OF COMPOSITE MATERIALS

There are a large and increasing number of materials in all four classes of composites: polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon/carbon composites (CCCs). In this section, we present mechanical and physical properties of some of the key materials in each class.

Initially, the excellent mechanical properties of composites was the main reason for their use. However, there are an increasing number of applications for which the unique and tailorable physical properties of composites are key considerations. For example, the extremely high-thermal conductivity and tailorable coefficient of thermal expansion (CTE) of some composite material systems are leading to their increasing use in electronic packaging. Similarly, the extremely high-stiffness, near-zero CTE, and low density of carbon fiber-reinforced polymers have made these composites the materials of choice in spacecraft structures.

Composites are complex, heterogeneous, and often anisotropic material systems. Their properties are affected by many variables, including *in situ* constituent properties; reinforcement form, volume fraction and geometry; properties of the interphase, the region where the reinforcement and matrix are joined (also called the interface); and void content. The process by which the composite is made affects many of these variables. The same matrix material and reinforcements, when combined by different processes, may result in composites with very different properties.

Several other important things must be kept in mind when considering composite properties. For one, most composites are proprietary material systems made by proprietary processes. There are few industry or government specifications for composites, as there are for many monolithic structural metals. However, this is also the case for many monolithic ceramics and polymers, which are widely used engineering materials. Despite their inherently proprietary nature, some widely used composite materials made by a number of manufacturers have similar properties. A notable example is standard-modulus (SM) carbon fiber-reinforced epoxy.

Another critical issue is that properties are sensitive to the test methods by which they are measured, and there are many different test methods used throughout the industry. Further, test results are very sensitive to the skill of the technician performing the test. Because of these factors, it is very common to find significant differences in reported properties of what is nominally the same composite material.

In Section 9.2, we discussed the issue of size effect, which is the decrease in strength with increasing material volume that is observed in monolithic ceramics key reinforcing fibers. There is some evidence, suggestive but not conclusive, of size effects in composite strength properties, as well. However, if composite strength size effects exist at all, they are much less severe than for fibers by themselves. The reason is that the presence of a matrix results in very different failure mechanisms. However, until the issues are resolved definitively, caution should be used in extrapolating strength data from small coupons to large structures, which may have volumes many orders of magnitude greater.

As mentioned earlier, the properties of composites are very sensitive to reinforcement form, volume fraction, and geometry. This is illustrated in Table 9.5, which presents the properties of several common types of E-glass fiber-reinforced polyester composites. The reinforcement forms are discontinuous fibers, woven roving (a heavy fabric), and straight, parallel continuous fibers. As we shall see, discontinuous reinforcement is not as efficient as continuous. However, discontinuous fibers allow the composite material to flow during processing, facilitating fabrication of complex molded parts.

The composites using discontinuous fibers are divided into three categories. One is bulk molding compound (BMC), also called dough molding compound, in which fibers are relatively short, about 3–12 mm, and are nominally randomly oriented in three dimensions. BMC also has a very high loading of mineral particles, such as calcium carbonate, which are added for a variety of reasons: to reduce dimensional changes from resin shrinkage, to obtain a smooth surface, and to reduce cost, among others. Because it contains both particulate and fibrous reinforcement, BMC can be considered a type of hybrid composite.

The second type of composite is chopped strand mat (CSM), which contains discontinuous fibers, typically about 25 mm long, nominally randomly oriented in two directions. The third material is sheet molding compound (SMC), which contains chopped fibers 25–50 mm in length, also nominally randomly oriented in two dimensions. Like BMC, SMC also contains particulate mineral fillers, such as calcium carbonate and clay.

Table 9.5 Effect of Fiber Form and Volume Fraction on Mechanical Properties of E-Glass-Reinforced Polyester[4]

	Bulk Molding Compound	Sheet Molding Compound	Chopped Strand Mat	Woven Roving	Unidirectional Axial	Unidirectional Transverse
Glass content (wt %)	20	30	30	50	70	70
Tensile modulus GPa (Msi)	9 (1.3)	13 (1.9)	7.7 (1.1)	16 (2.3)	42 (6.1)	12 (1.7)
Tensile strength MPa (Ksi)	45 (6.5)	85 (12)	95 (14)	250 (36)	750 (110)	50 (7)

The first thing to note in comparing the materials in Table 9.5 is that fiber content, here presented in the form of weight percent, differs considerably for the four materials. This is significant, because, as discussed in Section 9.2, the strength and stiffness of polyester and most polymer matrices is considerably lower than those of E-glass, carbon, and other reinforcing fibers. Composites reinforced with randomly oriented fibers tend to have lower volume fractions than those made with aligned fibers or fabrics. There is a notable exception to this. Some composites with discontinuous-fiber reinforcement are made by chopping up composites reinforced with aligned continuous fibers or fabrics that have high-fiber contents.

Examination of Table 9.5 shows that the modulus of SMC is considerably greater than that of CSM, even though both have the same fiber content. This is because SMC also has particulate reinforcement. Note, however, that although the particles improve modulus, they do not increase strength. This is generally the case for particle-reinforced polymers, but, as we will see later, particles often do enhance the strengths of MMCs and CMCs, as well as their moduli.

We observe that the modulus of the BMC composite is greater than that of CSM and SMC, even though the former has a much lower fiber content. Most likely, this results from the high-mineral content and also the possibility that the fibers are oriented in the direction of test, and are not truly random. Many processes, especially those involving material flow, tend to orient fibers in one or more preferred directions. If so, then one would find the modulus of the BMC to be much lower than the one presented in the table if measured in other directions. This illustrates one of the limitations of using discontinuous fiber reinforcement: it is often difficult to control fiber orientation.

The moduli and strengths of the composites reinforced with fabrics and aligned fibers are much higher than those with discontinuous fibers, when the former two types of materials are tested parallel to fiber directions. For example, the tensile strength of woven roving is more than twice that of CSM. The properties presented are measured parallel to the warp direction of the fabric (the warp direction is the lengthwise direction of the fabric). The elastic and strength properties in the fill direction, perpendicular to the warp, typically are similar to, but somewhat lower than, those in the warp direction. Here, we assume that the fabric is "balanced," which means that the number of fibers in the warp and fill directions per unit length are approximately equal. Note, however, that the elastic modulus, tensile strength, and compressive strength at 45° to the warp and fill directions of a fabric are much lower than the corresponding values in the warp and fill directions. This is discussed further in the sections that cover design.

As Table 9.5 shows, the axial modulus and tensile strength of the unidirectional composite are much greater than those of the fabric. However, the modulus and strength of the unidirectional composite in the transverse direction are considerably lower than the corresponding axial properties. Further, the transverse strength is considerably lower than that of SMC and CSM. In general, the strength of PMCs is weak in directions for which there are no fibers. The low transverse moduli and strengths of unidirectional PMCs are commonly overcome by use of laminates with fibers in several directions. Low through-thickness strength can be improved by use of three-dimensional reinforcement forms. Often, the designer simply assures that through-thickness stresses are within the capability of the material.

In this section, we present representative mechanical and physical properties of key composite materials of interest for a broad range of mechanical engineering applications. The properties represent a distillation of values from many sources. Because of space limitations, it is necessary to be selective in our choice of materials and properties presented. It is simply not possible to present a complete set of data that will cover every possible application. As discussed earlier, there are many textile forms, such as woven fabrics, used as reinforcements. However, we concentrate on aligned, continuous fibers because they produce the highest strength and stiffness. To do a thorough evaluation of composites, the design engineer should consider alternative reinforcement forms. Unless otherwise stated, room temperature property values are presented. We consider mechanical properties in Section 9.3.1 and physical in Section 9.3.2.

9.3.1 Mechanical Properties of Composite Materials

In this section, we consider mechanical properties of key PMCs, MMCs, CMCs, and CCCs that are of greatest interest for mechanical engineering applications.

Mechanical Properties of Polymer Matrix Composites

As discussed earlier, polymers are relatively weak, low-stiffness materials. In order to obtain materials with mechanical properties that are acceptable for structural applications, it is necessary to reinforce them with continuous or discontinuous fibers. The addition of ceramic or metallic particles to polymers results in materials which have increased modulus, but, as a rule, strength typically does not increase significantly, and may actually decrease. However, there are many particle-reinforced polymers used in electronic packaging, primarily because of their physical properties. For these applications, ceramic particles, such as alumina, aluminum nitride, boron nitride, and even diamond, are added to obtain an electrically insulating material with higher thermal conductivity and lower CTE than the monolithic base polymer. Metallic particles such as silver and aluminum are added to create materials which are both electrically and thermally conductive. These materials have replaced lead-based solders in many applications. There are also magnetic composites made by incorporating ferrous or permanent magnet particles in various polymers. A common example is magnetic tape used to record audio and video.

We focus on composites reinforced with continuous fibers because they are the most efficient structural materials. Table 9.6 presents room temperature mechanical properties of unidirectional polymer matrix composites reinforced with key fibers: E-glass, aramid, boron, standard-modulus (SM) PAN (polyacrilonitrile) carbon, ultrahigh-strength (UHS) PAN carbon, ultrahigh-modulus (UHM) PAN carbon, ultrahigh-modulus (UHM) pitch carbon, and ultrahigh-thermal conductivity (UHK) pitch carbon. We assume that the fiber volume fraction is 60%, a typical value. As discussed in Section 9.2, UHS PAN carbon is the strongest type of intermediate-modulus (IM) carbon fiber.

The properties presented in Table 9.6 are representative of what can be obtained at room temperature with a well-made PMC employing an epoxy matrix. Epoxies are widely used, provide good mechanical properties, and can be considered a reference matrix material. Properties of composites using other resins may differ from these, and have to be examined on a case-by-case basis.

The properties of PMCs, especially strengths, depend strongly on temperature. The temperature dependence of polymer properties differs considerably. This is also true for different epoxy formulations, which have different cure and glass transition temperatures. Some polymers, such as polyimides, have good elevated temperature properties that allow them to compete with titanium. There are aircraft gas turbine engine components employing polyimide matrices that see service temperatures as high as 290°C (550°F). Here again, the effect of temperature on composite properties has to be considered on a case-by-case basis.

The properties shown in Table 9.6 are axial, transverse and shear moduli, Poisson's ratio, tensile and compressive strengths in the axial and transverse directions, and inplane shear strength. The Poisson's ratio presented is called the major Poisson's ratio. It is defined as the ratio of the magnitude of transverse strain divided by axial strain when the composite is loaded in the axial direction. Note that transverse moduli and strengths are much lower than corresponding axial values.

As discussed in Section 9.2, carbon fibers display nonlinear stress–strain behavior. Their moduli increase under increasing tensile stress and decrease under increasing compressive stress. This makes the method of calculating modulus critical. Various tangent and secant definitions are used throughout the industry, contributing to the confusion in reported properties. The values presented in Table 9.6, which are approximate, are based on tangents to the stress–strain curves at the origin. Using this definition, tensile and compressive moduli are usually very similar. However, this is not the case for moduli using various secant definitions. Using these definitions typically produces compression moduli that are significantly lower than tension moduli.

Because of the low transverse strengths of unidirectional laminates, they are rarely used in structural applications. The design engineer uses laminates with layers in several directions to meet requirements for strength, stiffness, buckling, and so on. There are an infinite number of laminate geometries that can be selected. For comparative purposes, it is useful to consider quasi-isotropic laminates, which have the same elastic properties in all directions in the plane. Laminates are quasi-isotropic when they have the same percentage of layers every $180/n°$, where $n \geq 3$. The most common quasi-isotropic laminates have layers which repeat every 60, 45, or 30°. We note, however, that strength properties in the plane are not isotropic for these laminates, although they tend to become more uniform as the angle of repetition becomes smaller.

Table 9.7 presents the mechanical properties of quasi-isotropic laminates. Note that the moduli and strengths are much lower than the axial properties of unidirectional laminates made of the same material. In most applications, laminate geometry is such that the maximum axial modulus and tensile and compressive strengths fall somewhere between axial unidirectional and quasi-isotropic values.

The tension-tension fatigue behavior of unidirectional composites, discussed in Section 9.1, is one of their great advantages over metals (Fig. 9.6). In general the tension-tension S–N curves (curves of maximum stress plotted as a function of cycles to failure) of PMCs reinforced with carbon, boron, and aramid fibers are relatively flat. Glass fiber-reinforced composites show a greater reduction in strength with increasing number of cycles. Still, PMCs reinforced with HS glass are widely used in applications for which fatigue resistance is a critical design consideration, such as helicopter rotors.

Metals are more likely to fail in fatigue when subjected to fluctuating tensile rather than compressive load. This is because they tend to fail by crack propagation under fatigue loading. However, the failure modes in composites are very different and more complex. One consequence is that composites tend to be more susceptible to fatigue failure when loaded in compression. Figure 9.6 shows the cycles to failure as a function of maximum stress for carbon fiber-reinforced epoxy laminates subjected to tension–tension and compression–compression fatigue. The laminates have 60% of their layers oriented at 0°, 20% at +45° and 20% at −45°. They are subjected to a fluctuating load in the 0° direction. The ratios of minimum stress-to-maximum stress (R) for tensile and compressive fatigue are 0.1 and 10, respectively. We observe that the reduction in strength is much greater for compression–compression fatigue. However, the composite compressive fatigue strength at 10^7 cycles is still considerably greater than the corresponding tensile value for aluminum.

Table 9.6 Mechanical Properties of Selected Unidirectional Polymer Matrix Composites

Fiber	Axial Modulus GPa (Msi)	Transverse Modulus GPa (Msi)	Inplane Shear Modulus GPa (Msi)	Poisson's Ratio	Axial Tensile Strength MPa (Ksi)	Transverse Tensile Strength MPa (Ksi)	Axial Compressive Strength MPa (Ksi)	Transverse Compressive Strength MPa (Ksi)	Inplane Shear Strength MPa (Ksi)
E-glass	45 (6.5)	12 (1.8)	5.5 (0.8)	0.28	1020 (150)	40 (7)	620 (90)	140 (20)	70 (10)
Aramid	76 (11)	5.5 (0.8)	2.1 (0.3)	0.34	1240 (180)	30 (4.3)	280 (40)	140 (20)	60 (9)
Boron	210 (30)	19 (2.7)	4.8 (0.7)	0.25	1240 (180)	70 (10)	3310 (480)	280 (40)	90 (13)
SM carbon (PAN)	145 (21)	10 (1.5)	4.1 (0.6)	0.25	1520 (220)	41 (6)	1380 (200)	170 (25)	80 (12)
UHS carbon (PAN)	170 (25)	10 (1.5)	4.1 (0.6)	0.25	3530 (510)	41 (6)	1380 (200)	170 (25)	80 (12)
UHM carbon (PAN)	310 (45)	9 (1.3)	4.1 (0.6)	0.20	1380 (200)	41 (6)	760 (110)	170 (25)	80 (12)
UHM carbon (pitch)	480 (70)	9 (1.3)	4.1 (0.6)	0.25	900 (130)	20 (3)	280 (40)	100 (15)	41 (6)
UHK carbon (pitch)	480 (70)	9 (1.3)	4.1 (0.6)	0.25	900 (130)	20 (3)	280 (40)	100 (15)	41 (6)

Table 9.7 Mechanical Properties of Selected Quasi-Isotropic Polymer Matrix Composites

Fiber	Axial Modulus GPa (Msi)	Transverse Modulus GPa (Msi)	Inplane Shear Modulus GPa (Msi)	Poisson's Ratio	Axial Tensile Strength MPa (Ksi)	Transverse Tensile Strength MPa (Ksi)	Axial Compressive Strength MPa (Ksi)	Transverse Compressive Strength MPa (Ksi)	Inplane Shear Strength MPa (Ksi)
E-glass	23 (3.4)	23 (3.4)	9.0 (1.3)	0.28	550 (80)	550 (80)	330 (48)	330 (48)	250 (37)
Aramid	29 (4.2)	29 (4.2)	11 (1.6)	0.32	460 (67)	460 (67)	190 (28)	190 (28)	65 (9.4)
Boron	80 (11.6)	80 (11.6)	30 (4.3)	0.33	480 (69)	480 (69)	1100 (160)	1100 (160)	360 (52)
SM carbon (PAN)	54 (7.8)	54 (7.8)	21 (3.0)	0.31	580 (84)	580 (84)	580 (84)	580 (84)	410 (59)
UHS carbon (PAN)	63 (9.1)	63 (9.1)	21 (3.0)	0.31	1350 (200)	1350 (200)	580 (84)	580 (84)	410 (59)
UHM carbon (PAN)	110 (16)	110 (16)	41 (6.0)	0.32	490 (71)	490 (71)	270 (39)	70 (39)	205 (30)
UHM carbon (pitch)	165 (24)	165 (24)	63 (9.2)	0.32	310 (45)	310 (45)	96 (14)	96 (14)	73 (11)
UHK carbon (pitch)	165 (24)	165 (24)	63 (9.2)	0.32	310 (45)	310 (45)	96 (14)	96 (14)	73 (11)

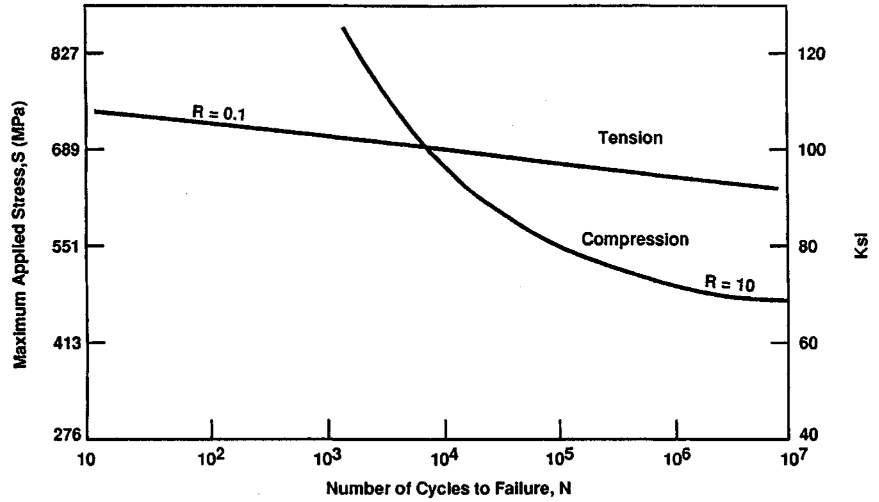


Fig. 9.6 Cycles to failure as a function of maximum stress for carbon fiber-reinforced epoxy laminates loaded in tension-tension (R = 0.1) and compression-compression (R = −10) fatigue (after Ref. 5.).

Polymer matrix composites reinforced with carbon and boron are very resistant to deformation and failure under sustained static load when they are loaded in a fiber-dominated direction. (These phenomena are called creep and creep rupture, respectively.) The creep and creep rupture behavior of aramid is not quite as good. Glass fibers display significant creep, and creep rupture is an important design consideration. Polymers are viscoelastic materials that typically display significant creep when they are not constrained with fibers. Therefore, creep should be considered when composites are subjected to significant stresses in matrix-dominated directions, such as the laminate through-thickness direction.

Mechanical Properties of Metal Matrix Composites

Monolithic metallic alloys are the most widely used materials in mechanical engineering applications. By reinforcing them with continuous fibers, discontinuous fibers, whiskers and particles, we create new materials with enhanced or modified properties, such as higher strength and stiffness, better wear resistance, lower CTE, and so on. In some cases, the improvements are dramatic.

The greatest increases in strength and modulus are achieved with continuous fibers. However, the relatively high-cost of many continuous reinforcing fibers used in MMCs has limited the application of these materials. The most widely used MMCs are reinforced with discontinuous fibers or particles. This may change as new, lower-cost continuous fibers and processes are developed and as cost drops with increasing production volume.

Continuous Fiber-Reinforced MMCs. One of the major advantages of MMCs reinforced with continuous fibers over PMCs is that many, if not most, unidirectional MMCs have much greater transverse strengths, which allow them to be used in a unidirectional configuration. Table 9.8 presents representative mechanical properties of selected unidirectional MMCs reinforced with continuous fibers corresponding to a nominal fiber volume fraction of 50%. The values represent a distillation obtained from numerous sources. In general, the axial moduli of the composites are much greater than those of the monolithic base metals used for the matrices. However, MMC transverse strengths are typically lower than those of the parent matrix materials.

Mechanical Properties of Discontinuous Fiber-Reinforced MMCs. One of the primary mechanical engineering applications of discontinuous fiber-reinforced MMCs is in internal combustion engine components (see Section 9.5.4). Fibers are added primarily to improve the wear resistance and elevated temperature strength and fatigue properties of aluminum. The improvement in wear resistance eliminates the need for cast iron sleeves in engine blocks and cast iron insert rings in pistons. Fiber-reinforced aluminum composites also have higher thermal conductivities than cast iron and, when fiber volume fractions are relatively low, their CTEs are closer to that of unreinforced aluminum, reducing thermal stresses.

The key reinforcements used in internal combustion engine components to increase wear resistance are discontinuous alumina and alumina–silica fibers. In one application, Honda Prelude engine

Table 9.8 Mechanical Properties of Selected Unidirectional Continuous Fiber-Reinforced Metal Matrix Composites

Fiber	Matrix	Density g/cm^3 (Pci)	Axial Modulus GPa (Msi)	Transverse Modulus GPa (Msi)	Axial Tensile Strength MPa (Ksi)	Transverse Tensile Strength MPa (Ksi)	Axial Compressive Strength MPa (Ksi)
UHM carbon (pitch)	Aluminum	2.4 (0.090)	450 (65)	15 (5)	690 (100)	15 (5)	340 (50)
Boron	Aluminum	2.6 (0.095)	210 (30)	140 (20)	1240 (180)	140 (20)	1720 (250)
Alumina	Aluminum	3.2 (0.12)	240 (35)	130 (19)	1700 (250)	120 (17)	1800 (260)
Silicon carbide	Titanium	3.6 (0.13)	260 (38)	170 (25)	1700 (250)	340 (50)	2760 (400)

blocks, carbon fibers are combined with alumina to tailor both wear resistance and coefficient of friction of cylinder walls. Wear resistance is not an inherent property, so that there is no single value that characterizes a material. However, in engine tests, it was found that ring groove wear for an alumina fiber-reinforced aluminum piston was significantly less than that for one with a cast iron insert.

Mechanical Properties of Particle-Reinforced MMCs. Particle-reinforced metals are a particularly important class of MMCs for engineering applications. A wide range of materials fall into this category, and a number of them have been used for many years. An important example is a material consisting of tungsten carbide particles embedded in a cobalt matrix that is used extensively in cutting tools and dies. This composite, often referred to as a cermet, cemented carbide, or simply, but incorrectly, "tungsten carbide," has much better fracture toughness than monolithic tungsten carbide, which is a brittle ceramic material. Another interesting MMC, tungsten carbide particle-reinforced silver, is a key circuit breaker contact pad material. Here, the composite provides good electrical conductivity and much greater hardness and wear resistance than monolithic silver, which is too soft to be used in this application. Ferrous alloys reinforced with titanium carbide particles, discussed in the next subsection, have been used for many years in commercial applications. Compared to the monolithic base metals, they offer greater wear resistance and stiffness and lower density.

Mechanical Properties of Titanium Carbide Particle-Reinforced Steel. A number of ferrous alloys reinforced with titanium carbide particles have been used in mechanical system applications for many years. To illustrate the effect of the particulate reinforcements, we consider a particular composite consisting of austenitic stainless steel reinforced with 45% by volume of titanium carbide particles. The modulus of the composite is 304 GPa (44 Msi) compared to 193 GPa (28 Msi) for the monolithic base metal. The specific gravity of the composite is 6.45, about 20% lower than that of monolithic matrix, 8.03. The specific stiffness of the composite is almost double that of the unreinforced metal.

Mechanical Properties of Silicon Carbide Particle-Reinforced Aluminum. Aluminum reinforced with silicon carbide particles is one of the most important of the newer types of MMCs. A wide range of materials fall into this category. They are made by a variety of processes, which are discussed in Section 9.4. Properties depend on the type of particle, particle volume fraction, matrix alloy, and the process used to make them. Table 9.9 shows how representative composite properties vary with particle volume fraction. In general, as particle volume fraction increases, modulus and yield strength increase and fracture toughness and tensile ultimate strain decrease. Particle reinforcement also improves short-term elevated temperature strength properties and fatigue resistance.

Mechanical Properties of Alumina Particle-Reinforced Aluminum. Alumina particles are used to reinforce aluminum as an alternative to silicon carbide particles because they do not react as readily with the matrix at high temperatures and are less expensive. Consequently, alumina-reinforced composites can be used in a wider range of processes and applications. However, the stiffness and thermal conductivity of alumina are lower than the corresponding properties of silicon carbide and these characteristics are reflected in somewhat lower values for composite properties.

Mechanical Properties of Ceramic Matrix Composites

Ceramics, in general, are characterized by high stiffness and hardness, resistance to wear, corrosion and oxidation, and high-temperature operational capability. However, they also have serious deficiencies that have severely limited their use in applications that are subjected to significant tensile stresses. Ceramics have very low fracture toughness, which makes them very sensitive to the presence of small flaws. This results in great strength scatter and poor resistance to thermal and mechanical shock. Civil engineers recognized this deficiency long ago and, in construction, ceramic materials like stone and concrete are rarely used to carry tensile loads. In concrete, this function has been relegated to reinforcing bars made of steel or, more recently, PMCs. An important exception has been in lightly loaded structures where dispersed reinforcing fibers of asbestos, steel, glass and carbon allow modest tensile stresses to be supported.

In CMCs, fibers, whiskers, and particles are combined with ceramic matrices to improve fracture toughness, which reduces strength scatter and improves thermal and mechanical shock resistance. By a wide margin, the greatest increases in fracture resistance result from the use of continuous fibers. Table 9.10 compares fracture toughnesses of structural metallic alloys with those of monolithic ceramics and CMCs reinforced with whiskers and continuous fibers. The low fracture toughness of monolithic ceramics gives rise to very small critical flaw sizes. For example, the critical flaw sizes for monolithic ceramics corresponding to a failure stress of 700 MPa (about 100 Ksi) are in the range of 20–80 micrometers. Flaws of this size are difficult to detect with conventional nondestructive techniques.

The addition of continuous fibers to ceramics can, if done properly, significantly increase the effective fracture toughness of ceramics. For example, as Table 9.10 shows, addition of silicon carbide fibers to a silicon carbide matrix results in a CMC having a fracture toughness in the range of aluminum alloys.

Table 9.9 Mechanical Properties of Silicon Carbide Particle-Reinforced Aluminum

Property	Aluminum (6061-T6)	Titanium (6Al-4V)	Steel (4340)	Composite Particle Volume Fraction		
				25	55	70
Modulus, GPa (Msi)	69 (10)	113 (16.5)	200 (29)	114 (17)	186 (27)	265 (38)
Tensile yield strength, MPa (Ksi)	275 (40)	1000 (145)	1480 (215)	400 (58)	495 (72)	225 (33)
Tensile ultimate strength, MPa (Ksi)	310 (45)	1100 (160)	1790 (260)	485 (70)	530 (77)	225 (33)
Elongation (%)	15	5	10	3.8	0.6	0.1
Density, g/cm^3 (lb/in.^{3})	2.77 (0.10)	4.43 (0.16)	7.76 (0.28)	2.88 (0.104)	2.96 (0.107)	3.00 (0.108)
Specific modulus, GPa	5	26	26	40	63	88

Table 9.10 Fracture Toughness of Structural Alloys, Monolithic Ceramics, and Ceramic Matrix Composites

Matrix	Reinforcement	Fracture Toughness MPa $m^{1/2}$
Aluminum	none	30–45
Steel	none	40–65[a]
Alumina	none	3–5
Silicon carbide	none	3–4
Alumina	Zirconia particles[b]	6–15
Alumina	Silicon carbide whiskers	5–10
Silicon carbide	Continuous silicon carbide fibers	25–30

[a] The toughness of some alloys can be much higher.
[b] Transformation-toughened.

The addition of continuous fibers to a ceramic matrix also changes the failure mode. Figure 9.7 compares the tensile stress-strain curves for a typical monolithic ceramic and a conceptual continuous fiber-reinforced CMC. The monolithic material has a linear stress-strain curve and fails catastrophically at a low strain level. However, the CMC displays a nonlinear stress-strain curve with much more area under the curve, indicating that more energy is absorbed during failure and that the material has a less catastrophic failure mode. The fiber-matrix interphase properties must be carefully tailored and maintained over the life of the composite to obtain this desirable behavior.

Although the CMC stress-strain curve looks, at first, like that of an elastic-plastic metal, this is deceiving. The departure from linearity in the CMC results from internal damage mechanisms, such as the formation of microcracks in the matrix. The fibers bridge the cracks, preventing them from propagating. However, the internal damage is irreversible. As the figure shows, the slope of the stress-strain curve during unloading and subsequent reloading is much lower than that representing initial loading. For an elastic–plastic material, the slopes of the unloading and reloading curves are parallel to the initial elastic slope.

There are numerous CMCs at various stages of development. One of the most mature types consists of a silicon carbide matrix reinforced with fabric woven of silicon carbide-based fibers. These composites are commonly referred to as SiC/SiC. We consider one version. Because the modulus of the particular silicon carbide-based fibers used in this material is lower than that of pure silicon carbide, the modulus of the composite, about 210 GPa (30 Msi), is lower than that of monolithic silicon carbide, 440 GPa (64 Msi). The flexural strength of the composite parallel to the fabric warp direction, about 300 MPa (44 Ksi), is maintained to a temperature of at least 1100°C for short

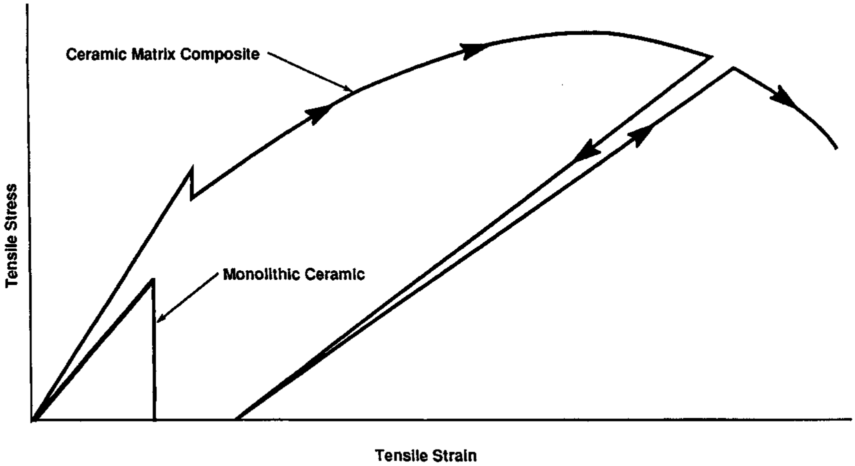


Fig. 9.7 Stress-strain curves for a monolithic ceramic and ceramic matrix composite reinforced with continuous fibers.

times. Long-term strength behavior depends on degradation of the fibers, matrix, and interphase. Because of the continuous fiber reinforcement, SiC/SiC displays excellent resistance to severe thermal shock.

Mechanical Properties of Carbon/Carbon Composites

Carbon/carbon composites consist of continuous and discontinuous carbon fibers embedded in carbon matrices. As for other composites, there are a wide range of materials that fall in this category. The variables affecting properties include type of fiber, reinforcement form, and volume fraction and matrix characteristics.

Historically, CCCs were first used because of their excellent resistance to high-temperature ablation. Initially, strengths and stiffnesses were low, but these properties have steadily increased over the years. As discussed in Section 9.5, CCCs are an important class of materials in high-temperature applications such as aircraft brakes, rocket nozzles, racing car brakes and clutches, glass-making equipment, and electronic packaging, among others.

One of the most significant limitations of CCCs is oxidation, which begins at a temperature threshold of approximately 370°C (700°F) for unprotected materials. Addition of oxidation inhibitors raises the threshold substantially. In inert atmospheres, CCCs retain their properties to temperatures as high as 2800°C (5000°F).

Carbon matrices are typically weak, brittle, low-stiffness materials. As a result, transverse and through-thickness elastic moduli and strength properties of unidirectional CCCs are low. Because of this, two-dimensional and three-dimensional reinforcement forms are commonly used. In the direction of fibrous reinforcement, it is possible to obtain moduli as high as 340 GPa (50 Msi), tensile strengths as high as 700 MPa (100 Ksi), and compressive strengths as high as 800 MPa (110 Ksi). In directions orthogonal to fiber directions, elastic moduli are in the range of 10 MPa (1.5 Ksi), tensile strengths 14 MPa (2 Ksi), and compressive strengths 34 MPa (5 Ksi).

9.3.2 Physical Properties of Composite Materials

Material physical properties are critical for many applications. In this category, we include, among others, density, CTE, thermal conductivity, and electromagnetic characteristics. In this section, we concentrate on the properties of most general interest to mechanical engineers: density, CTE, and thermal conductivity.

Thermal control is a particularly important consideration in electronic packaging because failure rates of semiconductors increase exponentially with temperature. Since conduction is an important method of heat removal, thermal conductivity is a key material property. For many applications, such as spacecraft, aircraft, and portable systems, weight is also an important factor, and consequently, material density is also significant. A useful figure of merit is specific thermal conductivity, defined as thermal conductivity divided by density. Specific thermal conductivity is analogous to specific modulus and specific strength.

In addition to thermal conductivity and density, CTE is also of great significance in many applications. For example, semiconductors and ceramic substrates used in electronics are brittle materials with coefficients of expansion in the range of about 3–7 ppm/K. Semiconductors and ceramic substrates are typically attached to supporting components, such as packages, printed circuit boards (PCBs), and heat sinks with solder or an adhesive. If the CTE of the supporting material is significantly different from that of the ceramic or semiconductor, thermal stresses arise when the assembly is subjected to a change in temperature. These stresses can result in failure of the components or the joint between them.

A great advantage of composites is that there are an increasing number of material systems that combine high thermal conductivity with tailorable CTE, low density, and excellent mechanical properties. Composites can truly be called multifunctional materials.

The key composite materials of interest for thermal control are PMCs, MMCs, and CCCs reinforced with ultrahigh-thermal conductivity (UHK) carbon fibers, which, as discussed in Section 9.2, are made from pitch; silicon carbide particle-reinforced aluminum; beryllium oxide particle-reinforced beryllium; and diamond particle-reinforced aluminum and copper. There also are a number of other special CCCs developed specifically for thermal control applications.

Table 9.11 presents physical properties of a variety of unidirectional composites reinforced with UHK carbon fibers, along with those of monolithic copper and 6063 aluminum for comparison. Unidirectional composites are useful for directing heat in a particular direction. The particular fibers represented have a nominal axial thermal conductivity of 1100 W/m K. Predicted properties are shown for four matrices: epoxy, aluminum, copper, and carbon. Typical reinforcement volume fractions (V/O) are assumed. As Table 9.11 shows, the specific axial thermal conductivities of the composites are significantly greater than those of aluminum and copper.

Figure 9.8 presents thermal conductivity as a function of CTE for various materials used in electronic packaging. Materials shown include silicon (Si) and gallium arsenide (GaAs) semiconductors; alumina (Al_2O_3), beryllium oxide (BeO), and aluminum nitride (AlN) ceramic substrates; and monolithic aluminum, beryllium, copper, silver, and Kovar®, a nickel-iron alloy. Other monolithic

Table 9.11 Physical Properties of Selected Unidirectional Composites and Monolithic Metals

Matrix	Reinforcement	V/O %	Density g/cm³ (Pci)	Axial Coefficient of Thermal Expansion ppm/K (ppm/F)	Axial Thermal Conductivity W/m K (BTU/h · ft · F)	Transverse Thermal Conductivity W/m K (BTU/h · ft · F)	Specific Axial Thermal Conductivity W/m K (BTU/h · ft · F)
Aluminum (6063)	—	—	2.7 (0.098)	23 (13)	218 (126)	218 (126)	81
Copper	—	—	8.9 (0.32)	17 (9.8)	400 (230)	400 (230)	45
Epoxy	UHK carbon fibers	60	1.8 (0.065)	−1.2 (−0.7)	660 (380)	2 (1.1)	370
Aluminum	UHK carbon fibers	50	2.45 (0.088)	−0.5 (−0.3)	660 (380)	50 (29)	110
Copper	UHK carbon fibers	50	5.55 (0.20)	−0.5 (−0.3)	745 (430)	140 (81)	130
Carbon	UHK carbon fibers	40	1.85 (0.067)	−1.5 (−0.8)	740 (430)	45 (26)	400

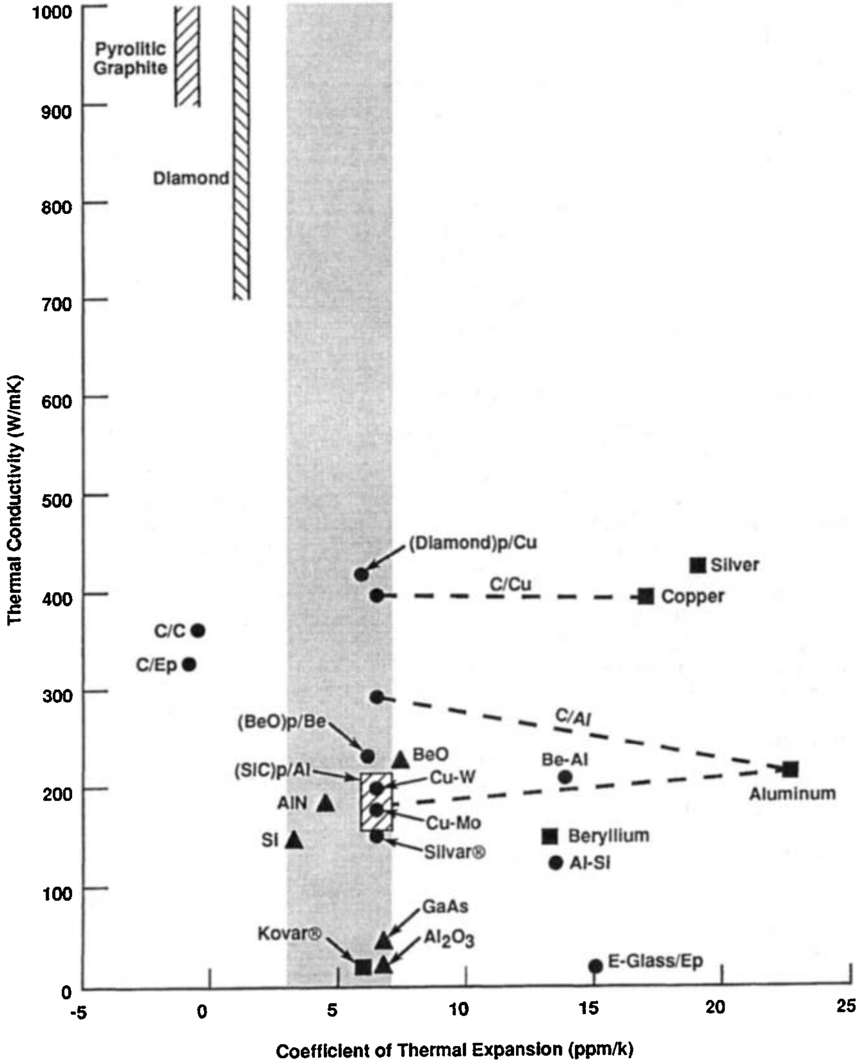


Fig. 9.8 Thermal conductivity as a function of coefficient of thermal expansion for selected monolithic materials and composites used in electronic packaging.

materials included are diamond and pyrolitic graphite, which have very high thermal conductivities in some forms. The figure also presents metal–metal composites, such as copper–tungsten (Cu–W), copper–molybdenum (Cu–Mo), beryllium–aluminum (Be–Al), aluminum–silicon (Al–Si), and Silvar™, which contains silver and a nickel iron alloy. The latter materials can be considered composites rather than true alloys because the two components have low solubility and appear as distinct phases at room temperature.

As Figure 9.8 shows, aluminum, copper, and silver have relatively high thermal conductivities but have CTEs much greater than desirable for most electronic packaging applications. By combining these metals with various reinforcements, it is possible to create new materials having CTEs isotropic in two dimensions (quasi-isotropic) or three dimensions in the desired range. The figure shows a number of composites: copper reinforced with UHK carbon fibers (C/Cu), aluminum reinforced with UHK carbon fibers (C/Al), carbon reinforced with UHK carbon fibers (C/C), epoxy reinforced with UHK carbon fibers (C/Ep), aluminum reinforced with silicon carbide particles [(SiC)p/Al], beryllium oxide particle-reinforced beryllium [(BeO)p/Be], diamond particle-reinforced copper [(Diamond)p/Cu], and E-glass fiber-reinforced epoxy (E-glass/Ep). With the exception of E-glass/Ep, C/Ep, and

C/C, all of the composites have some configurations with CTEs in the desired range. The thermal conductivities of the composites presented are generally similar to, or better than, that of aluminum, while their CTEs are much closer to the goal range of 3–7 ppm/K. E-glass/Ep is an exception.

Note that although the CTEs of C/Ep and C/C are lower than desired for electronic packaging applications, the differences between their CTEs and those of ceramics and semiconductors are much less than the differences for aluminum and copper. Consequently, use of the composites can result in lower thermal stresses for a given temperature change.

The physical properties of the materials shown in Figure 9.8 and others are presented in Table 9.12.

The advantages of composites are even greater than those of conventional packaging materials when weight is considered. Figure 9.9 presents the specific thermal conductivities and CTEs of the materials appearing in Figure 9.8. Here, we find order-of-magnitude improvements. As discussed earlier, when a critical property is increased by an order of magnitude it tends to have a revolutionary effect on technology. Several composites demonstrate this level of improvement; as a result, composites are being used in an increasing number of electronic packaging and thermal control applications, as discussed in Section 9.5.

Physical Properties of Polymer Matrix Composites

Table 9.13 presents physical properties of the polymer matrix composites discussed in Section 9.3.1. A fiber volume fraction of 60% is assumed. The densities of all of the materials are considerably lower than that of aluminum, and some are lower than that of magnesium. This reflects the low densities of both fibers and matrix materials. The low densities of most polymers give PMCs a significant advantage over most MMCs and CMCs, all other things being equal.

We observe that all of the composites have relatively low-axial CTEs. This results from the combination of low-fiber-axial CTE, high fiber stiffness, and low matrix stiffness. Note that the axial CTEs of PMCs reinforced with aramid fibers and some carbon fibers are negative. This means that, contrary to the general behavior of most monolithic materials, they contract when heated. The transverse CTEs of the composites are all positive, and much larger than the magnitudes of the corresponding axial CTEs. This results from the high CTE of the matrix and a Poisson effect caused by constraint of the matrix in the axial direction and lack of constraint in the transverse direction. The transverse CTE of aramid composites is particularly high because the fibers have a relatively high positive radial CTE.

The axial thermal conductivities of composites reinforced with glass, aramid, boron, and a number of the carbon fibers are relatively low. In fact, E-glass and aramid PMCs are often used as thermal insulators. As Table 9.13 shows, most PMCs have relatively high thermal resistivities in the transverse direction, as a result of the low thermal conductivities of the matrix and the fibers in the radial direction. Through-thickness conductivities of laminates tend to be similar to the transverse thermal conductivities of unidirectional composites.

Table 9.14 shows the inplane thermal conductivities and CTEs of quasi-isotropic laminates made from the same material as in Table 9.13. Here again, a fiber volume fraction of 60% is assumed.

We observe that the CTEs of the quasi-isotropic composites are higher than the axial values of corresponding unidirectional composites. Note, however, that the CTEs of quasi-isotropic composites reinforced with aramid and carbon fibers are very small. By appropriate selection of fiber, matrix, and fiber volume fraction, it is possible to obtain quasi-isotropic materials with CTEs very close to zero. Note that through-thickness CTEs for these laminates typically will be positive and relatively large. However, this is not a significant issue for many applications.

Turning to thermal conductivity, we find that quasi-isotropic laminates reinforced with UHM pitch carbon fibers have an inplane thermal conductivity similar to that of aluminum alloys, while UHK pitch carbon fibers provide laminates with a conductivity more than 50% higher. Both materials have densities 35% lower than aluminum.

As mentioned above, through-thickness thermal conductivities of laminates tend to be similar to the transverse thermal conductivities of unidirectional composites, which are relatively low. However, if laminate thickness is small, this may not be a significant limitation.

Physical Properties of Metal Matrix Composites

In this section, we consider physical properties of selected unidirectional fiber-reinforced MMCs and of silicon carbide particle-reinforced aluminum MMCs.

Physical Properties of Continuous Fiber-Reinforced Metal Matrix Composites. Table 9.11 presents physical properties of unidirectional composites consisting of UHK pitch carbon fibers in aluminum and copper matrices. These materials both have very low, slightly negative axial CTEs for the assumed fiber volume fraction of 50%. As the table shows, the axial thermal conductivities for MMCs with aluminum and copper matrices are substantially greater than that of monolithic copper. A major advantage of having thermally conductive matrix materials is that the resulting composite

Table 9.12 Physical Properties of Isotropic and Quasi-Isotropic Composites and Monolithic Materials Used in Electronic Packaging

Matrix	Reinforcement	V/O %	Density g/cm^3 (Pci)	Coefficient of Thermal Expansion ppm/K (ppm/F)	Thermal Conductivity W/m K (BTU/h · ft · F)	Specific Thermal Conductivity W/m K
Aluminum (6063)	—	—	2.7 (0.098)	23 (13)	218 (126)	81
Copper	—	—	8.9 (0.32)	17 (9.8)	400 (230)	45
Beryllium	—	—	1.86 (0.067)	13 (7.2)	150 (87)	81
Magnesium	—	—	1.80 (0.065)	25 (14)	54 (31)	12
Titanium	—	—	4.4 (0.16)	9.5 (5.3)	16 (9.5)	4
Stainless steel (304)	—	—	8.0 (0.29)	17 (9.6)	16 (9.4)	2
Molybdenum	—	—	10.2 (0.37)	5.0 (2.8)	140 (80)	14
Tungsten	—	—	19.3 (0.695)	4.5 (2.5)	180 (104)	9
Invar®	—	—	8.0 (0.29)	1.6 (0.9)	10 (6)	1
Kovar®	—	—	8.3 (0.30)	5.9 (3.2)	17 (10)	2
Alumina (99% pure)	—	—	3.9 (0.141)	6.7 (3.7)	20 (12)	5
Beryllia	—	—	2.9 (0.105)	6.7 (3.7)	250 (145)	86
Aluminum nitride	—	—	3.2 (0.116)	4.5 (2.5)	250 (145)	78
Silicon	—	—	2.3 (0.084)	4.1 (2.3)	150 (87)	65
Gallium arsenide	—	—	5.3 (0.19)	5.8 (3.2)	44 (25)	8
Diamond	—	—	3.5 (0.13)	1.0 (0.6)	2000 (1160)	570
Pyrolitic graphite	—	—	2.3 (0.083)	−1 (−0.6)	1700 (980)	750
Aluminum-silicon	—	—	2.5 (0.091)	13.5 (7.5)	126 (73)	50
Beryllium-aluminum	—	—	2.1 (0.076)	13.9 (7.7)	210 (121)	100
Copper-tungsten (10/90)	—	—	17 (0.61)	6.5 (3.6)	209 (121)	12
Copper-molybdenum (15/85)	—	—	10 (0.36)	6.6 (3.7)	184 (106)	18
Aluminum	SiC particles	70	3.0 (0.108)	6.5 (3.6)	190 (110)	63
Beryllium	BeO particles	60	2.6 (0.094)	6.1 (3.4)	240 (139)	92
Copper	Diamond particles	55	5.9 (0.21)	5.8 (3.2)	420 (243)	71
Epoxy	UHK carbon fibers	60	1.8 (0.065)	−0.7 (−0.4)	330 (191)	183
Aluminum	UHK carbon fibers	26	2.6 (0.094)	6.5 (3.6)	290 (168)	112
Copper	UHK carbon fibers	26	7.2 (0.26)	6.5 (3.6)	400 (230)	56
Carbon	UHK carbon fibers	40	1.8 (0.065)	−1 (−0.6)	360 (208)	195

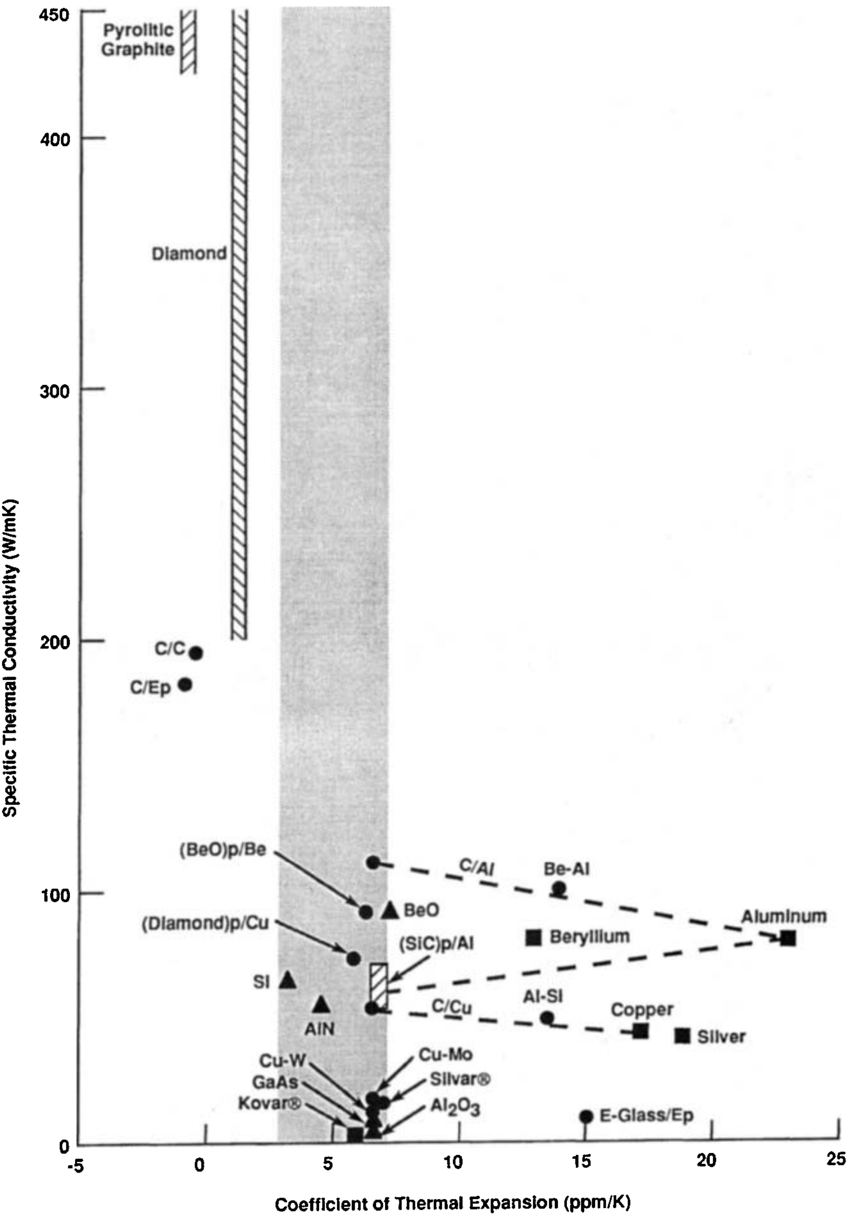


Fig. 9.9 Specific thermal conductivity (thermal conductivity divided by specific gravity) for selected monolithic materials and composites used in electronic packaging.

transverse and through-thickness thermal conductivities are more than an order of magnitude higher than those of an epoxy-matrix composite.

Table 9.12 presents the properties of quasi-isotropic composites composed of aluminum and copper matrices reinforced with UHK pitch carbon fibers. Here, the fiber volume fraction of about 26% has been chosen to achieve an inplane similar to that of aluminum oxide, 6.5 ppm/K (3.6 ppm/F). The inplane thermal conductivities of the aluminum- and copper-matrix composites are 290 W/m K (168 BTU/h · ft · F) and 400 W/m K (230 BTU/h · ft · F), respectively. These values are considerably greater than those of any other material with a similar CTE, with the exception of diamond particle-reinforced copper, which is discussed later. Because of the lower fiber volume fractions, the through-

Table 9.13 Physical Properties of Selected Unidirectional Polymer Matrix Composites

Fiber	Density g/cm^3 (Pci)	Axial CTE 10^{-6}/K (10^{-6}/F)	Transverse CTE 10^{-6}/K (10^{-6}/F)	Axial Thermal Conductivity W/m K (BTU/h · ft · F)	Transverse Thermal Conductivity W/m K (BTU/h · ft · F)
E-glass	2.1 (0.075)	6.3 (3.5)	22 (12)	1.2 (0.7)	0.6 (0.3)
Aramid	1.38 (0.050)	−4.0 (−2.2)	58 (32)	1.7 (1.0)	0.1 (0.08)
Boron	2.0 (0.073)	4.5 (2.5)	23 (13)	2.2 (1.3)	0.7 (0.4)
SM carbon (PAN)	1.58 (0.057)	0.9 (0.5)	27 (15)	5 (3)	0.5 (0.3)
UHS carbon (PAN)	1.61 (0.058)	0.5 (0.3)	27 (15)	10 (6)	0.5 (0.3)
UHM carbon (PAN)	1.66 (0.060)	−0.9 (−0.5)	40 (22)	45 (26)	0.5 (0.3)
UHM carbon (pitch)	1.80 (0.065)	−1.1 (−0.6)	27 (15)	380 (220)	10 (6)
UHK carbon (pitch)	1.80 (0.065)	−1.1 (−0.6)	27 (15)	660 (380)	10 (6)

Table 9.14 Physical Properties of Selected Quasi-Isotropic Polymer Matrix Composites

Fiber	Density g/cm^3 (Pci)	Axial CTE 10^{-6}/K (10^{-6}/F)	Transverse CTE 10^{-6}/K (10^{-6}/F)	Axial Thermal Conductivity W/m K (BTU/h · ft · F)	Transverse Thermal Conductivity W/m K (BTU/h · ft · F)
E-glass	2.1 (0.075)	10 (5.6)	10 (5.6)	0.9 (0.5)	0.9 (0.5)
Aramid	1.38 (0.050)	1.4 (0.8)	1.4 (0.8)	0.9 (0.5)	0.9 (0.5)
Boron	2.0 (0.073)	6.5 (3.6)	6.5 (3.6)	1.4 (0.8)	1.4 (0.8)
SM carbon (PAN)	1.58 (0.057)	3.1 (1.7)	3.1 (1.7)	2.8 (1.6)	2.8 (1.6)
UHS carbon (PAN)	1.61 (0.058)	2.3 (1.3)	2.3 (1.3)	6 (3)	6 (3)
UHM carbon (PAN)	1.66 (0.060)	0.4 (0.2)	0.4 (0.2)	23 (13)	23 (13)
UHM carbon (pitch)	1.80 (0.065)	−0.4 (−0.2)	−0.4 (−0.2)	195 (113)	195 (113)
UHK carbon (pitch)	1.80 (0.065)	−0.4 (−0.2)	−0.4 (−0.2)	335 (195)	335 (195)

thickness thermal conductivities of these composites will be somewhat higher than those of the unidirectional composites presented in Table 9.11.

Physical Properties of Particle-Reinforced Metal Matrix Composites. In this section, we consider the physical properties of silicon carbide particle-reinforced aluminum and diamond particle-reinforced copper.

Physical Properties of Silicon Carbide Particle-Reinforced Metal Matrix Composites. The physical properties of particle-reinforced composites tend to be isotropic (in three dimensions). As for all composites, the physical properties of silicon carbide particle-reinforced aluminum depend on constituent properties and reinforcement volume fraction. Figure 9.4 shows how the CTE of (SiC)p/Al varies with particle volume fraction for typical commercial materials. Table 9.15 presents density and CTE for several specific volume fractions, along with data for monolithic aluminum, titanium, and steel.

Thermal conductivity depends strongly on the corresponding properties of the matrix, reinforcement, and particle volume fraction. The thermal conductivity of very pure silicon carbide is slightly higher than that of copper. However, those of commercial particles are much lower. The thermal conductivities of silicon carbide particle-reinforced aluminum used in electronic packaging applications tend to be in the range of monolithic aluminum alloys, about 160–218 W/m K (92–126 Btu/h · ft · F).

Physical Properties of Diamond Particle-Reinforced Copper Metal Matrix Composites. Table 9.12 presents the physical properties of diamond particle-reinforced copper composites, which are developmental materials. As for other particle-reinforced composites, the properties can be expected to be relatively isotropic. This material has a thermal conductivity somewhat higher than that of monolithic copper, a much lower density, and a CTE in the range of semiconductors and ceramic substrates. This unique combination of properties makes this composite an attractive candidate for electronic packaging applications.

Physical Properties of Ceramic Matrix Composites

As discussed in Section 9.1, there are many CMCs and they are at various stages of development. One of the more mature systems is silicon carbide fiber-reinforced silicon carbide (SiC/SiC). For a fabric-reinforced composite with a fiber volume fraction of 40%, the density is 2.5 g/cm^3 (0.090 Pci), the CTE is 3 ppm/K (1.7 ppm/F), the inplane thermal conductivity is 19 W/m K (11 BTU/h · ft · F) and the through-thickness value is 9.5 W/m K (5.5 BTU/h · ft · F).

Physical Properties of Carbon/Carbon Composites

The CTE of CCCs depends on fiber type, volume fraction, and geometry and matrix characteristics. In the fiber direction, CTE tends to be negative with a small absolute value. Perpendicular to the fiber direction, composite CTE is dominated by matrix properties. As a rule, the magnitude of transverse CTE is small. Both positive and negative values have been reported.

It is well known that in some forms carbon has exceptionally high thermal conductivities. For example, pyrolitic graphite can have a thermal conductivity as high as 2000 W/m K (1160 BTU/h · ft · F), five times that of copper. The conductivity of some types of diamond is much higher. Some CCCs also have very high thermal conductivities. Values have been reported as high as 400 W/m K (230 BTU/h · ft · F) for quasi-isotropic composites and 700 W/m K (400 BTU/h · ft · F) for unidirectional materials.

9.4 PROCESSES

Selection of the processes by which a system will be fabricated is a key part of design. Processes for making composites have a critical influence on material properties, reliability, cost and schedule. One of the big advantages of composites is that there are processes that allow consolidation of parts, which can reduce overall complexity and cost and improve performance. Many processes allow fabrication of parts to their final shape (net shape processes) or close to their final shape (near-net shape processes). This can eliminate or reduce the need for, and cost associated with, machining and joining. This section describes key fabrication processes for the four classes of composites.

Conceptually, fabrication of composite components consists of four parts: combination of constituents, material consolidation, shaping, and joining. Some processes combine two or more of these steps. There are a number of processes, especially those based on infiltration of liquid matrices, that have analogues in all four classes of composites. Infiltration processes typically use a preform, in which the reinforcement is shaped and held together by a temporary (fugitive) or permanent binder. In the case of fibrous reinforcements, the preform must maintain the correct fiber orientation and volume fraction during processing to make sure that the strength and stiffness properties of the finished part meet design requirements.

An important consideration in all processes is minimization of voids, or porosity, which typically has a deleterious effect on properties.

Table 9.15 Physical Properties of Silicon Carbide Particle-Reinforced Aluminum

Property	Aluminum (6061-T6)	Titanium (6Al-4V)	Steel (4340)	Composite Particle Volume Fraction		
				25	55	70
CTE, $10^{-6}/K$ ($10^{-6}/F$)	23 (13)	9.5 (5.3)	12 (6.6)	16.4 (9.1)	10.4 (5.8)	6.2 (3.4)
Thermal Conductivity W/m K (BTU/h · ft · F)	218 (126)	16 (9.5)	17 (9.4)	160–220 (92–126)	160–220 (92–126)	160–220 (92–126)
Density, g/cm^3 (Pci)	2.77 (0.10)	4.43 (0.16)	7.76 (0.28)	2.88 (0.104)	2.96 (0.107)	3.00 (0.108)

9.4.1 Polymer Matrix Composites

There are a large and increasing number of processes for making PMC parts. Many are not very labor-intensive and can make near-net shape components. For thermoplastic matrices reinforced with discontinuous fibers, one of the most widely used processes is injection molding. However, as discussed in Section 9.3, the stiffness and strength of resulting parts are relatively low. This section focuses on processes for making composites with continuous fibers.

Many PMC processes combine fibers and matrices directly. However, a number use an intermediate material called a prepreg, which stands for preimpregnated material, consisting of fibers embedded in a thermoplastic or partially cured thermoset matrix. The most common forms of prepreg are unidirectional tapes and impregnated tows and fabrics.

Material consolidation is commonly achieved by application of heat and pressure. For thermosetting resins, consolidation involves a complex physical–chemical process, which is accelerated by subjecting the material to elevated temperature. However, some resins undergo cure at room temperature. Another way to cure resins without temperature is by use of electron bombardment. As part of the consolidation process, uncured laminates are often placed in an evacuated bag, called a vacuum bag, which applies atmospheric pressure when evacuated. The vacuum-bagged assembly is typically cured in an oven or autoclave. The latter also applies pressure significantly above the atmospheric level.

PMC parts are usually shaped by use of molds made from a variety of materials: steel, aluminum, bulk graphite, and also PMCs reinforced with E-glass and carbon fibers. Sometimes molds with embedded heaters are used.

The key processes for making PMC parts are filament winding, fiber placement, compression molding, pultrusion, prepreg lay-up, resin film infusion and resin transfer molding. The latter process uses a fiber preform which is placed in a mold.

9.4.2 Metal Matrix Composites

An important consideration in selection of manufacturing processes for MMCs is that reinforcements and matrices can react at elevated temperatures, degrading material properties. To overcome this problem, reinforcements are often coated with barrier materials. Many of the processes for making MMCs with continuous fiber reinforcements are very expensive. However, considerable effort has been devoted to development of relatively inexpensive processes that can make net shape or near-net shape parts that require little or no machining to achieve their final configuration.

Manufacturing processes for MMCs are based on a variety of approaches for combining constituents and consolidating the resulting material: powder metallurgy, ingot metallurgy, plasma spraying, chemical vapor deposition, physical vapor deposition, electrochemical plating, diffusion bonding, hot pressing, remelt casting, pressureless casting, and pressure casting. The last two processes use preforms.

Some MMCs are made by *in situ* reaction. For example, a composite consisting of aluminum reinforced with titanium carbide particles has been made by introducing a gas containing carbon into a molten alloy containing aluminum and titanium.

9.4.3 Ceramic Matrix Composites

As for MMCs, an important consideration in fabrication of CMCs is that reinforcements and matrices can react at high temperatures. An additional issue is that ceramics are very difficult to machine, so that it is desirable to fabricate parts that are close to their final shape. A number of CMC processes have this feature. In addition, some processes make it possible to fabricate CMC parts that would be difficult or impossible to create out of monolithic ceramics.

Key processes for CMCs include chemical vapor infiltration (CVI); infiltration of preforms with slurries, sol-gels, and molten ceramics; *in situ* chemical reaction; sintering; hot pressing; and hot isostatic processing. Another process infiltrates preforms with selected polymers that are then pyrolyzed to form a ceramic material.

9.4.4 Carbon/Carbon Composites

CCCs are primarily made by chemical vapor infiltration (CVI), also called chemical vapor deposition (CVD), and by infiltration of pitch or various resins. Following infiltration, the material is pyrolyzed, which removes most non-carbonaceous elements. This process is repeated several times until the desired material density is achieved.

9.5 APPLICATIONS

Composites are now being used in a large and increasing number of important mechanical engineering applications. In this section, we discuss some of the more significant current and emerging applications.

It is generally known that glass fiber-reinforced polymer (GFRP) composites have been used extensively as engineering materials for decades. The most widely recognized applications are prob-