1

Introduction to Composite Materials

Chapter Objectives

- Define a composite, enumerate advantages and drawbacks of composites over monolithic materials, and discuss factors that influence mechanical properties of a composite.
- Classify composites, introduce common types of fibers and matrices, and manufacturing, mechanical properties, and applications of composites.
- Discuss recycling of composites.
- Introduce terminology used for studying mechanics of composites.

1.1 Introduction

> You are no longer to supply the people with straw for making bricks; let them go and gather their own straw.
>
> **Exodus 5:7**

Israelites using bricks made of clay and reinforced with straw are an early example of application of composites. The individual constituents, clay and straw, could not serve the function by themselves but did when put together. Some believe that the straw was used to keep the clay from cracking, but others suggest that it blunted the sharp cracks in the dry clay.

Historical examples of composites are abundant in the literature. Significant examples include the use of reinforcing mud walls in houses with bamboo shoots, glued laminated wood by Egyptians (1500 B.C.), and laminated metals in forging swords (A.D. 1800). In the 20th century, modern composites were used in the 1930s when glass fibers reinforced resins. Boats and aircraft were built out of these glass composites, commonly called *fiberglass*. Since the 1970s, application of composites has widely increased due to development of new fibers such as carbon, boron, and aramids,* and new composite systems with matrices made of metals and ceramics.

This chapter gives an overview of composite materials. The question–answer style of the chapter is a suitable way to learn the fundamental aspects of this vast subject. In each section, the questions progressively become more specialized and technical in nature.

What is a composite?

A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other. One constituent is called the *reinforcing phase* and the one in which it is embedded is called the *matrix*. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc.

Give some examples of naturally found composites.

Examples include wood, where the lignin matrix is reinforced with cellulose fibers and bones in which the bone-salt plates made of calcium and phosphate ions reinforce soft collagen.

What are advanced composites?

Advanced composites are composite materials that are traditionally used in the aerospace industries. These composites have high performance reinforcements of a thin diameter in a matrix material such as epoxy and aluminum. Examples are graphite/epoxy, Kevlar®†/epoxy, and boron/aluminum composites. These materials have now found applications in commercial industries as well.

Combining two or more materials together to make a composite is more work than just using traditional monolithic metals such as steel and aluminum. What are the advantages of using composites over metals?

Monolithic metals and their alloys cannot always meet the demands of today's advanced technologies. Only by combining several materials can one meet the performance requirements. For example, trusses and benches used in satellites need to be dimensionally stable in space during temperature changes between –256°F (–160°C) and 200°F (93.3°C). Limitations on coefficient of thermal expansion‡ thus are low and may be of the order of ±1 ×

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* Aramids are aromatic compounds of carbon, hydrogen, oxygen, and nitrogen.

† Kevlar® is a registered trademark of E.I. duPont deNemours and Company, Inc., Wilimington, DE.

‡ Coefficient of thermal expansion is the change in length per unit length of a material when heated through a unit temperature. The units are in./in./°F and m/m/°C. A typical value for steel is 6.5×10^{-6} in./in.°F (11.7×10^{-6} m/m°C).

10^{-7} in./in./°F ($\pm 1.8 \times 10^{-7}$ m/m/°C). Monolithic materials cannot meet these requirements; this leaves composites, such as graphite/epoxy, as the only materials to satisfy them.

In many cases, using composites is more efficient. For example, in the highly competitive airline market, one is continuously looking for ways to lower the overall mass of the aircraft without decreasing the stiffness* and strength† of its components. This is possible by replacing conventional metal alloys with composite materials. Even if the composite material costs may be higher, the reduction in the number of parts in an assembly and the savings in fuel costs make them more profitable. Reducing one lbm (0.453 kg) of mass in a commercial aircraft can save up to 360 gal (1360 l) of fuel per year;[1] fuel expenses are 25% of the total operating costs of a commercial airline.[2]

Composites offer several other advantages over conventional materials. These may include improved strength, stiffness, fatigue‡ and impact resistance,** thermal conductivity,†† corrosion resistance,‡‡ etc.

How is the mechanical advantage of composite measured?

For example, the axial deflection, u, of a prismatic rod under an axial load, P, is given by

$$u = \frac{PL}{AE}, \tag{1.1}$$

where

L = length of the rod
E = Young's modulus of elasticity of the material of the rod

Because the mass, M, of the rod is given by

$$M = \rho AL, \tag{1.2}$$

where ρ = density of the material of the rod, we have

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* Stiffness is defined as the resistance of a material to deflection.

† Strength is defined as the stress at which a material fails.

‡ Fatigue resistance is the resistance to the lowering of mechanical properties such as strength and stiffness due to cyclic loading, such as due to take-off and landing of a plane, vibrating a plate, etc.

** Impact resistance is the resistance to damage and to reduction in residual strength to impact loads, such as a bird hitting an airplane or a hammer falling on a car body.

†† Thermal conductivity is the rate of heat flow across a unit area of a material in a unit time, when the temperature gradient is unity in the direction perpendicular to the area.

‡‡ Corrosion resistance is the resistance to corrosion, such as pitting, erosion, galvanic, etc.

$$M = \frac{PL^2}{4} \frac{1}{E/\rho} . \tag{1.3}$$

This implies that the lightest beam for specified deflection under a specified load is one with the highest (E/ρ) value.

Thus, to measure the mechanical advantage, the (E/ρ) ratio is calculated and is called the *specific modulus* (ratio between the Young's modulus* (E) and the density† (ρ) of the material). The other parameter is called the *specific strength* and is defined as the ratio between the strength (σ_{ult}) and the density of the material (ρ), that is,

$$\text{Specific modulus} = \frac{E}{\rho},$$

$$\text{Specific strength} = \frac{\sigma_{ult}}{\rho}.$$

The two ratios are high in composite materials. For example, the strength of a graphite/epoxy unidirectional composite‡ could be the same as steel, but the specific strength is three times that of steel. What does this mean to a designer? Take the simple case of a rod designed to take a fixed axial load. The rod cross section of graphite/epoxy would be same as that of the steel, but the mass of graphite/epoxy rod would be one third of the steel rod. This reduction in mass translates to reduced material and energy costs. Figure 1.1 shows how composites and fibers rate with other traditional materials in terms of specific strength.[3] Note that the unit of specific strength is inches in Figure 1.1 because specific strength and specific modulus are also defined in some texts as

$$\text{Specific modulus} = \frac{E}{\rho g},$$

$$\text{Specific strength} = \frac{\sigma_{ult}}{\rho g}.$$

where g is the acceleration due to gravity (32.2 ft/s^2 or 9.81 m/s^2).

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* Young's modulus of an elastic material is the initial slope of the stress–strain curve.

† Density is the mass of a substance per unit volume.

‡ A unidirectional composite is a composite lamina or rod in which the fibers reinforcing the matrix are oriented in the same direction.

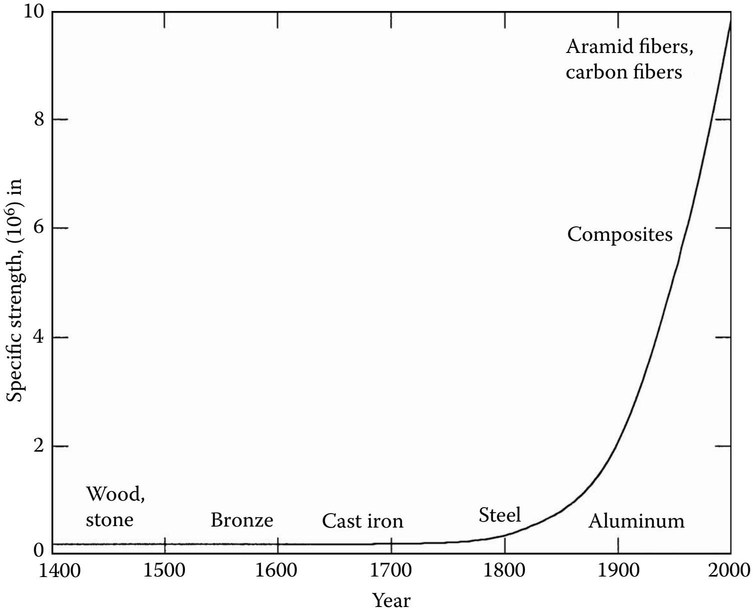

FIGURE 1.1
Specific strength as a function of time of use of materials. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

Values of specific modulus and strength are given in Table 1.1 for typical composite fibers, unidirectional composites,* cross-ply† and quasi-isotropic‡ laminated composites, and monolithic metals.

On a first look, fibers such as graphite, aramid, and glass have a specific modulus several times that of metals, such as steel and aluminum. This gives a false impression about the mechanical advantages of composites because they are made not only of fibers, but also of fibers and matrix combined; matrices generally have lower modulus and strength than fibers. Is the comparison of the specific modulus and specific strength parameters of unidirectional composites to metals now fair? The answer is no for two reasons. First, unidirectional composite structures are acceptable only for carrying simple loads such as uniaxial tension or pure bending. In structures with complex requirements of loading and stiffness, composite structures including angle plies will be necessary. Second, the strengths and elastic moduli of unidirectional composites given in Table 1.1 are those in the direction of the fiber. The strength and elastic moduli perpendicular to the fibers are far less.

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* A unidirectional laminate is a laminate in which all fibers are oriented in the same direction.

† A cross-ply laminate is a laminate in which the layers of unidirectional lamina are oriented at right angles to each other.

‡ Quasi-isotropic laminate behaves similarly to an isotropic material; that is, the elastic properties are the same in all directions.

TABLE 1.1

Specific Modulus and Specific Strength of Typical Fibers, Composites, and Bulk Metals

Material Units	Specific gravity[a]	Young's modulus (Msi)	Ultimate strength (ksi)	Specific modulus (Msi-in.^{3}/lb)	Specific strength (ksi-in.^{3}/lb)
System of Units: USCS					
Graphite fiber	1.8	33.35	299.8	512.9	4610
Aramid fiber	1.4	17.98	200.0	355.5	3959
Glass fiber	2.5	12.33	224.8	136.5	2489
Unidirectional graphite/epoxy	1.6	26.25	217.6	454.1	3764
Unidirectional glass/epoxy	1.8	5.598	154.0	86.09	2368
Cross-ply graphite/epoxy	1.6	13.92	54.10	240.8	935.9
Cross-ply glass/epoxy	1.8	3.420	12.80	52.59	196.8
Quasi-isotropic graphite/epoxy	1.6	10.10	40.10	174.7	693.7
Quasi-isotropic glass/epoxy	1.8	2.750	10.60	42.29	163.0
Steel	7.8	30.00	94.00	106.5	333.6
Aluminum	2.6	10.00	40.00	106.5	425.8

Material Units	Specific gravity	Young's modulus (GPa)	Ultimate strength (MPa)	Specific modulus (GPa-m^3/kg)	Specific strength (MPa-m^3/kg)
System of Units: SI					
Graphite fiber	1.8	230.00	2067	0.1278	1.148
Aramid fiber	1.4	124.00	1379	0.08857	0.9850
Glass fiber	2.5	85.00	1550	0.0340	0.6200
Unidirectional graphite/epoxy	1.6	181.00	1500	0.1131	0.9377
Unidirectional glass/epoxy	1.8	38.60	1062	0.02144	0.5900
Cross-ply graphite/epoxy	1.6	95.98	373.0	0.06000	0.2331
Cross-ply glass/epoxy	1.8	23.58	88.25	0.01310	0.0490
Quasi-isotropic graphite/epoxy	1.6	69.64	276.48	0.04353	0.1728
Quasi-isotropic glass/epoxy	1.8	18.96	73.08	0.01053	0.0406
Steel	7.8	206.84	648.1	0.02652	0.08309
Aluminum	2.6	68.95	275.8	0.02652	0.1061

[a] Specific gravity of a material is the ratio between its density and the density of water.

A comparison is now made between popular types of laminates such as cross-ply and quasi-isotropic laminates. Figure 1.2 shows the specific strength plotted as a function of specific modulus for various fibers, metals, and composites.

Are specific modulus and specific strength the only mechanical parameters used for measuring the relative advantage of composites over metals?

No, it depends on the application.[4] Consider compression of a column, where it may fail due to buckling. The Euler buckling formula gives the critical load at which a long column buckles as[5]

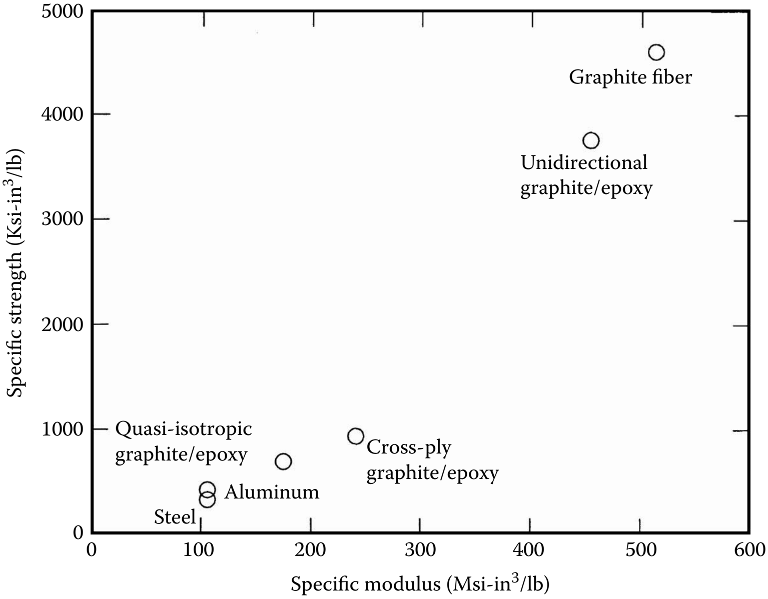

FIGURE 1.2
Specific strength as a function of specific modulus for metals, fibers, and composites.

$$P_{cr} = \frac{\pi^2 EI}{L^2}, \tag{1.4}$$

where

P_{cr} = critical buckling load (lb or N)
E = Young's modulus of column (lb/in.^{2} or N/m^2)
I = second moment of area (in.^{4} or m^4)
L = length of beam (in. or m)

If the column has a circular cross section, the second moment of area is

$$I = \pi \frac{d^4}{64} \tag{1.5}$$

and the mass of the rod is

$$M = \rho \frac{\pi d^2 L}{4}, \tag{1.6}$$

where

M = mass of the beam (lb or kg)
ρ = density of beam (lb/in.^{3} or kg/m^3)
d = diameter of beam (in. or m)

Because the length, L, and the load, P, are constant, we find the mass of the beam by substituting Equation (1.5) and Equation (1.6) in Equation (1.4) as

$$M = \frac{2L^2\sqrt{P_{cr}}}{\sqrt{\pi}} \frac{1}{E^{1/2}/\rho} \, . \tag{1.7}$$

This means that the lightest beam for specified stiffness is one with the highest value of $E^{1/2}/\rho$.

Similarly, we can prove that, for achieving the minimum deflection in a beam under a load along its length, the lightest beam is one with the highest value of $E^{1/3}/\rho$. Typical values of these two parameters, $E^{1/2}/\rho$ and $E^{1/3}/\rho$ for typical fibers, unidirectional composites, cross-ply and quasi-isotropic laminates, steel, and aluminum are given in Table 1.2. Comparing these numbers with metals shows composites drawing a better advantage for these two parameters. Other mechanical parameters for comparing the performance of composites to metals include resistance to fracture, fatigue, impact, and creep.

Yes, composites have distinct advantages over metals. Are there any drawbacks or limitations in using them?

Yes, drawbacks and limitations in use of composites include:

- High cost of fabrication of composites is a critical issue. For example, a part made of graphite/epoxy composite may cost up to 10 to 15 times the material costs. A finished graphite/epoxy composite part may cost as much as \$300 to \$400 per pound (\$650 to \$900 per kilogram). Improvements in processing and manufacturing techniques will lower these costs in the future. Already, manufacturing techniques such as SMC (sheet molding compound) and SRIM (structural reinforcement injection molding) are lowering the cost and production time in manufacturing automobile parts.
- Mechanical characterization of a composite structure is more complex than that of a metal structure. Unlike metals, composite materials are not isotropic, that is, their properties are not the same in all directions. Therefore, they require more material parameters. For example, a single layer of a graphite/epoxy composite requires *nine*

TABLE 1.2

Specific Modulus Parameters E/ρ, $E^{1/2}/\rho$, and $E^{1/3}/\rho$ for Typical Materials

Material Units	Specific gravity	Young's modulus (Msi)	E/ρ (Msi-in.^{3}/lb)	$E^{1/2}/\rho$ (psi$^{1/2}$-in.^{3}/lb)	$E^{1/3}/\rho$ (psi$^{1/3}$-in.^{3}/lb)
System of Units: USCS					
Graphite fiber	1.8	33.35	512.8	88,806	4,950
Kevlar fiber	1.4	17.98	355.5	83,836	5,180
Glass fiber	2.5	12.33	136.5	38,878	2,558
Unidirectional graphite/epoxy	1.6	26.25	454.1	88,636	5,141
Unidirectional glass/epoxy	1.8	5.60	86.09	36,384	2,730
Cross-ply graphite/epoxy	1.6	13.92	240.8	64,545	4,162
Cross-ply glass/epoxy	1.8	3.42	52.59	28,438	2,317
Quasi-isotropic graphite/epoxy	1.6	10.10	174.7	54,980	3,740
Quasi-isotropic glass/epoxy	1.8	2.75	42.29	25,501	2,154
Steel	7.8	30.00	106.5	19,437	1,103
Aluminum	2.6	10.00	106.5	33,666	2,294

Material Units	Specific gravity	Young's modulus (GPa)	E/ρ (GPa-m^3/kg)	$E^{1/2}/\rho$ (Pa-m^3/kg)	$E^{1/3}/\rho$ (Pa$^{1/3}$-m^3/kg)
System of Units: SI					
Graphite fiber	1.8	230.00	0.1278	266.4	3.404
Kevlar fiber	1.4	124.00	0.08857	251.5	3.562
Glass fiber	2.5	85.00	0.034	116.6	1.759
Unidirectional graphite/epoxy	1.6	181.00	0.1131	265.9	3.535
Unidirectional glass/epoxy	1.8	38.60	0.02144	109.1	1.878
Cross-ply graphite/epoxy	1.6	95.98	0.060	193.6	2.862
Cross-ply glass/epoxy	1.8	23.58	0.0131	85.31	1.593
Quasi-isotropic graphite/epoxy	1.6	69.64	0.04353	164.9	2.571
Quasi-isotropic glass/epoxy	1.8	18.96	0.01053	76.50	1.481
Steel	7.8	206.84	0.02652	58.3	0.7582
Aluminum	2.6	68.95	0.02662	101.0	1.577

stiffness and strength constants for conducting mechanical analysis. In the case of a monolithic material such as steel, one requires only *four* stiffness and strength constants. Such complexity makes structural analysis computationally and experimentally more complicated and intensive. In addition, evaluation and measurement techniques of some composite properties, such as compressive strengths, are still being debated.

- Repair of composites is not a simple process compared to that for metals. Sometimes critical flaws and cracks in composite structures may go undetected.

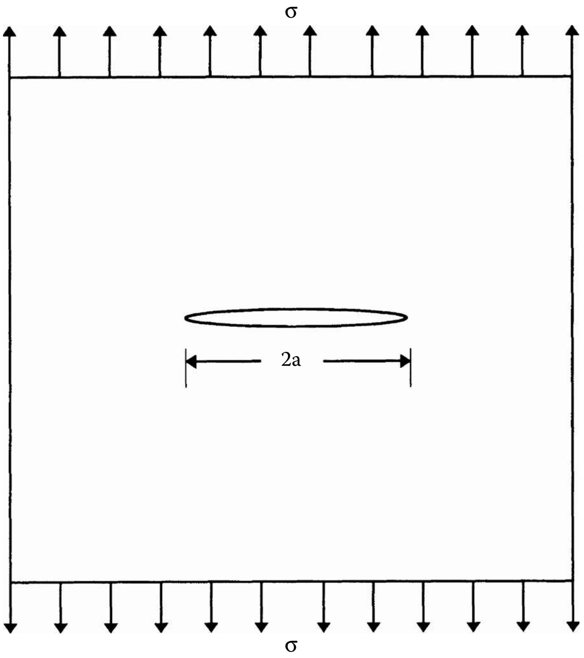

FIGURE 1.3
A uniformly loaded plate with a crack.

- Composites do not have a high combination of strength and fracture toughness* compared to metals. In Figure 1.4, a plot is shown for fracture toughness vs. yield strength for a 1-in. (25-mm) thick material.[3] Metals show an excellent combination of strength and fracture toughness compared to composites. (Note: The transition areas in Figure 1.4 will change with change in the thickness of the specimen.)
- Composites do not necessarily give higher performance in all the properties used for material selection. In Figure 1.5, six primary material selection parameters — strength, toughness, formability,

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* In a material with a crack, the value of the stress intensity factor gives the measure of stresses in the crack tip region. For example, for an infinite plate with a crack of length $2a$ under a uniaxial load σ (Figure 1.3), the stress intensity factor is

$$K = \sigma\sqrt{\pi a} \ .$$

If the stress intensity factor at the crack tip is greater than the critical stress intensity factor of the material, the crack will grow. The greater the value of the critical stress intensity factor is, the tougher the material is. The critical stress intensity factor is called the fracture toughness of the material. Typical values of fracture toughness are $23.66 \text{ ksi}\sqrt{\text{in.}}$ $(26 \text{ MPa}\sqrt{\text{m}})$ for aluminum and $25.48 \text{ ksi}\sqrt{\text{in.}}$ $(28 \text{ MPa}\sqrt{\text{m}})$ for steel.

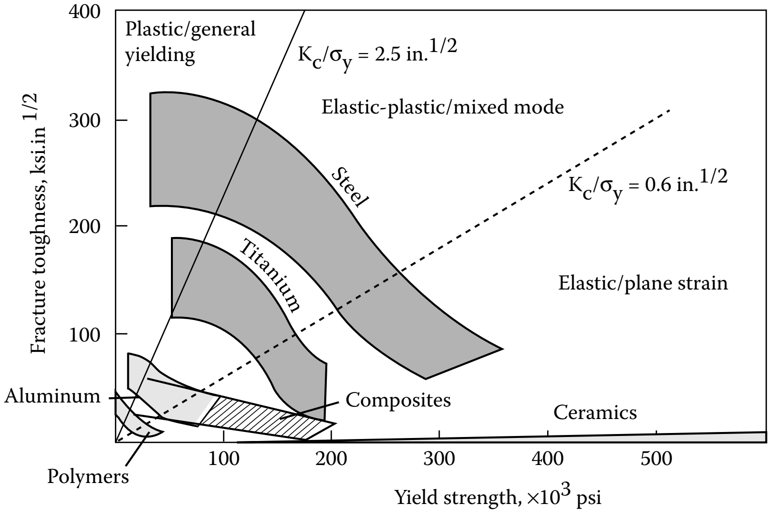

FIGURE 1.4
Fracture toughness as a function of yield strength for monolithic metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

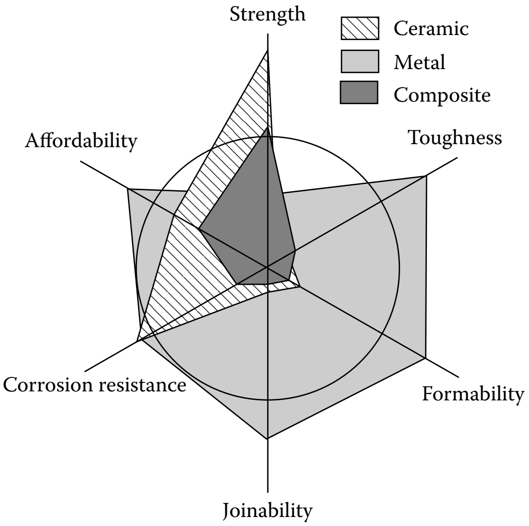

FIGURE 1.5
Primary material selection parameters for a hypothetical situation for metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

joinability, corrosion resistance, and affordability — are plotted.[3] If the values at the circumference are considered as the normalized required property level for a particular application, the shaded areas show values provided by ceramics, metals, and metal–ceramic composites. Clearly, composites show better strength than metals, but lower values for other material selection parameters.

Why are fiber reinforcements of a thin diameter?

The main reasons for using fibers of thin diameter are the following:

- Actual strength of materials is several magnitudes lower than the theoretical strength. This difference is due to the inherent flaws in the material. Removing these flaws can increase the strength of the material. As the fibers become smaller in diameter, the chances of an inherent flaw in the material are reduced. A steel plate may have strength of 100 ksi (689 MPa), while a wire made from this steel plate can have strength of 600 ksi (4100 MPa). Figure 1.6 shows how the strength of a carbon fiber increases with the decrease in its diameter.[6]

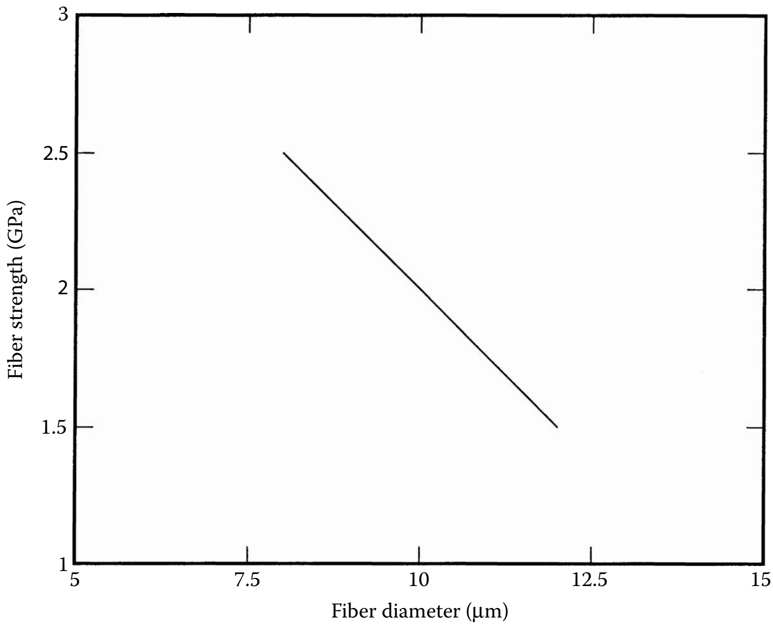

FIGURE 1.6
Fiber strength as a function of fiber diameter for carbon fibers. (Reprinted from Lamotte, E. De, and Perry, A.J., *Fibre Sci. Technol.*, 3, 159, 1970. With permission from Elsevier.)

- For higher ductility* and toughness, and better transfer of loads from the matrix to fiber, composites require larger surface area of the fiber–matrix interface. For the same volume fraction of fibers in a composite, the area of the fiber–matrix interface is inversely proportional to the diameter of the fiber and is proved as follows.

  Assume a lamina consisting of N fibers of diameter D. The fiber–matrix interface area in this lamina is

  $$A_I = N\,\pi\,D\,L. \tag{1.8}$$

  If one replaces the fibers of diameter, D, by fibers of diameter, d, then the number of fibers, n, to keep the fiber volume the same would be

  $$n = N\left(\frac{D}{d}\right)^2. \tag{1.9}$$

  Then, the fiber–matrix interface area in the resulting lamina would be

  $$\begin{aligned} A_{II} &= n\,\pi\,d\,L. \\ &= \frac{N\pi D^2 L}{d} \\ &= \frac{4\,(\text{Volume of fibers})}{d}. \end{aligned} \tag{1.10}$$

  This implies that, for a fixed fiber volume in a given volume of composite, the area of the fiber–matrix interface is inversely proportional to the diameter of the fiber.

- Fibers able to bend without breaking are required in manufacturing of composite materials, especially for woven fabric composites. Ability to bend increases with a decrease in the fiber diameter and is measured as flexibility. Flexibility is defined as the inverse of bending stiffness and is proportional to the inverse of the product of the elastic modulus of the fiber and the fourth power of its diameter; it can be proved as follows.

  Bending stiffness is the resistance to bending moments. According to the Strength of Materials course, if a beam is subjected to a pure bending moment, M,

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[*] Ductility is the ability of a material to deform without fracturing. It is measured by extending a rod until fracture and measuring the initial (A_i) and final (A_f) cross-sectional area. Then ductility is defined as $R = 1 - (A_f/A_i)$.

$$\frac{d^2v}{dx^2} = \frac{M}{EI}, \tag{1.11}$$

where

v = deflection of the centroidal line (in. or m)
E = Young's modulus of the beam (psi or Pa)
I = second moment of area (in.^{4} or m^4)
x = coordinate along the length of beam (in. or m)

The bending stiffness, then, is EI and the flexibility is simply the inverse of EI. Because the second moment of area of a cylindrical beam of diameter d is

$$I = \frac{\pi d^4}{64}, \tag{1.12}$$

then

$$\text{Flexibility} \propto \frac{1}{Ed^4}. \tag{1.13}$$

For a particular material, unlike strength, the Young's modulus does not change appreciably as a function of its diameter. Therefore, the flexibility for a particular material is inversely proportional to the fourth power of the diameter.

What fiber factors contribute to the mechanical performance of a composite?

Four fiber factors contribute to the mechanical performance of a composite[7]:

- *Length*: The fibers can be long or short. Long, continuous fibers are easy to orient and process, but short fibers cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish, and dimensional stability. However, short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures. Short fibers have fewer flaws and therefore have higher strength.
- *Orientation*: Fibers oriented in one direction give very high stiffness and strength in that direction. If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations. However, for the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of unidirectional composites.

- *Shape*: The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and square-shaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.
- *Material*: The material of the fiber directly influences the mechanical performance of a composite. Fibers are generally expected to have high elastic moduli and strengths. This expectation and cost have been key factors in the graphite, aramids, and glass dominating the fiber market for composites.

What are the matrix factors that contribute to the mechanical performance of composites?

Use of fibers by themselves is limited, with the exceptions of ropes and cables. Therefore, fibers are used as reinforcement to matrices. The matrix functions include binding the fibers together, protecting fibers from the environment, shielding from damage due to handling, and distributing the load to fibers. Although matrices by themselves generally have low mechanical properties compared to those of fibers, the matrix influences many mechanical properties of the composite. These properties include transverse modulus and strength, shear modulus and strength, compressive strength, interlaminar shear strength, thermal expansion coefficient, thermal resistance, and fatigue strength.

Other than the fiber and the matrix, what other factors influence the mechanical performance of a composite?

Other factors include the fiber–matrix interface. It determines how well the matrix transfers the load to the fibers. Chemical, mechanical, and reaction bonding may form the interface. In most cases, more than one type of bonding occurs.

- Chemical bonding is formed between the fiber surface and the matrix. Some fibers bond naturally to the matrix and others do not. Coupling agents* are often added to form a chemical bond.
- The natural roughness or etching of the fiber surface causing interlocking may form a mechanical bond between the fiber and matrix.
- If the thermal expansion coefficient of the matrix is higher than that of the fiber, and the manufacturing temperatures are higher than the operating temperatures, the matrix will radially shrink more than the fiber. This causes the matrix to compress around the fiber.

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* Coupling agents are compounds applied to fiber surfaces to improve the bond between the fiber and matrix. For example, silane finish is applied to glass fibers to increase adhesion with epoxy matrix.

- Reaction bonding occurs when atoms or molecules of the fiber and the matrix diffuse into each other at the interface. This interdiffusion often creates a distinct interfacial layer, called the interphase, with different properties from that of the fiber or the matrix. Although this thin interfacial layer helps to form a bond, it also forms microcracks in the fiber. These microcracks reduce the strength of the fiber and thus that of the composite.

Weak or cracked interfaces can cause failure in composites and reduce the properties influenced by the matrix. They also allow environmental hazards such as hot gases and moisture to attack the fibers.

Although a strong bond is a requirement in transferring loads from the matrix to the fiber, weak debonding of the fiber–matrix interface is used advantageously in ceramic matrix composites. Weak interfaces blunt matrix cracks and deflect them along the interface. This is the main source of improving toughness of such composites up to five times that of the monolithic ceramics.

What is the world market of composites?

The world market for composites is only 10×10^9 US dollars as compared to more than 450×10^9 US dollars for steel. The annual growth of composites is at a steady rate of 10%. Presently, composite shipments are about 3×10^9 lb annually. Figure 1.7 gives the relative market share of US composite shipments and shows transportation clearly leading in their use. Table 1.3 shows the market share of composites since 1990.

1.2 Classification

How are composites classified?

Composites are classified by the geometry of the reinforcement — particulate, flake, and fibers (Figure 1.8) — or by the type of matrix — polymer, metal, ceramic, and carbon.

- *Particulate* composites consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.
- *Flake* composites consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake compos-

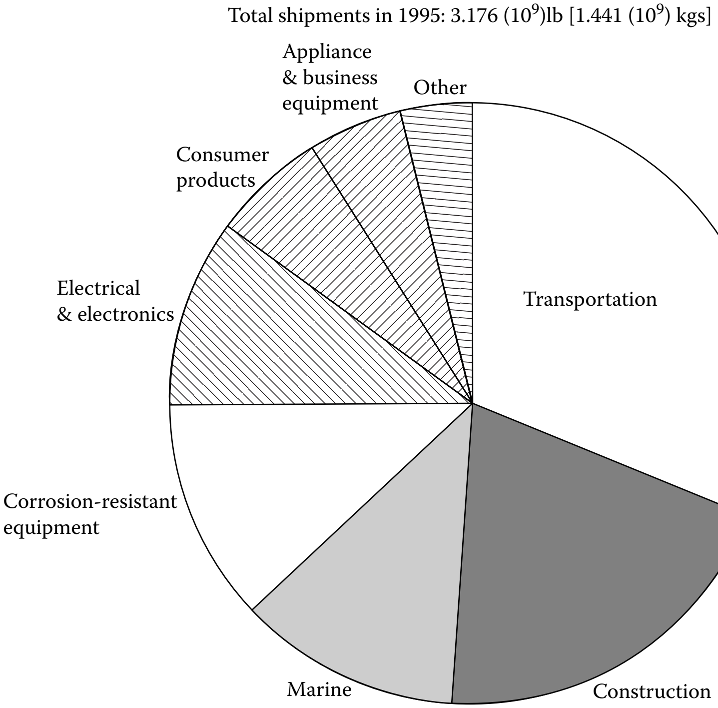
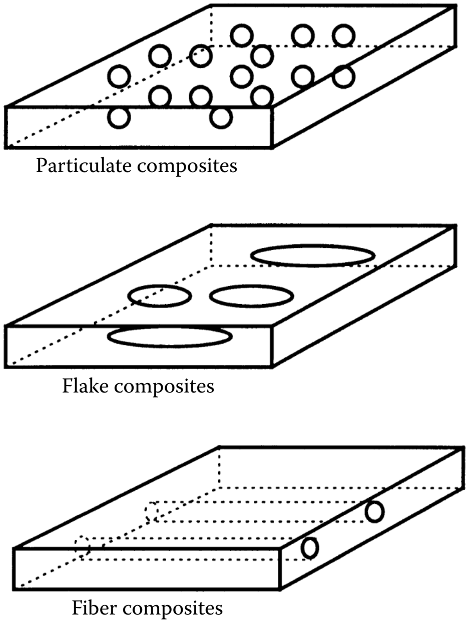


FIGURE 1.7
Approximate shipments of polymer-based composites in 1995. (Source: Data used in figure published with permission of the SPI, Inc.; http://www.socplas.org.)

TABLE 1.3
U.S. Composites Shipment in 10^6 lb, Including Reinforced Thermoset and Thermoplastic Resin Composites, Reinforcements, and Fillers

Markets	1990	1991	1992	1993	1994	1995
Aircraft/aerospace/military	39	38.7	32.3	25.4	24.2	24.0
Appliance/business equipment	153	135.2	143.2	147.5	160.7	166.5
Construction	468	420.0	483.0	530.0	596.9	626.9
Consumer products	165	148.7	162.2	165.7	174.8	183.6
Corrosion-resistant equipment	350	355.0	332.3	352.0	376.3	394.6
Electrical/electronic	241	231.1	260.0	274.9	299.3	315.1
Marine	375	275.0	304.4	319.3	363.5	375.1
Transportation	705	682.2	750.0	822.1	945.6	984.0
Other	79	73.8	83.4	89.3	101.8	106.6
TOTAL	**2575**	**2360**	**2551**	**2726**	**3043.1**	**3176.4**

Source: Published with permission of the SPI, Inc.



Particulate composites

Flake composites

Fiber composites

FIGURE 1.8
Types of composites based on reinforcement shape.

ites provide advantages such as high out-of-plane flexural modulus,* higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.

- *Fiber* composites consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic† and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics such as calcium–alumino silicate. Continuous fiber composites are emphasized in this book and are further discussed in this chapter by the types of matrices: polymer, metal, ceramic, and carbon. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.
- *Nanocomposites* consist of materials that are of the scale of nanometers (10^{-9} m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm. At this scale, the

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* Out of plane flexural stiffness is the resistance to deflection under bending that is out of the plane, such as bending caused by a heavy stone placed on a simply supported plate.

† Anisotropic materials are the opposite of isotropic materials like steel and aluminum; they have different properties in different directions. For example, the Young's modulus of a piece of wood is higher (different) in the direction of the grain than in the direction perpendicular to the grain. In comparison, a piece of steel has the same Young's modulus in all directions.

properties of materials are different from those of the bulk material. Generally, advanced composite materials have constituents on the microscale (10^{-6} m). By having materials at the nanometer scale, most of the properties of the resulting composite material are better than the ones at the microscale. Not all properties of nanocomposites are better; in some cases, toughness and impact strength can decrease.

Applications of nanocomposites include packaging applications for the military in which nanocomposite films show improvement in properties such as elastic modulus, and transmission rates for water vapor, heat distortion, and oxygen.[8]

Body side molding of the 2004 Chevrolet Impala is made of olefin-based nanocomposites.[9] This reduced the weight of the molding by 7% and improved its surface quality. General Motors™ currently uses 540,000 lb of nanocomposite materials per year.

Rubber containing just a few parts per million of metal conducts electricity in harsh conditions just like solid metal. Called Metal Rubber®, it is fabricated molecule by molecule by a process called electrostatic self-assembly. Awaited applications of the Metal Rubber include artificial muscles, smart clothes, flexible wires, and circuits for portable electronics.[10]

1.2.1 Polymer Matrix Composites

What are the most common advanced composites?

The most common advanced composites are polymer matrix composites (PMCs) consisting of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin diameter fibers (e.g., graphite, aramids, boron). For example, graphite/epoxy composites are approximately five times stronger than steel on a weight-for-weight basis. The reasons why they are the most common composites include their low cost, high strength, and simple manufacturing principles.

What are the drawbacks of polymer matrix composites?

The main drawbacks of PMCs include low operating temperatures, high coefficients of thermal and moisture expansion,* and low elastic properties in certain directions.

What are the typical mechanical properties of some polymer matrix composites? Compare these properties with metals.

Table 1.4 gives typical mechanical properties of common polymer matrix composites.

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* Some materials, such as polymers, absorb or deabsorb moisture that results in dimensional changes. The coefficient of moisture expansion is the change in length per unit length per unit mass of moisture absorbed per unit mass of the substance.

TABLE 1.4

Typical Mechanical Properties of Polymer Matrix Composites and Monolithic Materials

Property	Units	Graphite/ epoxy	Glass/ epoxy	Steel	Aluminum
System of units: USCS					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	Msi	26.25	5.598	30.0	10.0
Ultimate tensile strength	ksi	217.6	154.0	94.0	40.0
Coefficient of thermal expansion	μin./in./°F	0.01111	4.778	6.5	12.8
System of units: SI					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	GPa	181.0	38.6	206.8	68.95
Ultimate tensile strength	MPa	150.0	1062	648.1	275.8
Coefficient of thermal expansion	μm/m/°C	0.02	8.6	11.7	23

TABLE 1.5

Typical Mechanical Properties of Fibers Used in Polymer Matrix Composites

Property	Units	Graphite	Aramid	Glass	Steel	Aluminum
System of units: USCS						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	Msi	33.35	17.98	12.33	30	10.0
Ultimate tensile strength	ksi	299.8	200.0	224.8	94	40.0
Axial coefficient of thermal expansion	μin./in./°F	–0.722	–2.778	2.778	6.5	12.8
System of units: SI						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	GPa	230	124	85	206.8	68.95
Ultimate tensile strength	MPa	2067	1379	1550	648.1	275.8
Axial coefficient of thermal expansion	μm/m/°C	–1.3	–5	5	11.7	23

Give names of various fibers used in advanced polymer composites.

The most common fibers used are glass, graphite, and Kevlar. Typical properties of these fibers compared with bulk steel and aluminum are given in Table 1.5.

Give a description of the glass fiber.

Glass is the most common fiber used in polymer matrix composites. Its advantages include its high strength, low cost, high chemical resistance, and good insulating properties. The drawbacks include low elastic modulus,

TABLE 1.6

Comparison of Properties of E-Glass and S-Glass

Property	Units	E-Glass	S-Glass
System of units: USCS			
Specific gravity	—	2.54	2.49
Young's modulus	Msi	10.5	12.4
Ultimate tensile strength	ksi	500	665
Coefficient of thermal expansion	μin./in./°F	2.8	3.1
System of units: SI			
Specific gravity	—	2.54	2.49
Young's modulus	GPa	72.40	85.50
Ultimate tensile strength	MPa	3447	4585
Coefficient of thermal expansion	μm/m/°C	5.04	5.58

TABLE 1.7

Chemical Composition of E-Glass and S-Glass Fibers

	% Weight	
Material	**E-Glass**	**S-Glass**
Silicon oxide	54	64
Aluminum oxide	15	25
Calcium oxide	17	0.01
Magnesium oxide	4.5	10
Boron oxide	8	0.01
Others	1.5	0.8

poor adhesion to polymers, high specific gravity, sensitivity to abrasion (reduces tensile strength), and low fatigue strength.

Types: The main types are E-glass (also called "fiberglass") and S-glass. The "E" in E-glass stands for electrical because it was designed for electrical applications. However, it is used for many other purposes now, such as decorations and structural applications. The "S" in S-glass stands for higher content of silica. It retains its strength at high temperatures compared to E-glass and has higher fatigue strength. It is used mainly for aerospace applications. Some property differences are given in Table 1.6.

The difference in the properties is due to the compositions of E-glass and S-glass fibers. The main elements in the two types of fibers are given in Table 1.7.

Other types available commercially are C-glass ("C" stands for corrosion) used in chemical environments, such as storage tanks; R-glass used in structural applications such as construction; D-glass (dielectric) used for applications requiring low dielectric constants, such as radomes; and A-glass (appearance) used to improve surface appearance. Combination types such

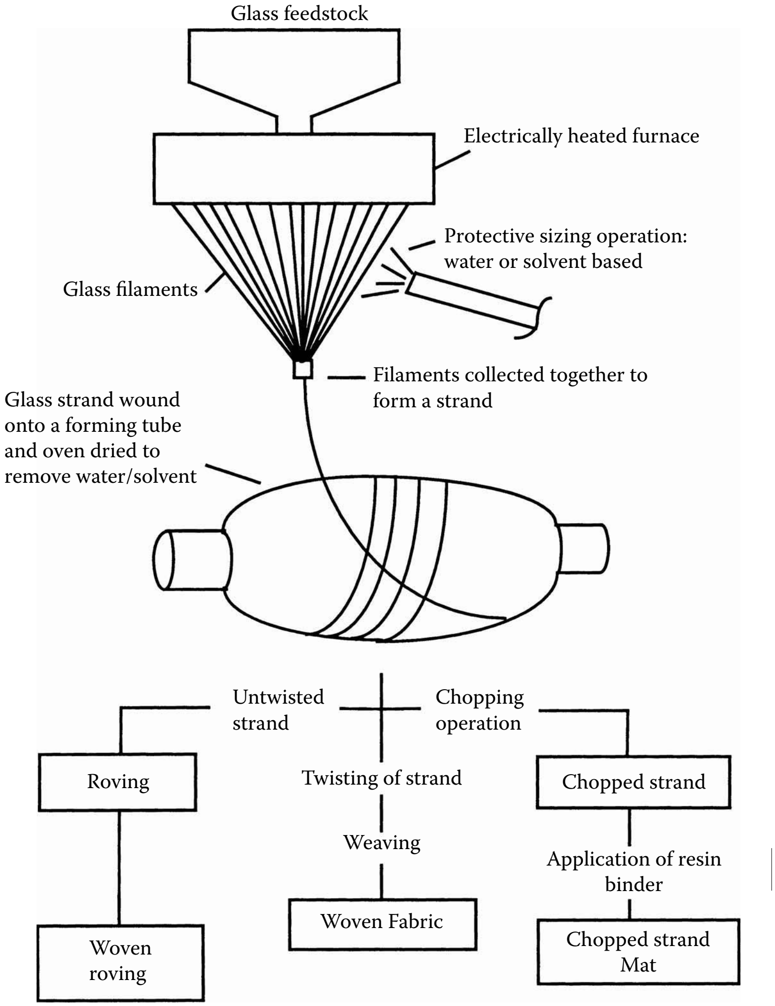

FIGURE 1.9
Schematic of manufacturing glass fibers and available glass forms. (From Bishop, W., in *Advanced Composites*, Partridge, I.K., Ed., Kluwer Academic Publishers, London, 1990, Figure 4, p. 177. Reproduced with kind permission of Springer.)

as E-CR glass ("E-CR" stands for electrical and corrosion resistance) and AR glass (alkali resistant) also exist.

Manufacturing: Glass fibers are made generally by drawing from a melt[11] as shown in Figure 1.9. The melt is formed in a refractory furnace at about 2550°F (1400°C) from a mixture that includes sand, limestone, and alumina. The melt is stirred and maintained at a constant temperature. It passes through as many as 250 heated platinum alloy nozzles of about 394 µin. (10 µm) diameter, where it is drawn into filaments of needed size at high speeds of about 361 mi/h (25 m/s). These fibers are sprayed with an organic sizing solution before they are drawn. The sizing solution is a mixture of binders, lubricants, and coupling and antistatic agents; binders allow filaments to be packed in strands, lubricants prevent abrasion of filaments, and coupling agents give better adhesion between the inorganic glass fiber and the organic matrix.

Fibers are then drawn into strands and wound on a forming tube. Strands are groups of more than 204 filaments. The wound array of strands is then removed and dried in an oven to remove any water or sizing solutions. The glass strand can then be converted into several forms as shown in Figure 1.9. Different forms of various fibers are shown in Figure 1.10.

Give a description of graphite fibers.

Graphite fibers are very common in high-modulus and high-strength applications such as aircraft components, etc. The advantages of graphite fibers include high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength. The drawbacks include high cost, low impact resistance, and high electrical conductivity.

Manufacturing: Graphite fibers have been available since the late 1800s. However, only since the early 1960s has the manufacturing of graphite fibers taken off. Graphite fibers are generally manufactured from three precursor materials: rayon, polyacrylonitrile (PAN), and pitch. PAN is the most popular precursor and the process to manufacture graphite fibers from it is given next (Figure 1.11).

PAN fibers are first stretched five to ten times their length to improve their mechanical properties and then passed through three heating processes. In the first process, called stabilization, the fiber is passed through a furnace between 392 and 572°F (200 and 300°C) to stabilize its dimensions during the subsequent high-temperature processes. In the second process, called carbonization, it is pyrolized* in an inert atmosphere of nitrogen or argon between 1832 and 2732°F (1000 and 1500°C). In the last process, called graphitization, it is heat treated above 4532°F (2500°C). The graphitization yields a microstructure that is more graphitic than that produced by carbonization. The fibers may also be subjected to tension in the last two heating processes to develop fibers with a higher degree of orientation.

At the end of this three-step heat treatment process, the fibers are surface treated to develop fiber adhesion and increase laminar shear strength when they are used in composite structures. They are then collected on a spool.

Properties: Table 1.8 gives properties of graphite fibers obtained from two different precursors.

Are carbon and graphite the same?

No,[7] they are different. Carbon fibers have 93 to 95% carbon content, but graphite has more than 99% carbon content. Also, carbon fibers are produced

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* Pyrolysis is defined as the decomposition of a complex organic substance to one of a simpler structure by means of heat.

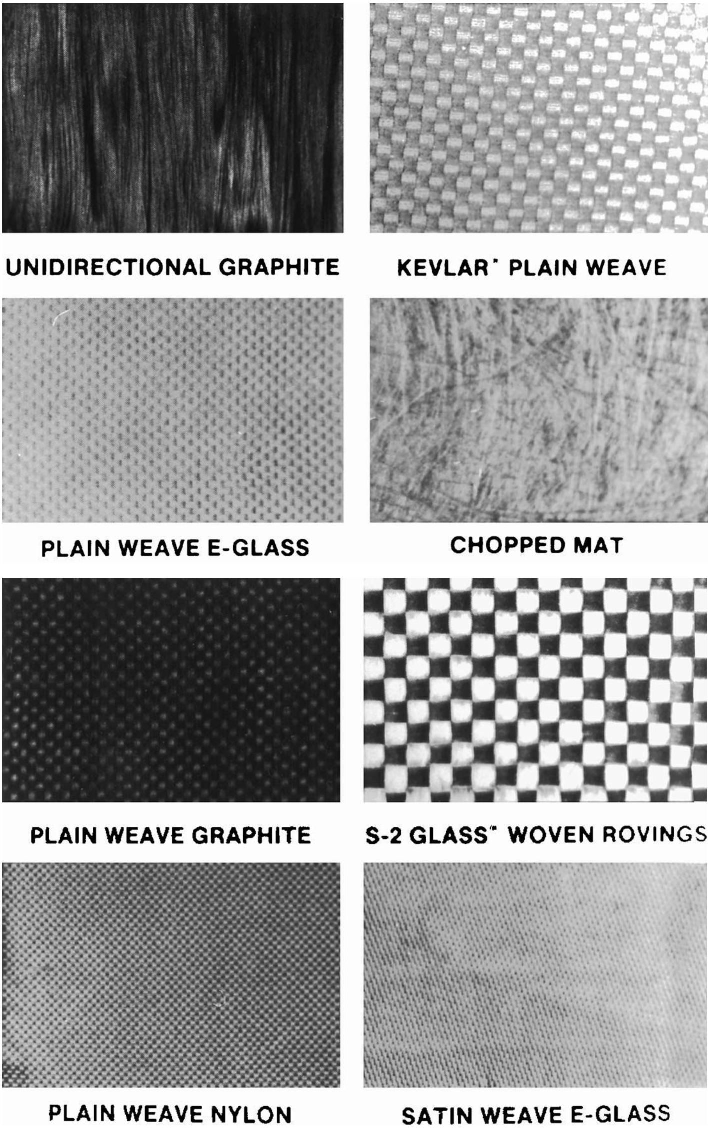

FIGURE 1.10
Forms of available fibers. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

at 2400°F (1316°C), and graphite fibers are typically produced in excess of 3400°F (1900°C).

Give a description of the aramid fiber.

An aramid fiber is an aromatic organic compound made of carbon, hydrogen, oxygen, and nitrogen. Its advantages are low density, high tensile

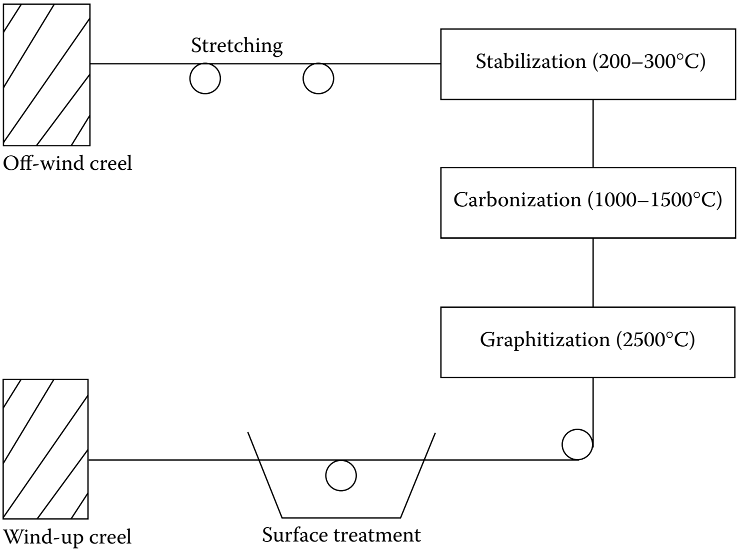

FIGURE 1.11
Stages of manufacturing a carbon fiber from PAN-based precursors.

TABLE 1.8
Mechanical Properties of Two Typical Graphite Fibers

Property	Units	PITCH	PAN
System of units: USCS			
Specific gravity	—	1.99	1.78
Young's modulus	Msi	55	35
Ultimate tensile strength	ksi	250	500
Axial coefficient of thermal expansion	μin/in/°F	–0.3	–0.7
System of units: SI			
Specific gravity	—	1.99	1.78
Young's modulus	GPa	379.2	241.3
Ultimate tensile strength	MPa	1723	3447
Axial coefficient of thermal expansion	μm/m/°C	–0.54	–1.26

strength, low cost, and high impact resistance. Its drawbacks include low compressive properties and degradation in sunlight.

Types: The two main types of aramid fibers are Kevlar 29®* and Kevlar 49®†. Both types of Kevlar fibers have similar specific strengths, but Kevlar 49 has a higher specific stiffness. Kevlar 29 is mainly used in bulletproof

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[*] Kevlar 29 is a registered trademark of E.I. duPont deNemours and Company, Inc., Wilmington, DE.

[†] Kevlar 49 is a registered trademark of E.I. duPont deNemours and Company, Inc., Wilmington, DE.

TABLE 1.9

Properties of Kevlar Fibers

Property	Units	Kevlar 29	Kevlar 49
System of units: USCS			
Specific gravity	—	1.44	1.48
Young's modulus	Msi	9	19
Ultimate tensile strength	ksi	525	525
Axial coefficient of thermal expansion	μin./in./°F	–1.111	–1.111
System of units: SI			
Specific gravity	—	1.44	1.48
Young's modulus	GPa	62.05	131.0
Ultimate tensile strength	MPa	3620	3620
Axial coefficient of thermal expansion	μm/m/°C	–2	–2

vests, ropes, and cables. High performance applications in the aircraft industry use Kevlar 49. Table 1.9 gives the relative properties of Kevlar 29 and Kevlar 49.

Manufacturing: The fiber is produced by making a solution of proprietary polymers and strong acids such as sulfuric acid. The solution is then extruded into hot cylinders at 392°F (200°C), washed, and dried on spools. The fiber is then stretched and drawn to increase its strength and stiffness.

Give names of various polymers used in advanced polymer composites.

These polymers include epoxy, phenolics, acrylic, urethane, and polyamide.

Why are there so many resin systems in advanced polymer composites?

Each polymer has its advantages and drawbacks in its use[12]:

- Polyesters: The advantages are low cost and the ability to be made translucent; drawbacks include service temperatures below 170°F (77°C), brittleness, and high shrinkage* of as much as 8% during curing.
- Phenolics: The advantages are low cost and high mechanical strength; drawbacks include high void content.
- Epoxies: The advantages are high mechanical strength and good adherence to metals and glasses; drawbacks are high cost and difficulty in processing.

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* Shrinkage in resins is found by measuring the density of the resin before and after cross-linking. If ρ is the density before cross-linking and ρ′ is the density after cross-linking. The percent shrinkage is defined as shrinkage = $(\rho' - \rho)/\rho' \times 100$.

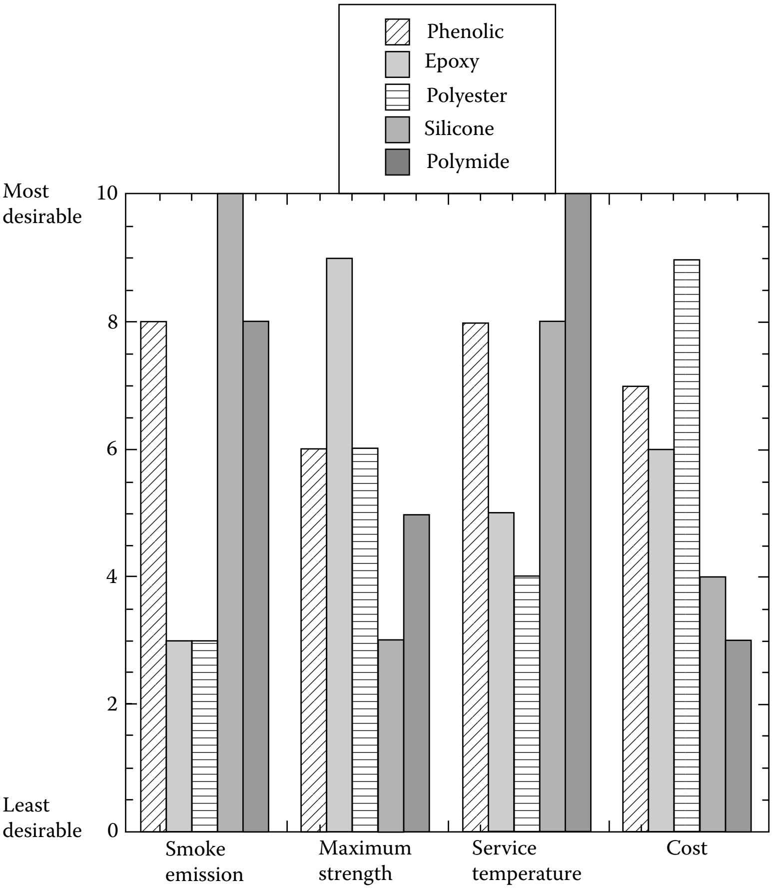

FIGURE 1.12
Comparison of performance of several common matrices used in polymer matrix composites. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

As can be seen, each of the resin systems has its advantages and drawbacks. The use of a particular system depends on the application. These considerations include mechanical strength, cost, smoke emission, temperature excursions, etc. Figure 1.12 shows the comparison of five common resins based on smoke emission, strength, service temperature, and cost.[12]

Give a description of epoxy.

Epoxy resins are the most commonly used resins. They are low molecular weight organic liquids containing epoxide groups. Epoxide has three members in its ring: one oxygen and two carbon atoms. The reaction of epichlorohydrin with phenols or aromatic amines makes most epoxies. Hardeners,*

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* Hardeners are substances that are added to polymers for aiding in curing of composites.

TABLE 1.10

Room Temperature Properties of a Typical Epoxy

Property	Units	Value
System of units: USCS		
Specific gravity	—	1.28
Young's modulus	Msi	0.55
Ultimate tensile strength	ksi	12.0
System of units: SI		
Specific gravity	—	1.28
Young's modulus	GPa	3.792
Ultimate tensile strength	MPa	82.74

plasticizers,* and fillers† are also added to produce epoxies with a wide range of properties of viscosity, impact, degradation, etc. The room temperature properties of a typical epoxy are given in Table 1.10.

Epoxy is the most common type of matrix material. Why?

Although epoxy is costlier than other polymer matrices, it is the most popular PMC matrix. More than two-thirds of the polymer matrices used in aerospace applications are epoxy based. The main reasons why epoxy is the most used polymer matrix material are

- High strength
- Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing
- Low volatility during cure
- Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement
- Available in more than 20 grades to meet specific property and processing requirements

Polymers are classified as thermosets and thermoplastics. What is the difference between the two? Give some examples of both.

Thermoset polymers are insoluble and infusible after cure because the chains are rigidly joined with strong covalent bonds; thermoplastics are formable at high temperatures and pressure because the bonds are weak and

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* Plasticizers are lubricants that improve the toughness, flexibility, processibility, and ductility of polymers. This improvement is generally at the expense of lower strength.

† Fillers are ingredients added to enhance properties such as strength, surface texture, and ultraviolet absorption of a polymer, and to lower the cost of polymers. Typical examples include chopped fabric and wood flour.

of the van der Waals type. Typical examples of thermoset include epoxies, polyesters, phenolics, and polyamide; typical examples of thermoplastics include polyethylene, polystyrene, polyether–ether–ketone (PEEK), and polyphenylene sulfide (PPS). The differences between thermosets and thermoplastics are given in the following table.[13]

Thermoplastics	Thermoset
Soften on heating and pressure, and thus easy to repair	Decompose on heating
High strains to failure	Low strains to failure
Indefinite shelf life	Definite shelf life
Can be reprocessed	Cannot be reprocessed
Not tacky and easy to handle	Tacky
Short cure cycles	Long cure cycles
Higher fabrication temperature and viscosities have made it difficult to process	Lower fabrication temperature
Excellent solvent resistance	Fair solvent resistance

What are prepregs?

Prepregs are a ready-made tape composed of fibers in a polymer matrix (Figure 1.13). They are available in standard widths from 3 to 50 in. (76 to 1270 mm). Depending on whether the polymer matrix is thermoset or thermoplastic, the tape is stored in a refrigerator or at room temperature, respectively. One can lay these tapes manually or mechanically at various orientations to make a composite structure. Vacuum bagging and curing under high pressures and temperatures may follow.

Figure 1.14 shows the schematic of how a prepreg is made.[14] A row of fibers is passed through a resin bath. The resin-impregnated fibers are then

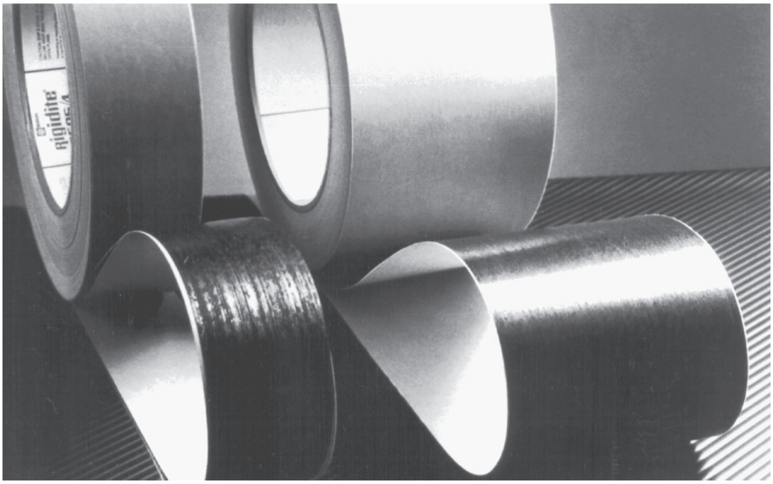

FIGURE 1.13
Boron/epoxy prepreg tape. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

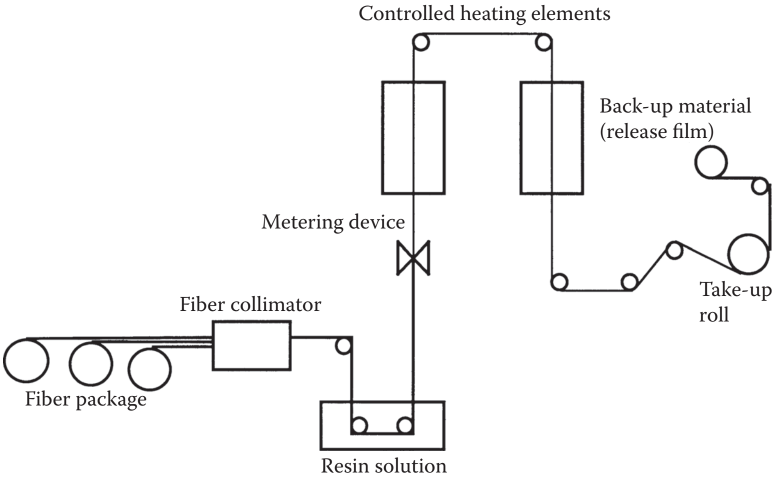

FIGURE 1.14
Schematic of prepreg manufacturing. (Reprinted from Mallick, P.K., *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*, Marcel Dekker, Inc., New York, Chap. 2, 1988, p. 62. Courtesy of CRC Press, Boca Raton, FL.)

heated to advance the curing reaction from A-stage* to the B-stage. A release film is now wound over a take-up roll and backed with a release film. The release film keeps the prepregs from sticking to each other during storage. Give examples of how a polymer matrix composite is manufactured.

Techniques of manufacturing a polymer matrix composite include *filament winding* (used generally for making pipes and tanks to handle chemicals), *autoclave forming* (used to make complex shapes and flat panels for structures in which low void content and high quality are important), and *resin transfer molding* (used extensively in the automotive industry because short production runs are necessary).

Filament winding: Fibers are impregnated with a resin by drawing them through an in-line resin bath (wet winding) (Figure 1.16) or prepregs (dry winding) are wound over a mandrel. Wet winding is inexpensive and lets one control the properties of the composite. Dry winding is cleaner, but more expensive and thus quite uncommon.

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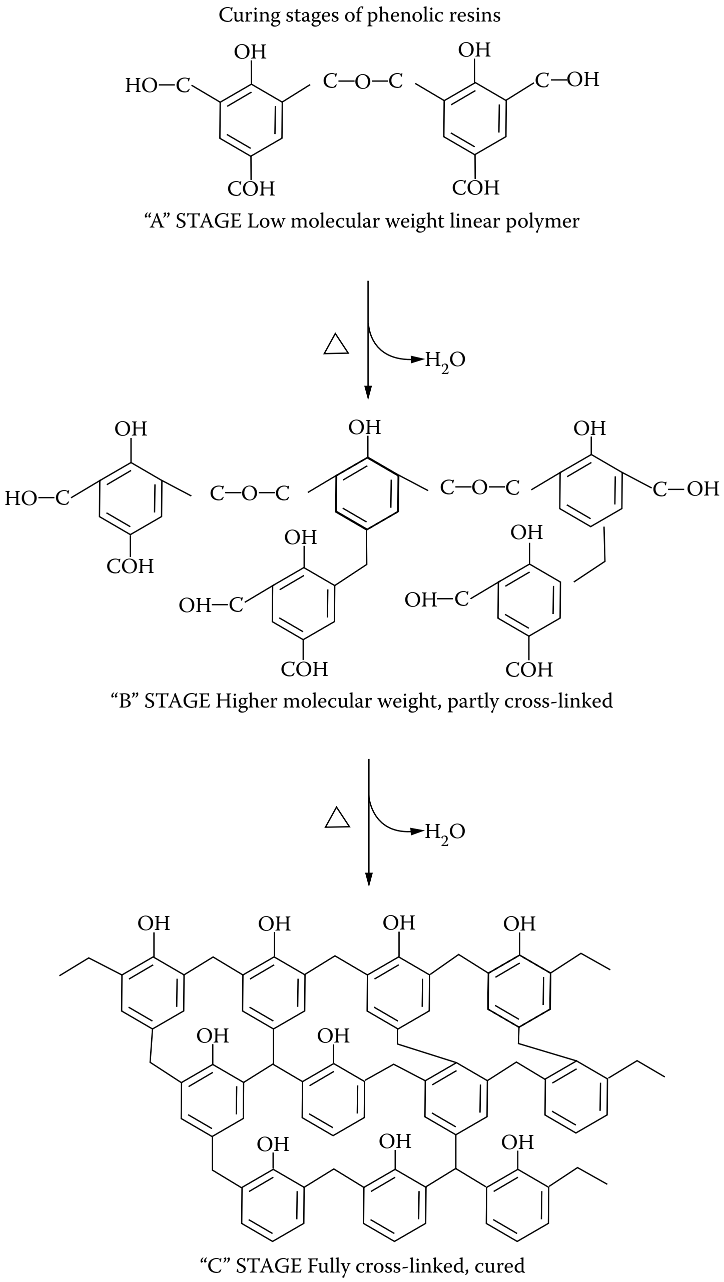
* Thermosetting resins have three curing stages: A, B, and C (Figure 1.15).

Resins are manufactured in the A-stage, in which the resin may be solid or liquid but is able to flow if heat is applied. The A-stage is also called the completely uncured stage.

The B-stage is the middle stage of the reaction of a thermosetting resin used when prepregs are manufactured. This stage allows easy processing and handling of composite layers, such as graphite/epoxy.

The C-stage is the final stage in the reaction of a thermosetting resin. This stage is accomplished when a composite structure is made out of composite layers. Heat and pressure may be applied at the B-stage to cure the resin completely. This stage results in irreversible hardening and insolubility.



Curing stages of phenolic resins

"A" STAGE Low molecular weight linear polymer

"B" STAGE Higher molecular weight, partly cross-linked

"C" STAGE Fully cross-linked, cured

FIGURE 1.15
Curing stages of phenolic resins. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

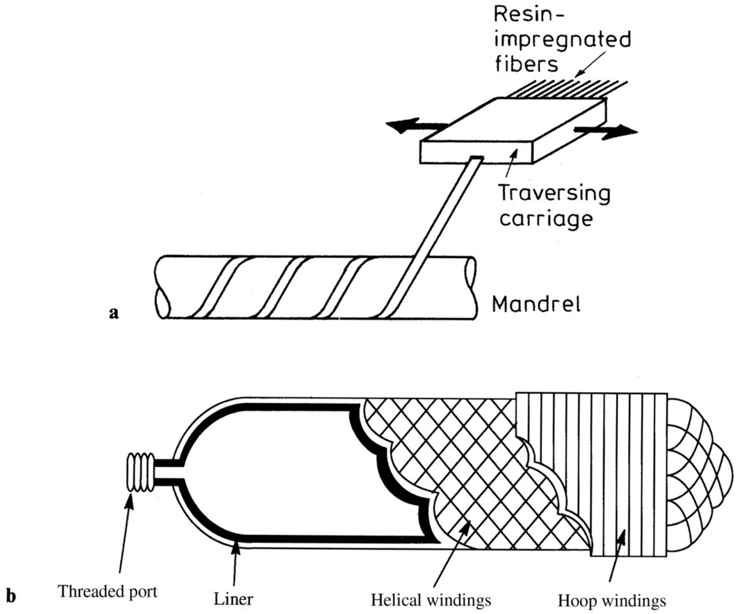


FIGURE 1.16
(a) Filament winding process; (b) filament wound pressure vessel with liner. (From Chawla, K.K., *Composite Materials — Science and Engineering*, Springer–Verlag, 1998. Reprinted by permission of Springer–Verlag.)

Depending on the desired properties of the product, winding patterns such as hoop, helical, and polar can be developed. The product is then cured with or without heat and pressure. Depending on the application, mandrels are made of wood, aluminum, steel, plaster, or salts. For example, steel mandrels are chosen for manufacturing large quantities of open-ended cylinders, and low-melting alloys or water-soluble salts are used for closed-ended cylinders so that one can easily remove the mandrel.

Autoclave forming: This method of manufacturing is used with composites available as prepregs. First, a peel ply made out of nylon or cellophane coated with Teflon* is placed on the mold.† Teflon is used for easy removal of the part and the peel ply achieves a desired finish that is smooth and wrinkle free. Replacing Teflon by mold releasing powders and liquids can also accomplish removal of the part. Prepregs of the required number are laid up one ply at a time by automated means or by hand. Each ply is pressed to remove any entrapped air and wrinkles. The lay-up is sealed at the edges to form a vacuum seal.

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* Teflon is a registered trademark of E.I. duPont deNemours and Company, Inc., Wilmington, DE.

† Mold: a structure around or in which the composite forms a desired shape. Molds are female and male. If the composite part is in the mold, it is called a female mold; if it is made around the mold, it is called a male mold. (See in Figure 1.17 the male mold that was used in making a human-powered submarine.)

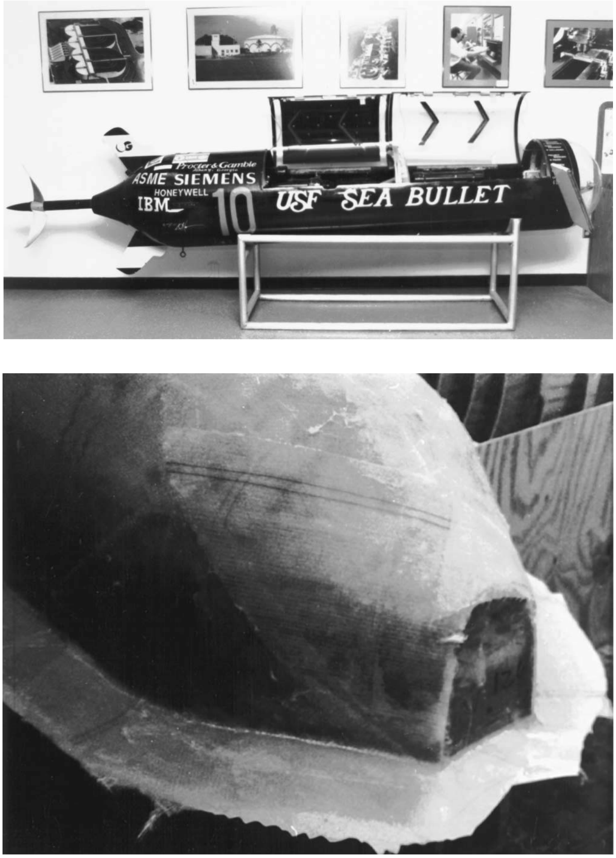


FIGURE 1.17
Human-powered submarine and its mold. (Courtesy of Professor G.H. Besterfield and student section of ASME, University of South Florida, Tampa.)

Now one establishes the bleeder system to get rid of the volatiles and excess resin during the heating and vacuum process that follows later. The bleeder system consists of several bleeder sheets made of glass cloth. These are placed on the edges and the top of the lay-up.

Then, vacuum connections are placed over the bleeders and the lay-up is bagged. A partial vacuum is developed to smooth the bag surface. The whole assembly is put in an autoclave (Figure 1.18), where heat and pressure are applied with an inert gas such as nitrogen. The vacuum system is kept functioning to remove volatiles during the cure cycle and to keep the part conformed to the mold. The cure cycle may last more than 5 h.

Resin transfer molding (RTM) (also called liquid molding): A low viscosity resin such as polyester or epoxy resin is injected under low pressure into a closed mold that contains the fiber preform. The resin flow is stopped and the part is allowed to cure. The cure is done at room temperature or at elevated temperatures. The latter is done if the part is to be used for high-temperature

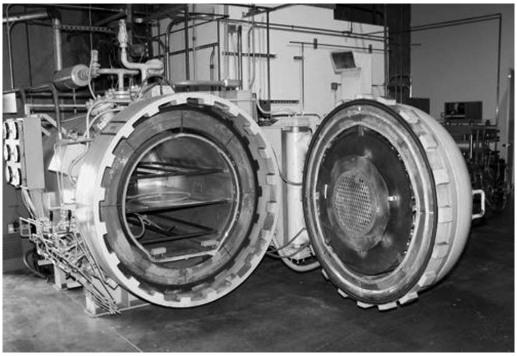


FIGURE 1.18
Autoclave used for processing polymer matrix composites. (Photo courtesy of ACP Composites, MN, http://www.acp_composites.com.)

application. The advantages of RTM are that it is less expensive than hand lay-up, can be automated, and does not need refrigerated storage for prepregs. Major drawbacks include the capital expense required for having two molds instead of one.[15]

Give typical applications of polymer matrix composites.

Applications of polymer matrix composites range from tennis racquets to the space shuttle. Rather than enumerating only the areas in which polymer-based composites are used, a few examples have been taken from each industry. Emphasis has been placed on why a composite material is the material of choice.

Aircraft: The military aircraft industry has mainly led the use of polymer composites. The percentage of structural weight of composites that was less than 2% in F-15s in the 1970s has increased to about 30% on the AV-8B in the 1990s. In both cases, the weight reduction over metal parts was more than 20%.

In commercial airlines, the use of composites has been conservative because of safety concerns. Use of composites is limited to secondary structures such as rudders and elevators made of graphite/epoxy for the Boeing 767 and landing gear doors made of Kevlar–graphite/epoxy. Composites are also used in panels and floorings of airplanes. Some examples of using composites in the primary structure are the all-composite Lear Fan 2100 plane and the tail fin of the Airbus A310-300. In the latter case, the tail fin consists of graphite/epoxy and aramid honeycomb. It not only reduced the weight of the tail fin by 662 lb (300 kg) but also reduced the number of parts from 2000 to 100. Skins of aircraft engine cowls shown in Figure 1.19 are also made of polymer matrix composites for reducing weight.[16]

With increasing competition in model airplane flying, the weight of composite materials has been reduced. Figure 1.20 shows a World War II model airplane with fuselage made of glass/epoxy, wings made of balsa-wood

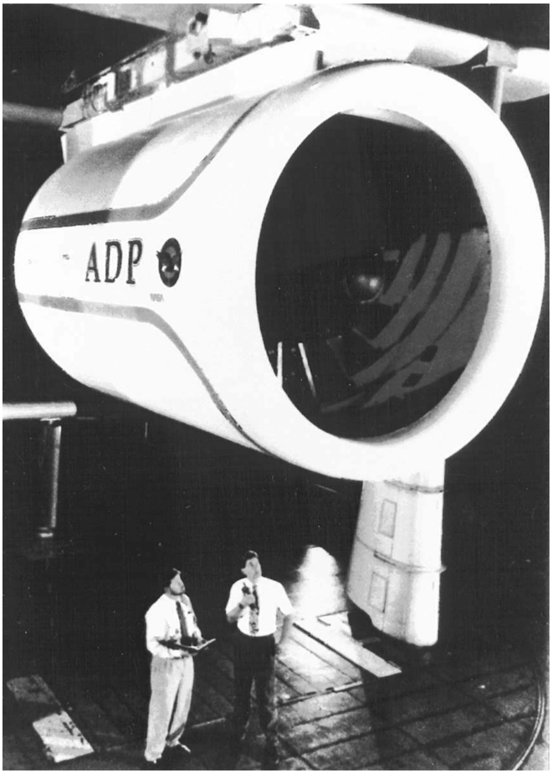


FIGURE 1.19
Aircraft engine cowling. (Photo provided courtesy of Alliant Techsystems, Inc.)

FIGURE 1.20
Model BF109 WWII German fighter plane using glass/epoxy-molded fuselage and wing spars of graphite/epoxy. (Photo courtesy of Russell A. Lepré, Tampa, FL.)

FIGURE 1.21
The BELL™ V-22 Osprey in combat configuration. (Courtesy of Bell Helicopter Textron Inc.)

facings/Styrofoam core sandwich construction, and wingspars made of graphite/epoxy.[17]

Helicopters and tiltrotors (Figure 1.21) use graphite/epoxy and glass/epoxy rotor blades that not only increase the life of blades by more than 100% over metals but also increase the top speeds.

Space: Two factors make composites the material of choice in space applications: high specific modulus and strength, and dimensional stability during large changes in temperature in space. Examples include the Graphite/epoxy-honeycomb payload bay doors in the space shuttle (Figure 1.22). Weight savings[7] over conventional metal alloys translate to higher payloads that cost as much as \$1000/lb (\$2208/kg). Also, for the space shuttles, graphite/epoxy was chosen primarily for weight savings and for small mechanical and thermal deflections concerning the remote manipulator arm, which deploys and retrieves payloads.

Figure 1.23 shows a high-gain antenna for the space station that uses sandwiches made of graphite/epoxy facings with an aluminum honeycomb core. Antenna ribs and struts in satellite systems use graphite/epoxy for their high specific stiffness and its ability to meet the dimensional stability[16] requirements due to large temperature excursions in space.

In June 2004, Paul G. Allen and Scaled Composites[18] launched the first privately manned vehicle, called SpaceshipOne, beyond the Earth's atmosphere (Figure 1.24). The spaceship reached a record-breaking altitude of approximately 62 miles (100 km). SpaceshipOne is constructed from graphite-epoxy composite materials; a *trowel-on* ablative thermal protection layer[19] protects its hotter sections.

Sporting goods: Graphite/epoxy is replacing metals in golf club shafts mainly to decrease the weight and use the saved weight in the head. This increase in the head weight has improved driving distances by more than 25 yards (23 m).

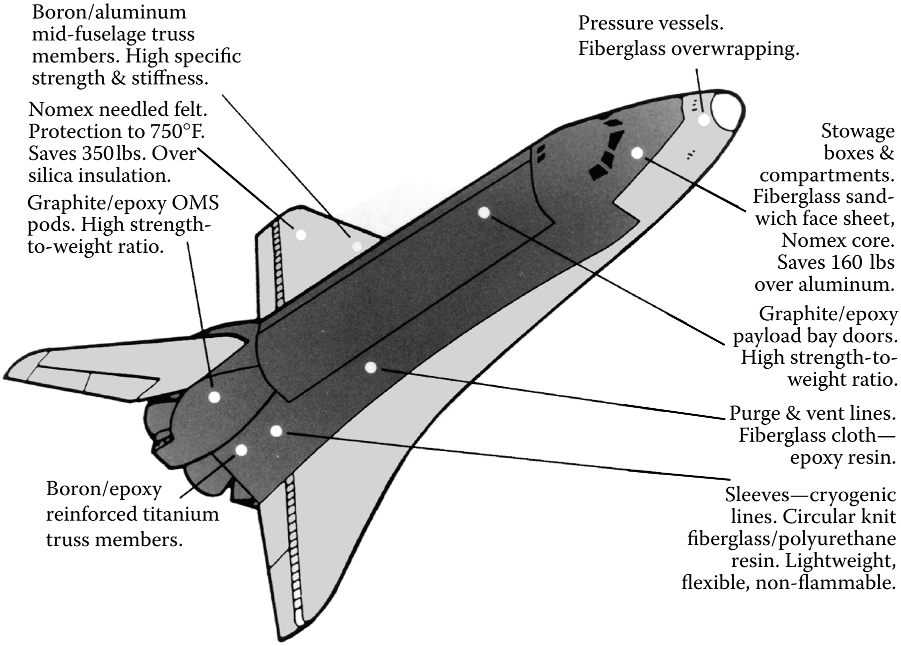


FIGURE 1.22
Use of composites in the space shuttle. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

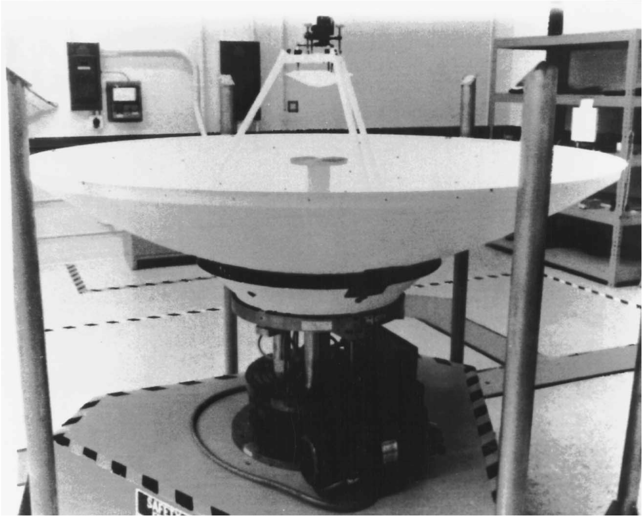


FIGURE 1.23
High-gain antenna for space station. (Photo provided courtesy of Alliant Techsystems, Inc.)

FIGURE 1.24
First privately manned vehicle (SpaceShipOne) to go beyond the Earth's atmosphere. (Photo provided courtesy of Scaled Composites, http://www.scaled.com.)

Bicycles use hybrid construction of graphite/epoxy composites wound on an aluminum tubing or chopped S-glass reinforced urethane foam. The graphite/epoxy composite increases the specific modulus of the tube and decreases the mass of the frame by 25%. Composites also allow frames to consist of one piece, which improves fatigue life and avoids stress concentration* found in metallic frames at their joints. Bicycle wheels made of carbon–polymide composites offer low weight and better impact resistance than aluminum.

Tennis and racquetball rackets with graphite/epoxy frames are now commonplace. The primary reasons for using composites are that they improve the torsional rigidity of the racquet and reduce risk of elbow injury due to vibration damping.† Ice hockey sticks are now manufactured out of hybrids such as Kevlar–glass/epoxy. Kevlar is added for durability and stiffness. Ski poles made of glass/polyester composites have higher strength, flexibility, and lower weight than conventional ski poles. This reduces stress and impact on upper body joints as the skier plants his poles.

Medical devices: Applications here include the use of glass–Kevlar/epoxy lightweight face masks for epileptic patients. Artificial portable lungs are made of graphite–glass/epoxy so that a patient can be mobile. X-ray tables made of graphite/epoxy facing sandwiches are used for their high stiffness, light weight, and transparency to radiation. The latter feature allows the

---

* If a loaded machine element has a discontinuity, the stresses are different at the discontinuity. The ratio between the stresses at the discontinuity and the nominal stress is defined as the stress concentration factor. For example, in a plate with a small hole, the stress concentration factor is three at the edge of the hole.

† Vibration damping is the ability of a material to dissipate energy during vibration. Damping of composites is higher than that of conventional metals such as steel and aluminum. Damping of composites depends on fiber volume fraction, orientation, constituent properties, and stacking sequence. Damping in composites is measured by calculating the ratio of energy dissipated to the energy stored.[20]

FIGURE 1.25
Rear fiberglass monosprings for Corvettes. (Photo courtesy of Vette Brakes and Products, St. Petersburg, FL, http://www.vbandp.com.)

patient to stay on one bed for an operation as well as x-rays and be subjected to a lower dosage of radiation.

Marine: The application of fiberglass in boats is well known. Hybrids of Kevlar–glass/epoxy are now replacing fiberglass for improved weight savings, vibration damping, and impact resistance. Kevlar–epoxy by itself would have poor compression properties.

Housings made of metals such as titanium to protect expensive oceanographic research instruments during explorations of sea wrecks are cost prohibitive. These housings are now made out of glass/epoxy and sustain pressures as high as 10 ksi (69 MPa) and extremely corrosive conditions.

Bridges made of polymer composite materials are gaining wide acceptance due to their low weight, corrosion resistance, longer life cycle, and limited earthquake damage. Although bridge components made of composites may cost $5/lb as opposed to components made of steel, reinforced concrete may only cost $0.30 to $1.00 per pound; the former weighs 80% less than the latter. Also, by lifetime costs, fewer composite bridges need to be built than traditional bridges.[21]

Automotive: The fiberglass body of the Corvette® comes to mind when considering automotive applications of polymer matrix composites. In addition, the Corvette has glass/epoxy composite leaf springs (Figure 1.25) with a fatigue life of more than five times that of steel. Composite leaf springs also give a smoother ride than steel leaf springs and give more rapid response to stresses caused by road shock. Moreover, composite leaf springs offer less chance of catastrophic failure, and excellent corrosion resistance.[22] By weight, about 8% of today's automobile parts are made of composites, including bumpers, body panels, and doors. However, since 1981, the average engine horsepower has increased by 84%, while average vehicle weight has increased by more than 20%. To overcome the increasing weight but also maintain the safety of modern vehicles, some estimate that carbon composite bodies will reduce the weight by 50%.[23]

Commercial: Fiber-reinforced polymers have many other commercial applications too. Examples include mops with pultruded fiberglass handles (Fig-

FIGURE 1.26
Fiberglass mop handle. (Photo courtesy of RTP Company, MN.)

ure 1.26). Some brooms used in pharmaceutical factories have handles that have no joints or seams; the surfaces are smooth and sealed. This keeps the bacteria from staying and growing. To have a handle that also is strong, rigid, and chemically and heat resistant, the material of choice is glass-fiber-reinforced polypropylene.[24] Other applications include pressure vessels for applications such as chemical plants. Garden tools (Figure 1.27)[25] can be made lighter than traditional metal tools and thus are suitable for children and people with physically challenged hands. Figure 1.27 shows the Powergear® Fiskars® anvil lopper. The handles of the lopper are made of Nyglass® composite, making it extremely lightweight and durable.

1.2.2 Metal Matrix Composites

What are metal matrix composites?

Metal matrix composites (MMCs), as the name implies, have a metal matrix. Examples of matrices in such composites include aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, and large coefficients of thermal expansion and thermal

FIGURE 1.27
Strong, efficient, and lightweight Fiskars Powergear anvil lopper. (Photo courtesy of Fiskars Brands, Inc.)

and electric conductivities of metals can be reduced, by the addition of fibers such as silicon carbide.

What are the advantages of metal matrix composites?

Metal matrix composites are mainly used to provide advantages over monolithic metals such as steel and aluminum. These advantages include higher specific strength and modulus by reinforcing low-density metals, such as aluminum and titanium; lower coefficients of thermal expansion by reinforcing with fibers with low coefficients of thermal expansion, such as graphite; and maintaining properties such as strength at high temperatures.

MMCs have several advantages over polymer matrix composites. These include higher elastic properties; higher service temperature; insensitivity to moisture; higher electric and thermal conductivities; and better wear, fatigue, and flaw resistances. The drawbacks of MMCs over PMCs include higher processing temperatures and higher densities.

Do any properties degrade when metals are reinforced with fibers?

Yes, reinforcing metals with fibers may reduce ductility and fracture toughness.[26] Ductility of aluminum is 48% and it can decrease to below 10% with

TABLE 1.11

Typical Mechanical Properties of Metal Matrix Composites

Property	Units	SiC/ aluminum	Graphite/ aluminum	Steel	Aluminum
System of units: USCS					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	Msi	17	18	30	10
Ultimate tensile strength	ksi	175	65	94	34
Coefficient of thermal expansion	μin./in./°F	6.9	10	6.5	12.8
System of units: SI					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	GPa	117.2	124.1	206.8	68.95
Ultimate tensile strength	MPa	1206	448.2	648.1	234.40
Coefficient of thermal expansion	μm/m/°C	12.4	18	11.7	23

simple reinforcements of silicon carbide whiskers. The fracture toughness of aluminum alloys is 18.2 to 36.4 ksi$\sqrt{\text{in.}}$ (20 to 40 MPa$\sqrt{\text{m}}$) and it reduces by 50% or more when reinforced with silicon fibers.

What are the typical mechanical properties of some metal matrix composites? Compare the properties with metals.

Typical mechanical properties of MMCs are given in Table 1.11.

Show one process of how metal matrix composites are manufactured.

Fabrication methods for MMCs are varied. One method of manufacturing them is diffusion bonding[26] (Figure 1.28), which is used in manufacturing boron/aluminum composite parts (Figure 1.29). A fiber mat of boron is placed between two thin aluminum foils about 0.002 in. (0.05 mm) thick. A polymer binder or an acrylic adhesive holds the fibers together in the mat. Layers of these metal foils are stacked at angles as required by the design. The laminate is first heated in a vacuum bag to remove the binder. The laminate is then hot pressed with a temperature of about 932°F (500°C) and pressure of about 5 ksi (35 MPa) in a die to form the required machine element.

What are some of the applications of metal matrix composites?

Metal matrix composites applications are

- *Space*: The space shuttle uses boron/aluminum tubes to support its fuselage frame. In addition to decreasing the mass of the space shuttle by more than 320 lb (145 kg), boron/aluminum also reduced the thermal insulation requirements because of its low thermal con-

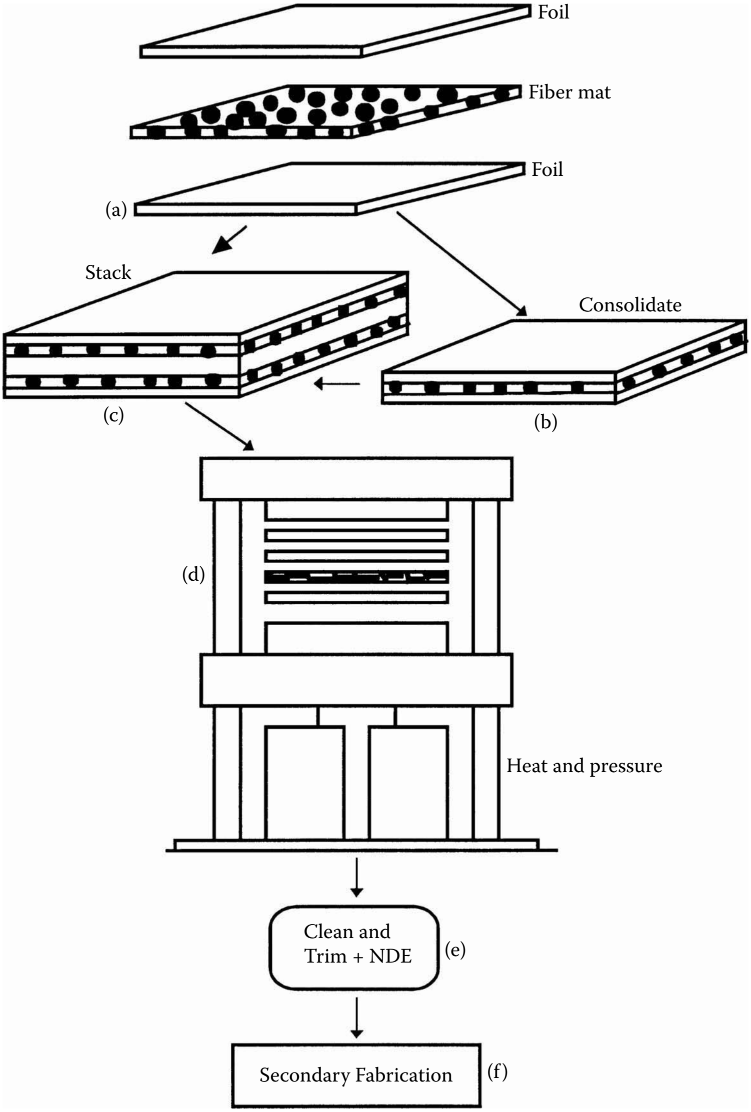


FIGURE 1.28
Schematic of diffusion bonding for metal matrix composites. (Reproduced with permission from Matthews, F.L. and Rawlings, R.D., *Composite Materials: Engineering and Science*, Chapman & Hall, London, 1994, Figure 3.1, p. 81. Copyright CRC Press, Boca Raton, FL.)

ductivity. The mast of the Hubble Telescope uses carbon-reinforced aluminum.

- *Military*: Precision components of missile guidance systems demand dimensional stability — that is, the geometries of the components cannot change during use.[27] Metal matrix composites such as SiC/aluminum composites satisfy this requirement because they have

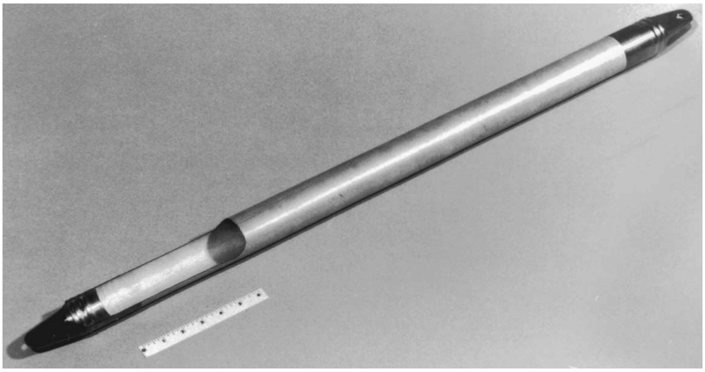
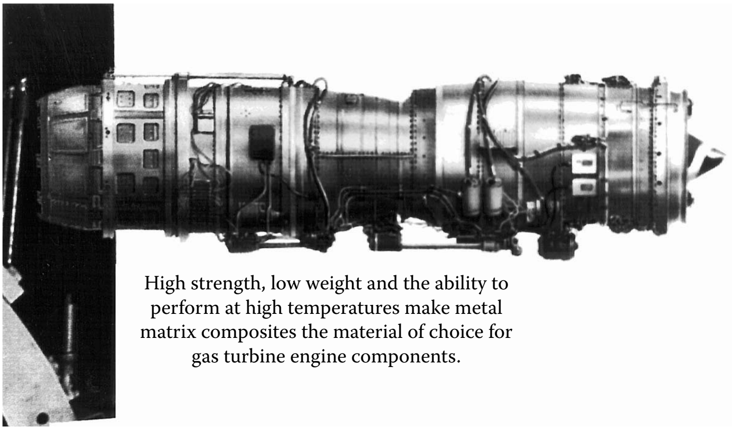


FIGURE 1.29
Boron/aluminum component made from diffusion bonding. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)



High strength, low weight and the ability to perform at high temperatures make metal matrix composites the material of choice for gas turbine engine components.

FIGURE 1.30
Gas turbine engine components made of metal matrix composites. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

high microyield strength.* In addition, the volume fraction of SiC can be varied to have a coefficient of thermal expansion compatible with other parts of the system assembly.

- *Transportation*: Metal matrix composites are finding use now in automotive engines that are lighter than their metal counterparts. Also, because of their high strength and low weight, metal matrix composites are the material of choice for gas turbine engines (Figure 1.30).

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* Microyield strength is a major design parameter for elements that are required to be dimensionally stable. It is defined as the stress required to create a plastic (residual) strain of 1×10^{-6} or 1 μm.

TABLE 1.12

Typical Fracture Toughness of Monolithic Materials and Ceramic Matrix Composites

Material	Fracture toughness (MPa $\sqrt{m}$)	Fracture toughness (ksi $\sqrt{in.}$)
Epoxy	3	2.73
Aluminum alloys	35	31.85
Silicon carbide	3	2.73
SiC/Al_2O_3	27	24.6
SiC/SiC	30	27.3

1.2.3 Ceramic Matrix Composites

What are ceramic matrix composites?

Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina calcium alumino silicate reinforced by fibers such as carbon or silicon carbide.

What are the advantages of ceramic matrix composites?

Advantages of CMCs include high strength, hardness, high service temperature limits* for ceramics, chemical inertness, and low density. However, ceramics by themselves have low fracture toughness. Under tensile or impact loading, they fail catastrophically. Reinforcing ceramics with fibers, such as silicon carbide or carbon, increases their fracture toughness (Table 1.12) because it causes gradual failure of the composite. This combination of a fiber and ceramic matrix makes CMCs more attractive for applications in which high mechanical properties and extreme service temperatures are desired.

What are the typical mechanical properties of some ceramic matrix composites? Compare them with metals.

Typical mechanical properties of ceramic matrix composites are given in Table 1.13.

Show one process of how ceramic matrix composites are manufactured.

One of the most common methods to manufacture ceramic matrix composites is called the hot pressing method.[28] Glass fibers in continuous tow are passed through slurry consisting of powdered matrix material, solvent such as alcohol, and an organic binder (Figure 1.31). The tow is then wound on a drum and dried to form prepreg tapes. The prepreg tapes can now be stacked to make a required laminate. Heating at about 932°F (500°C) burns out the binder. Hot pressing at high temperatures in excess of 1832°F (1000°C) and pressures of 1 to 2 ksi (7 to 14 MPa) follows this.

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* Current service temperatures limits are 750°F (400°C) for polymers, 1800°F (1000^{0}C) for metals and their alloys, and 2700°F (1500°C) for ceramics.

TABLE 1.13

Typical Mechanical Properties of Some Ceramic Matrix Composites

Property	Units	SiC/LAS	SiC/CAS	Steel	Aluminum
System of units: USCS					
Specific gravity	—	2.1	2.5	7.8	2.6
Young's modulus	Msi	13	17.55	30.0	10.0
Ultimate tensile strength	ksi	72	58.0	94.0	34.0
Coefficient of thermal expansion	μin./in./°F	2	2.5	6.5	12.8
System of units: SI					
Specific gravity	—	2.1	2.5	7.8	2.6
Young's modulus	GPa	89.63	121	206.8	68.95
Ultimate tensile strength	MPa	496.4	400	648.1	234.4
Coefficient of thermal expansion	μm/m/°C	3.6	4.5	11.7	23

What are the applications of ceramic matrix composites?

Ceramic matrix composites are finding increased application in high-temperature areas in which metal and polymer matrix composites cannot be used. This is not to say that CMCs are not attractive otherwise, especially considering their high strength and modulus, and low density. Typical applications include cutting tool inserts in oxidizing and high-temperature environments. Textron Systems Corporation® has developed fiber-reinforced ceramics with SCS™ monofilaments for future aircraft engines (Figure 1.32).

1.2.4 Carbon–Carbon Composites

What are carbon–carbon composites?

Carbon–carbon composites use carbon fibers in a carbon matrix. These composites are used in very high-temperature environments of up to 6000°F (3315°C), and are 20 times stronger and 30% lighter than graphite fibers.[29]

What are the advantages of carbon–carbon composites?

Carbon is brittle and flaw sensitive like ceramics. Reinforcement of a carbon matrix allows the composite to fail gradually and also gives advantages such as ability to withstand high temperatures, low creep at high temperatures, low density, good tensile and compressive strengths, high fatigue resistance, high thermal conductivity, and high coefficient of friction. Drawbacks include high cost, low shear strength, and susceptibility to oxidations at high temperatures. Typical properties of carbon–carbon composites are given in Table 1.14.

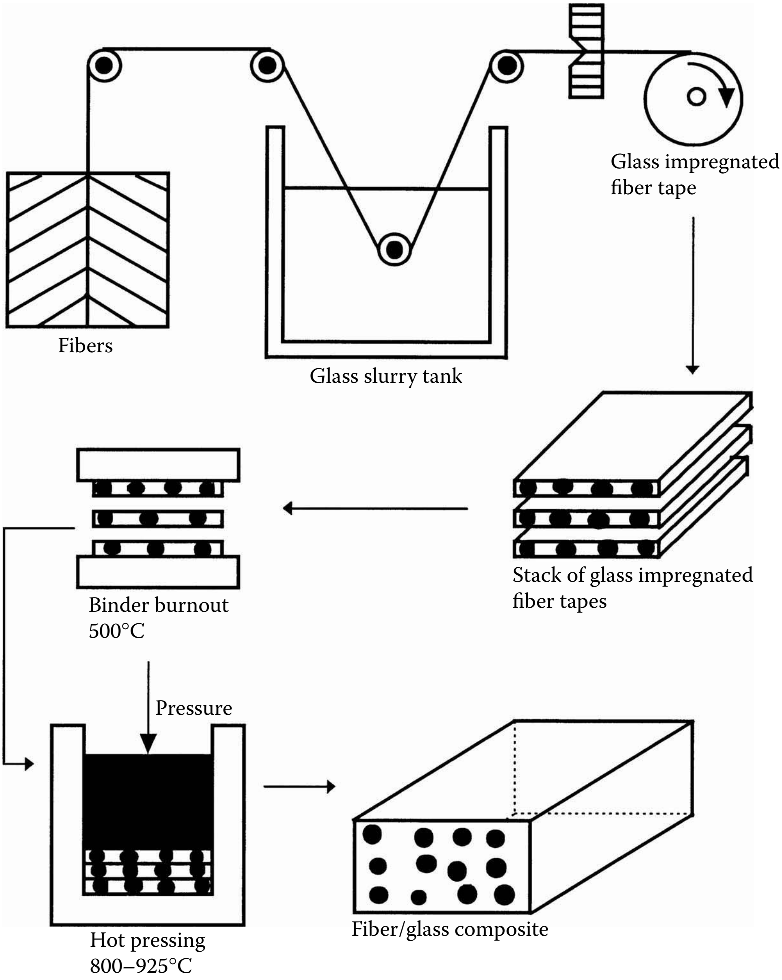

FIGURE 1.31
Schematic of slurry infiltration process for ceramic matrix composites. (From Chawla, K.K., *Science and Business Media from Ceramics Matrix Composites*, Kluwer Academic Publishers, London, 1993, Figure 4.1, p. 128. Reproduced with permission of Springer–Verlag.)

Give a typical method of processing a carbon–carbon composite.

A typical method for manufacturing carbon–carbon composites is called low-pressure carbonization[29] and is shown in Figure 1.33. A graphite cloth is taken, impregnated by resin (such as phenolic, pitch, and furfuryl ester), and laid up in layers. It is laid in a mold, cured, and trimmed. The part is then pyrolized, converting the phenolic resin to graphite. The composite is then impregnated by furfuryl alcohol. The process drives off the resin and any volatiles. The process is repeated three or four times until the level of porosity is reduced to an acceptable level. Each time, this process increases

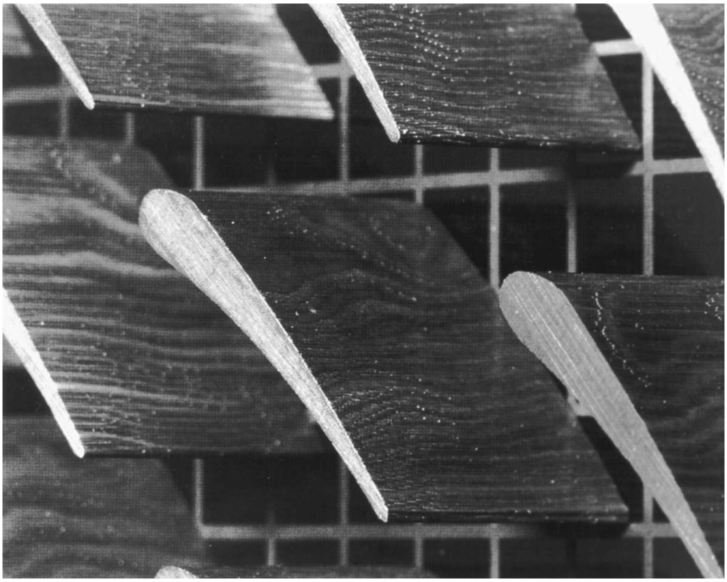

FIGURE 1.32
Ceramic matrix composites for high temperature and oxidation resistant application. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

TABLE 1.14

Typical Mechanical Properties of Carbon–Carbon Matrix Composites

Property	Units	C–C	Steel	Aluminum
System of units: USCS				
Specific gravity	—	1.68	7.8	2.6
Young's modulus	Msi	1.95	30	10
Ultimate tensile strength	ksi	5.180	94	40
Coefficient of thermal expansion	μin./in./°F	1.11	6.5	12.8
System of units: SI				
Specific gravity	—	1.68	7.8	2.6
Young's modulus	GPa	13.5	206.8	68.95
Ultimate strength	MPa	35.7	648.1	234.4
Coefficient of thermal expansion	μm/m/°C	2.0	11.7	23

its modulus and strength. Because carbon–carbon composites oxidize at temperatures as low as 842°F (450°C), an outer layer of silicon carbide may be deposited.[30]

What are the applications of carbon–carbon composites?

The main uses of carbon–carbon composites are the following:

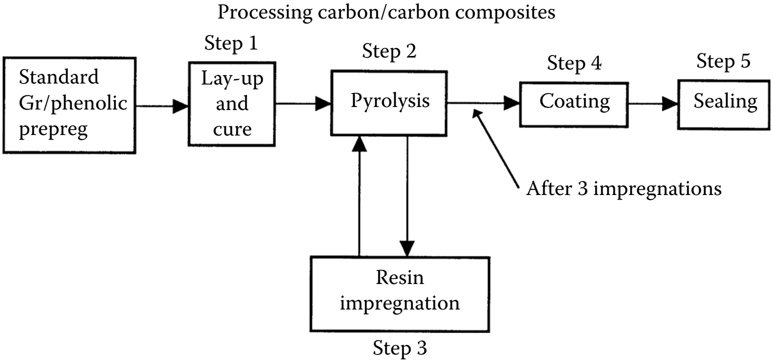

FIGURE 1.33
Schematic of processing carbon–carbon composites. (Reprinted with permission from Klein, A.J., *Adv. Mater. Processes*, 64–68, November 1986, ASM International.)

- *Space shuttle nose cones*: As the shuttle enters Earth's atmosphere, temperatures as high as 3092°F (1700°C) are experienced. Carbon–carbon composite is a material of choice for the nose cone because it has the lowest overall weight of all ablative* materials; high thermal conductivity to prevent surface cracking; high specific heat† to absorb large heat flux; and high thermal shock resistance to low temperatures in space of –238°F (–150°C) to 3092°F (1700°C) due to re-entry. Also, the carbon–carbon nose remains undamaged and can be reused many times.
- *Aircraft brakes*: The carbon–carbon brakes shown in Figure 1.34 cost \$440/lb (\$970/kg), which is several times more than their metallic counterpart; however, the high durability (two to four times that of steel), high specific heat (2.5 times that of steel), low braking distances and braking times (three-quarters that of berylium), and large weight savings of up to 990 lb (450 kg) on a commercial aircraft such as Airbus A300-B2K and A300-B4 are attractive.[29] As mentioned earlier, 1 lb (0.453 kg) weight savings on a full-service commercial aircraft can translate to fuel savings of about 360 gal/year (1360 L/year). Other advantages include reduced inventory due to longer endurance of carbon brakes.
- *Mechanical fasteners*: Fasteners needed for high temperature applications are made of carbon–carbon composites because they lose little strength at high temperatures.

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* Ablative materials absorb heat through pyrolysis at or near the exposed surfaces.

† Specific heat is the amount of heat required to heat a unit mass of a substance through a unit temperature.

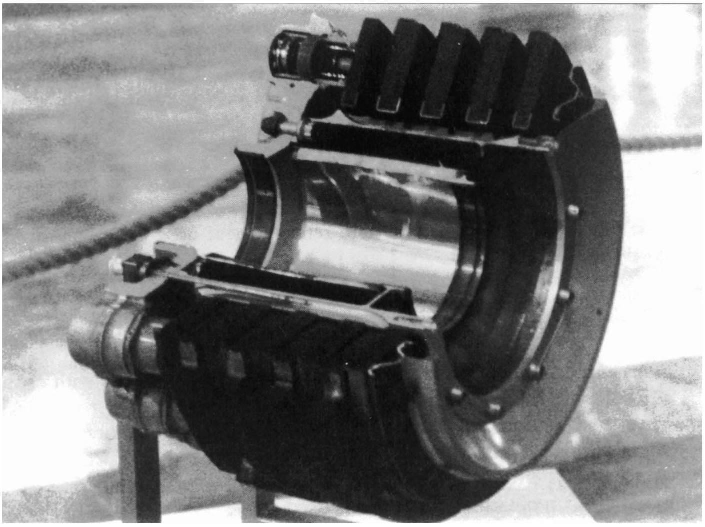

FIGURE 1.34
Sectioned carbon–carbon brake from Airbus A320. (From Savage, G., *Science and Business Media from Carbon–Carbon Composites*, Kluwer Academic Publishers, London, 1993, Figure 9.2, p. 325. Reproduced with kind permission of Springer–Verlag.)

1.3 Recycling Fiber-Reinforced Composites

What types of processes are used for recycling of composites?

The two main processes are called chemical and mechanical processes.

Why is recycling of composites complex?

This is because of the many variables in material types — thermoset vs. thermoplastics, long vs. short fibers, glass vs. carbon, etc.

What are the various steps in mechanical recycling of short fiber-reinforced composites?

These are shredding, separation, washing, grinding, drying, and extrusion.

Where are mechanically recycled short-fiber composites used?

The recycled material is available in powder or fiber form. Powder form is reused as paste for sheet-molding compounds, and the fiber form is used for reinforcement in bulk-molding compounds. One cannot use too much of these as replacements because the impact resistance and electrical properties degrade after about 20% content. Products from recycled plastics are limited to fences and benches.

Why is chemical recycling not as popular as mechanical recycling?

Chemical processing is very costly. Processes such as pyrolysis (decomposing materials in an oxygen-free atmosphere) produce many gases, and hydrogenation gives high filler content. However, General Motors has adapted pyrolysis to recycle composite automobile parts. Gases and oils are recovered, and the residues are used as fillers in concrete and roof shingles.

One other problem is the chlorine content. The scrap needs to be dehalogenated after separation, especially if carbon fibers were used as reinforcement. Glass fibers in recycled composites also pose the problem of low compressive strength of the new material.

What can one do if the different types of composites cannot be separated?

Incineration or use as fuel may be the only solution because metals, thermosets, and thermoplastics may be mixed, and they may be soiled with toxic materials. The fuel value* of polymer matrix composites is around 5000 BTU/lb (11,622 kJ/kg). This is about half the value for coal.

Which chemical process shows the most promise?

Incineration offers the most promise. Its advantages include minimal cost, high-volume reduction, and no residual material. It is also feasible for low scrap volume.

1.4 Mechanics Terminology

How is a composite structure analyzed mechanically?

A composite material consists of two or more constituents; thus, the analysis and design of such materials is different from that for conventional materials such as metals. The approach to analyze the mechanical behavior of composite structures is as follows (Figure 1.35).

1. Find the average properties of a composite ply from the individual properties of the constituents. Properties include stiffness, strength, thermal, and moisture expansion coefficients. Note that average properties are derived by considering the ply to be homogeneous. At this level, one can optimize for the stiffness and strength requirements of a lamina. This is called the *micromechanics* of a lamina.

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* Fuel value is the heat transferred when the products of complete combustion of a fuel are cooled to the initial temperature of air and fuel. Units of fuel value are Btu/lbm and J/kg. Typical fuel value for lignite coal is 7000 Btu/lbm.

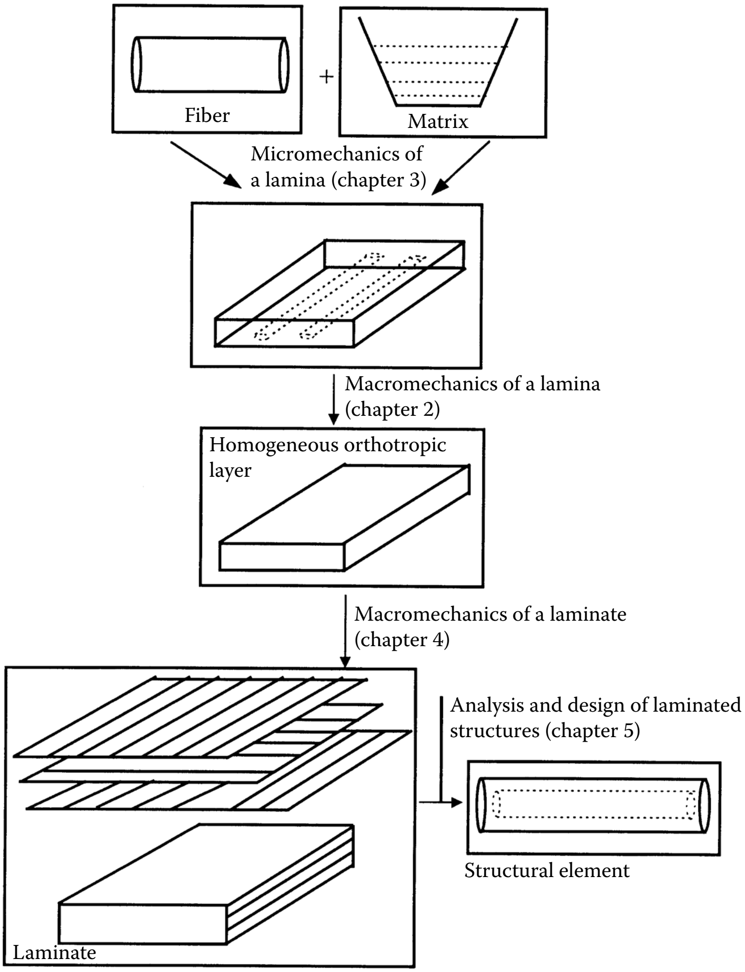

FIGURE 1.35
Schematic of analysis of laminated composites.

2. Develop the stress–strain relationships for a unidirectional/bidirectional lamina. Loads may be applied along the principal directions of symmetry of the lamina or off-axis. Also, one develops relationships for stiffness, thermal and moisture expansion coefficients, and strengths of angle plies. Failure theories of a lamina are based on stresses in the lamina and strength properties of a lamina. This is called the *macromechanics* of a lamina.

A structure made of composite materials is generally a laminate structure made of various laminas stacked on each other. Knowing the macromechanics of a single lamina, one develops the macromechanics of a laminate. Stiffness, strengths, and thermal and moisture expansion coefficients can be found for the whole laminate. Laminate failure is based on stresses and application of failure theories to each ply. This knowledge of analysis of composites can then eventually form the basis for the mechanical design of structures made of composites.

Several terms are defined to develop the fundamentals of the mechanical behavior of composites. These include the following.

What is an isotropic body?

An isotropic material has properties that are the same in all directions. For example, the Young's modulus of steel is the same in all directions.

What is a homogeneous body?

A homogeneous body has properties that are the same at all points in the body. A steel rod is an example of a homogeneous body. However, if one heats this rod at one end, the temperature at various points on the rod would be different. Because Young's modulus of steel varies with temperature, one no longer has a homogeneous body. The body is still isotropic because the properties at a particular point are still identical in all directions.

Are composite materials isotropic and/or homogeneous?

Most composite materials are neither isotropic nor homogeneous. For example, consider epoxy reinforced with long glass fibers. If one chooses a location on the glass fiber, the properties are different from a location on the epoxy matrix. This makes the composite material nonhomogeneous (not homogeneous). Also, the stiffness in the direction parallel to the fibers is higher than in the direction perpendicular to the fibers and thus the properties are not independent of the direction. This makes the composite material anisotropic (not isotropic).

What is an anisotropic material?

At a point in an anisotropic material, material properties are different in all directions.

What is a nonhomogeneous body?

A nonhomogeneous or inhomogeneous body has material properties that are a function of the position on the body.

What is a lamina?

A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix.

What is a laminate?

A laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be made up of different material systems.

What is a hybrid laminate?

Hybrid composites contain more than one fiber or one matrix system in a laminate. The main four types of hybrid laminates follow.

- *Interply hybrid laminates* contain plies made of two or more different composite systems. Examples include car bumpers made of glass/epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also lower the cost of the bumper.
- *Intraply hybrid composites* consist of two or more different fibers used in the same ply. Examples include golf clubs that use graphite and aramid fibers. Graphite fibers provide the torsional rigidity and the aramid fibers provide tensile strength and toughness.
- An *interply–intraply hybrid* consists of plies that have two or more different fibers in the same ply and distinct composite systems in more than one ply.
- *Resin hybrid laminates* combine two or more resins instead of combining two or more fibers in a laminate. Generally, one resin is flexible and the other one is rigid. Tests have proven that these resin hybrid laminates can increase shear and work of fracture properties by more than 50% over those of all-flexible or all-rigid resins.[31]

1.5 Summary

This chapter introduced advanced composite materials and enumerated the advantages and drawbacks of composite materials over monolithic materials. Fiber and matrix factors were discussed to understand their influence on mechanical properties of the composites. The classification of the composites based on the matrix materials — polymer, metal, and ceramics — was discussed. In addition, carbon–carbon composites were also examined. The manufacturing and mechanical properties and application of composites were described. Discussion also covered the recycling of composite materials as well as the terminology used in studying the mechanics of composite materials.

Key Terms

Composite
Advanced composite materials
Specific modulus
Specific strength

Material selection
Fiber factors
Matrix factors
Classification of composites
Polymer matrix composites
Resins
Prepregs
Thermosets
Thermoplastics
Autoclave
Resin transfer molding
Metal matrix composites
Diffusion bonding
Ceramic matrix composites
Carbon–carbon composites
Recycling
Isotropic body
Anisotropic body
Homogeneous body
Nonhomogeneous body
Lamina
Laminate
Hybrid laminate

Exercise Set

1.1 What is a composite?

1.2 Why did Israelites reinforce clay with straw?

1.3 Give a brief historical review of composites.

1.4 Give four examples of naturally found composites. What are the constituents of these natural composites?

1.5 Airbus A-300 saved 300 kg of mass by making the tailfin out of advanced composites. Estimate in gallons the amount of fuel saved per year.

1.6 Give the definitions and units of the following in the SI and USCS system of units:

Coefficient of thermal expansion

Coefficient of moisture expansion

Thermal conductivity

Young's modulus

Ultimate strength
Poisson's ratio
Specific modulus
Specific strength
Density
Specific gravity
Ductility
Fracture toughness
Specific heat

1.7 Draw the graphs for the ratios $E^{1/2}/\rho$ vs. $\sigma^{1/2}_{ult}/\rho$ for materials in Table 1.1.

1.8 A lamina consists of 100 fibers of 10-μm diameter. The fibers are 10 mm long. Find the interfacial area. What is the increase in the interfacial area if the diameter of the fiber is reduced to 5 μm and the total volume of fibers is kept constant?

1.9 Compare the flexibility of a 0.01-in. diameter steel wire to a 0.02-in. diameter aluminum wire. The Young's modulus of steel is 30 Msi and that of aluminum is 10 Msi.

1.10 What are the limitations of modern composites?

1.11 Enumerate six primary material selection parameters that are used in evaluating the use of a particular material.

1.12 How are composites classified?

1.13 Compare the specific modulus, specific strength, and coefficient of thermal expansion coefficient of a pitch based graphite fiber, Kevlar 49, and S-glass.

1.14 Describe one manufacturing method of polymer matrix composites other than those given in Chapter 1.

1.15 Why is epoxy the most popular resin?

1.16 Find ten applications of polymer matrix components other than those given in Chapter 1.

1.17 Give the advantages and drawbacks of metal matrix composites over polymer matrix composites.

1.18 Find three applications of metal matrix composites other than those given in Chapter 1.

1.19 Describe one manufacturing method of metal matrix composites other than given in Chapter 1.

1.20 Find three applications of ceramic matrix composites other than those given in Chapter 1.

1.21 Describe one manufacturing method of ceramic matrix composites other than those given in Chapter 1.

1.22 Find three applications of carbon matrix composites other than those given in Chapter 1.

1.23 Describe one manufacturing method of carbon matrix composites other than those given in Chapter 1.

1.24 Give the upper limit of operating temperatures of polymer, metal, ceramic, and carbon matrix composites.

1.25 Define the following:

Isotropic body

Homogeneous body

Anisotropic body

Nonhomogeneous body

Micromechanics

Macromechanics

Lamina

Laminate

1.26 Give an example of a:

Homogeneous body that is not isotropic

Nonhomogeneous body that is isotropic

1.27 Do all properties of composites always improve over their individual constituents? Give examples.

1.28 How are hybrid composites classified?

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