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In addition to metals, ceramics, and polymers, a fourth material category can be distinguished: composites. A **composite material** is a material system composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents. In certain respects, composites are the most interesting of the engineering materials because their structure is more complex than the other three types.

The technological and commercial interest in composite materials derives from the fact that their properties are not just different from their components but are often far superior. Some of the possibilities include:

- Composites can be designed that are very strong and stiff, yet very light in weight, giving them strength-to-weight and stiffness-to-weight ratios several times greater than steel or aluminum. These properties are highly desirable in applications ranging from commercial aircraft to sports equipment.
- Fatigue properties are generally better than for the common engineering metals. Toughness is often greater, too.
- Composites can be designed that do not corrode like steel; this is important in automotive and other applications.
- With composite materials, it is possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone.
- Better appearance and control of surface smoothness are possible with certain composite materials.

Along with the advantages, there are disadvantages and limitations associated with composite materials. These include: (1) properties of many important composites are anisotropic, which means the properties differ depending on the direction in which they are measured; (2) many of the polymer-based composites are subject to attack by chemicals or solvents, just as the

polymers themselves are susceptible to attack; (3) composite materials are generally expensive, although prices may drop as volume increases; and (4) certain of the manufacturing methods for shaping composite materials are slow and costly.

Several composite materials have already been encountered in the coverage of the three other material types. Examples include cemented carbides (tungsten carbide with cobalt binder); plastic molding compounds that contain fillers (e.g., cellulose fibers, wood flour); and rubber mixed with carbon black. These materials are not always identified as composites; however, technically, they fit the above definition. It could even be argued that a two-phase metal alloy (e.g., $\text{Fe} + \text{Fe}_3\text{C}$) is a composite material, although it is not classified as such. Perhaps the most important composite material of all is wood.

In discussing composite materials, the appropriate starting point is their technology and classification. There are many different materials and structures that can be used to form composites. The various categories are discussed here, devoting the most time to fiber-reinforced plastics, which are commercially the most important type.

9.1 Technology and Classification of Composite Materials

As noted in the definition, a composite material consists of two or more distinct phases. The term **phase** indicates a homogeneous material, such as a metal or ceramic in which all of the grains have the same crystal structure, or a polymer with no fillers. By combining the phases, using methods yet to be described, a new material is created with aggregate performance exceeding that of its parts. The effect is synergistic.

Composite materials can be classified in various ways. One possible classification distinguishes between (1) traditional and (2) synthetic composites. **Traditional composites** are those that occur in nature or have been produced by civilizations for many years. Wood is a naturally occurring composite material, while concrete (Portland cement plus sand or gravel) and asphalt mixed with gravel are traditional composites used in construction. **Synthetic composites** are modern material systems normally associated with the manufacturing industries, in which the components are first produced separately and then combined in a controlled way to achieve the desired structure, properties, and part geometry. These synthetic materials are the composites normally thought of in the context of engineered products, and this chapter is focused on these materials.

9.1.1 COMPONENTS IN A COMPOSITE MATERIAL

In its simplest form, a composite material consists of two phases: a primary phase and a secondary phase. The primary phase is the **matrix** within which the secondary phase is imbedded. The imbedded phase is sometimes referred to as a **reinforcing agent** (or similar term), because it usually serves to strengthen the composite. The reinforcing phase may be in the form of fibers, particles, or various other geometries. The phases are generally insoluble in each other, but strong adhesion must exist at their interface(s).

The matrix phase can be any of three basic material types: polymers, metals, or ceramics. The secondary phase may also be one of the three basic materials, or

TABLE • 9.1 Possible combinations of two-component composite materials.

Secondary phase (reinforcement)	Primary Phase (matrix)		
	Metal	Ceramic	Polymer
Metal	Powder metal parts infiltrated with a second metal	NA	Plastic molding compounds Steel-belted radial tires
Ceramic	Cermets ^a Fiber-reinforced metals	SiC whisker-reinforced Al ₂ O ₃	Plastic molding compounds Fiberglass-reinforced plastic
Polymer	Powder metal parts impregnated with polymer	NA	Plastic molding compounds Kevlar-reinforced epoxy
Elements (C, B)	Fiber-reinforced metals	NA	Rubber with carbon black B or C fiber-reinforced plastic

NA = not applicable currently.

^aCermets include cemented carbides.

it may be an element such as carbon or boron. Possible combinations in a two-component composite material can be organized as a 3×4 chart, as in Table 9.1. Note that certain combinations are not feasible, such as a polymer in a ceramic matrix. Also note that the possibilities include two-phase structures consisting of components of the same material type, such as fibers of Kevlar (polymer) in a plastic (polymer) matrix. In other composites the imbedded material is an element such as carbon or boron.

The classification system for composite materials used in this book is based on the matrix phase. The classes are listed here and discussed in Sections 9.2 through 9.4:

1. **Metal Matrix Composites** (MMCs) include mixtures of ceramics and metals, such as cemented carbides and other cermets, as well as aluminum or magnesium reinforced by strong, high stiffness fibers.
2. **Ceramic Matrix Composites** (CMCs) are the least common category. Aluminum oxide and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications.
3. **Polymer Matrix Composites** (PMCs). Thermosetting resins are the most widely used polymers in PMCs. Epoxy and polyester are commonly mixed with fiber reinforcement, and phenolic is mixed with powders. Thermoplastic molding compounds are often reinforced, usually with powders (Section 8.1.5).

The classification can be applied to traditional composites as well as synthetics. Concrete is a ceramic matrix composite, while asphalt and wood are polymer matrix composites.

The matrix material serves several functions in the composite. First, it provides the bulk form of the part or product made of the composite material. Second, it holds the imbedded phase in place, usually enclosing and often concealing it. Third, when a load is applied, the matrix shares the load with the secondary phase, in some cases deforming so that the stress is essentially born by the reinforcing agent.

FIGURE 9.1 Possible physical shapes of imbedded phases in composite materials: (a) fiber, (b) particle, and (c) flake.



9.1.2 THE REINFORCING PHASE

It is important to understand that the role played by the secondary phase is to reinforce the primary phase. The imbedded phase is most commonly one of the shapes illustrated in Figure 9.1: fibers, particles, or flakes. In addition, the secondary phase can take the form of an infiltrated phase in a skeletal or porous matrix.

Fibers *Fibers* are filaments of reinforcing material, generally circular in cross-section, although alternative shapes are sometimes used (e.g., tubular, rectangular, hexagonal). Diameters range from less than 0.0025 mm (0.0001 in) to about 0.13 mm (0.005 in), depending on material.

Fiber reinforcement provides the greatest opportunity for strength enhancement of composite structures. In fiber-reinforced composites, the fiber is often considered to be the principal constituent since it bears the major share of the load. Fibers are of interest as reinforcing agents because the filament form of most materials is significantly stronger than the bulk form. The effect of fiber diameter on tensile strength can be seen in Figure 9.2. As diameter is reduced, the material becomes oriented in the direction of the fiber axis and the probability of defects in the structure decreases significantly. As a result, tensile strength increases dramatically.

Fibers used in composites can be either continuous or discontinuous. **Continuous fibers** are very long; in theory, they offer a continuous path by which a load can be carried by the composite part. In reality, this is difficult to achieve due to variations in the fibrous material and processing. **Discontinuous fibers** (chopped sections of continuous fibers) are short lengths ($L/D \approx 100$). An important type of discontinuous fiber are **whiskers**—hair-like single crystals with diameters down to about 0.001 mm (0.00004 in) and very high strength.

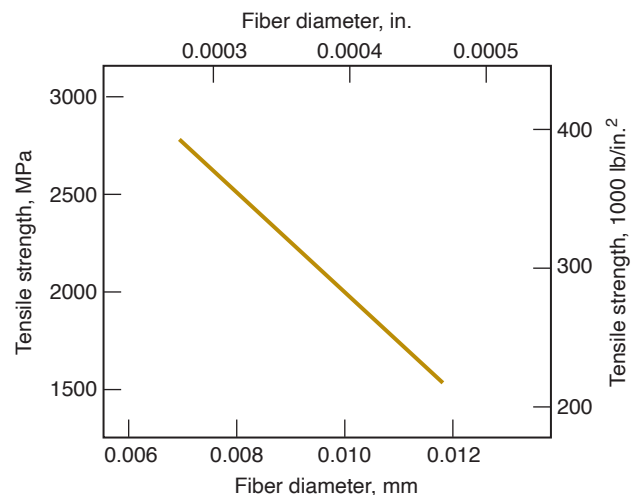
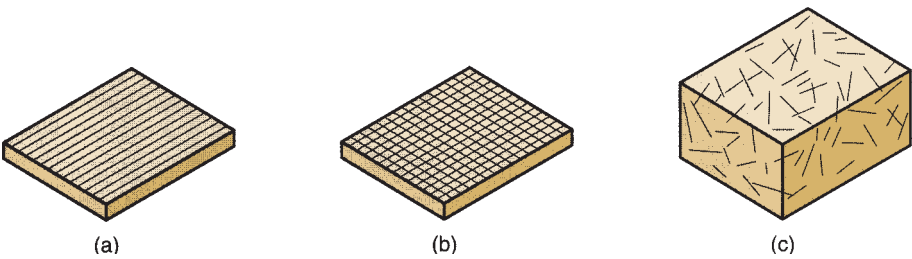


FIGURE 9.2 Relationship between tensile strength and diameter for a carbon fiber (Source: [1]). Other filament materials show similar relationships.

FIGURE 9.3 Fiber orientation in composite materials: (a) one-dimensional, continuous fibers; (b) planar, continuous fibers in the form of a woven fabric; and (c) random, discontinuous fibers.



Fiber orientation is another factor in composite parts. Three cases can be distinguished, illustrated in Figure 9.3: (a) one-dimensional reinforcement, in which maximum strength and stiffness are obtained in the direction of the fiber; (b) planar reinforcement, in some cases in the form of a two-dimensional woven fabric; and (c) random or three-dimensional in which the composite material tends to possess isotropic properties.

Various materials are used as fibers in fiber-reinforced composites: metals, ceramics, polymers, carbon, and boron. The most important commercial use of fibers is in polymer composites. However, use of fiber-reinforced metals and ceramics is growing. Following is a survey of the important types of fiber materials, with properties listed in Table 9.2:

- **Glass**—The most widely used fiber in polymers, the term *fiberglass* is applied to denote glass fiber-reinforced plastic (GFRP). The two common glass fibers are E-glass and S-glass (compositions listed in Table 7.5). E-glass is strong and low cost, but its modulus is less than other fibers. S-glass is stiffer, and its tensile strength is one of the highest of all fiber materials; however, it is more expensive than E-glass.
- **Carbon**—Carbon (Section 7.5.1) can be made into high-modulus fibers. Besides stiffness, other attractive properties include low-density and low-thermal

TABLE • 9.2 Typical properties of fiber materials used as reinforcement in composites.

Fiber Material	Diameter		Tensile Strength		Elastic Modulus	
	mm	mils ^a	MPa	lb/in ²	GPa	lb/in ²
Metal: Steel	0.13	5.0	1000	150,000	206	30 × 10 ⁶
Metal: Tungsten	0.013	0.5	4000	580,000	407	59 × 10 ⁶
Ceramic: Al ₂ O ₃	0.02	0.8	1900	275,000	380	55 × 10 ⁶
Ceramic: SiC	0.13	5.0	3275	475,000	400	58 × 10 ⁶
Ceramic: E-glass	0.01	0.4	3450	500,000	73	10 × 10 ⁶
Ceramic: S-glass	0.01	0.4	4480	650,000	86	12 × 10 ⁶
Polymer: Kevlar	0.013	0.5	3450	500,000	130	19 × 10 ⁶
Element: Carbon	0.01	0.4	2750	400,000	240	35 × 10 ⁶
Element: Boron	0.14	5.5	3100	450,000	393	57 × 10 ⁶

Compiled from [3], [7], [11], and other sources. Note that strength depends on fiber diameter (Figure 9.2); the properties in this table must be interpreted accordingly.

^a1 mil = 0.001 in.

expansion. C-fibers are generally a combination of graphite and amorphous carbon.

- **Boron**—Boron (Section 7.5.3) has a very high elastic modulus, but its high cost limits applications to aerospace components in which this property (and others) are critical.
- **Kevlar 49**—This is the most important polymer fiber; it is a highly crystalline aramid, a member of the polyamide family (Section 8.2.2). Its specific gravity is low, giving it one of the highest strength-to-weight ratios of all fibers.
- **Ceramics**—Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are the main fiber materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low-modulus metals such as aluminum and magnesium.
- **Metal**—Steel filaments, both continuous and discontinuous, are used as reinforcing fibers in plastics. Other metals are currently less common as reinforcing fibers.

Particles and Flakes A second common shape of the imbedded phase is *particulate*, ranging in size from microscopic to macroscopic. Particles are an important material form for metals and ceramics. The characterization and production of engineering powders are discussed in Chapters 15 and 16.

The distribution of particles in the composite matrix is random, and therefore strength and other properties of the composite material are usually isotropic. The strengthening mechanism depends on particle size. The microscopic size is represented by very fine powders (around $1\ \mu\text{m}$) distributed in the matrix in concentrations of 15% or less. The presence of these powders results in dispersion-hardening of the matrix, in which dislocation movement in the matrix material is restricted by the microscopic particles. In effect, the matrix itself is strengthened, and no significant portion of the applied load is carried by the particles.

As particle size increases to the macroscopic range, and the proportion of imbedded material increases to 25% and more, the strengthening mechanism changes. In this case, the applied load is shared between the matrix and the imbedded phase. Strengthening occurs due to the load-carrying ability of the particles and the bonding of particles in the matrix. This form of composite strengthening occurs in cemented carbides, in which tungsten carbide (WC) is held in a cobalt (Co) binder. The proportion of WC in the Co matrix is typically 80% or more.

Flakes are basically two-dimensional particles—small flat platelets. Two examples of this shape are the minerals mica (silicate of K and Al) and talc ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$), used as reinforcing agents in plastics. They are generally lower cost materials than polymers, and they add strength and stiffness to plastic molding compounds. Platelet sizes are usually in the range 0.01–1 mm (0.0004–0.040 in) across the flake, with a thickness of 0.001–0.005 mm (0.00004–0.00020 in).

Infiltrated Phase The fourth form of imbedded phase occurs when the matrix has the form of a porous skeleton (like a sponge), and the second phase is simply a *filler*. In this case, the imbedded phase assumes the shape of the pores in the matrix. Metallic fillers are sometimes used to infiltrate the open porous structure of parts made by powder metallurgy techniques (Section 15.3.4), in effect creating a composite material. Oil-impregnated sintered PM components, such as bearings and gears, might be considered another example of this category.

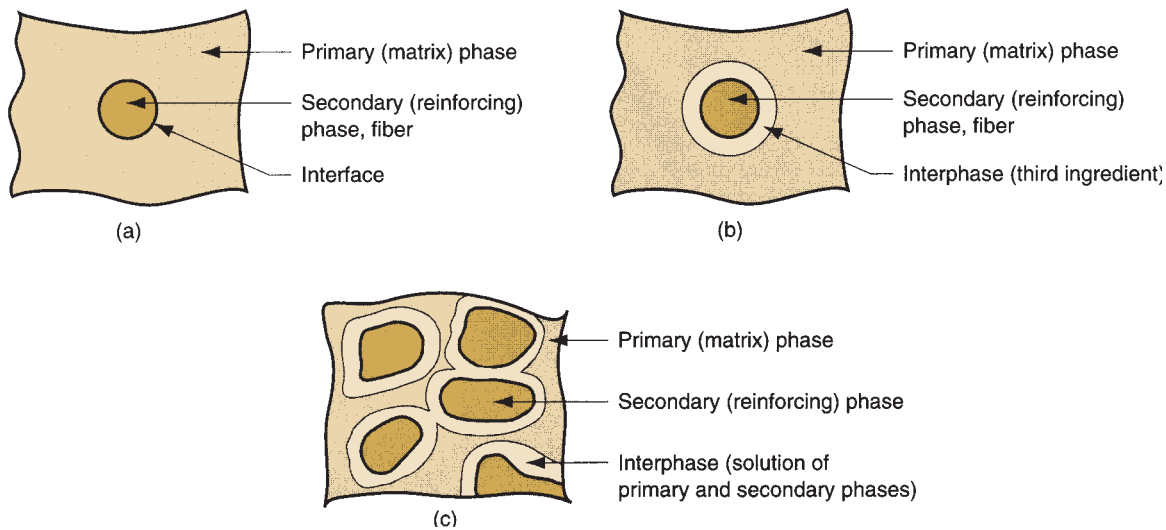


FIGURE 9.4 Interfaces and interphases between phases in a composite material: (a) direct bonding between primary and secondary phases; (b) addition of a third ingredient to bond the primary and secondary phases and form an interphase; and (c) formation of an interphase by solution of the primary and secondary phases at their boundary.

The Interface There is always an *interface* between constituent phases in a composite material. For the composite to operate effectively, the phases must bond where they join. In some cases, there is a direct bonding between the two ingredients, as suggested by Figure 9.4(a). In other cases, a third ingredient is added to promote bonding of the two primary phases. Called an *interphase*, this third ingredient can be thought of as an adhesive. An important example is the coating of glass fibers to achieve adhesion with thermosetting resin in fiberglass-reinforced plastics. As illustrated in Figure 9.4(b), this case results in two interfaces, one on either boundary of the interphase. Finally, a third form of interface occurs when the two primary components are not completely insoluble in each other; in this case, the interphase is formed consisting of a solution of the phases, as in Figure 9.4(c). An example occurs in cemented carbides (Section 9.2.1); at the high sintering temperatures used on these materials, some solubility results at the boundaries to create an interphase.

9.1.3 PROPERTIES OF COMPOSITE MATERIALS

In the selection of a composite material, an optimum combination of properties is usually being sought, rather than one particular property. For example, the fuselage and wings of an aircraft must be lightweight as well as strong, stiff, and tough. Finding a monolithic material that satisfies these requirements is difficult. Several fiber-reinforced polymers possess this combination of properties.

Another example is rubber. Natural rubber is a relatively weak material. In the early 1900s, it was discovered that by adding significant amounts of carbon black (almost pure carbon) to natural rubber, its strength is increased dramatically. The two ingredients interact to provide a composite material that is significantly stronger than either one alone. Rubber, of course, must also be vulcanized to achieve full strength.

Rubber itself is a useful additive in polystyrene (PS). One of the distinctive and disadvantageous properties of polystyrene is its brittleness. Although most other polymers have considerable ductility, PS has virtually none. Rubber (natural or synthetic) can be added in modest amounts (5–15%) to produce high-impact polystyrene, which has much superior toughness and impact strength.

Properties of a composite material are determined by three factors: (1) the materials used as component phases in the composite, (2) the geometric shapes of the constituents and resulting structure of the composite system, and (3) the manner in which the phases interact with one another.

Rule of Mixtures The properties of a composite material are a function of the starting materials. Certain properties of a composite material can be computed by means of a **rule of mixtures**, which involves calculating a weighted average of the constituent material properties. Density is an example of this averaging rule. The mass of a composite material is the sum of the masses of the matrix and reinforcing phases:

$$m_c = m_m + m_r \quad (9.1)$$

where m = mass, kg (lb); and the subscripts c , m , and r indicate composite, matrix, and reinforcing phases, respectively. Similarly, the volume of the composite is the sum of its constituents:

$$V_c = V_m + V_r + V_v \quad (9.2)$$

where V = volume, cm^3 (in^3). V_v is the volume of any voids in the composite (e.g., pores). The density of the composite is the mass divided by the volume.

$$\rho_c = \frac{m_c}{V_c} = \frac{m_m + m_r}{V_c} \quad (9.3)$$

Because the masses of the matrix and reinforcing phase are their respective densities multiplied by their volumes,

$$m_m = \rho_m V_m \quad \text{and} \quad m_r = \rho_r V_r$$

these terms can be substituted into Equation (9.3) so that

$$\rho_c = f_m \rho_m + f_r \rho_r \quad (9.4)$$

where $f_m = V_m/V_c$ and $f_r = V_r/V_c$ are simply the volume fractions of the matrix and reinforcing phases.

Fiber-Reinforced Composites Determining mechanical properties of composites from constituent properties is usually more involved. The rule of mixtures can sometimes be used to estimate the modulus of elasticity of a fiber-reinforced composite made of continuous fibers where E_c is measured in the longitudinal direction. The situation is depicted in Figure 9.5(a); it is assumed that the fiber material is much stiffer than the matrix and that the bonding between the two phases is secure. Under this model, the modulus of the composite can be predicted as follows:

$$E_c = f_m E_m + f_r E_r \quad (9.5)$$

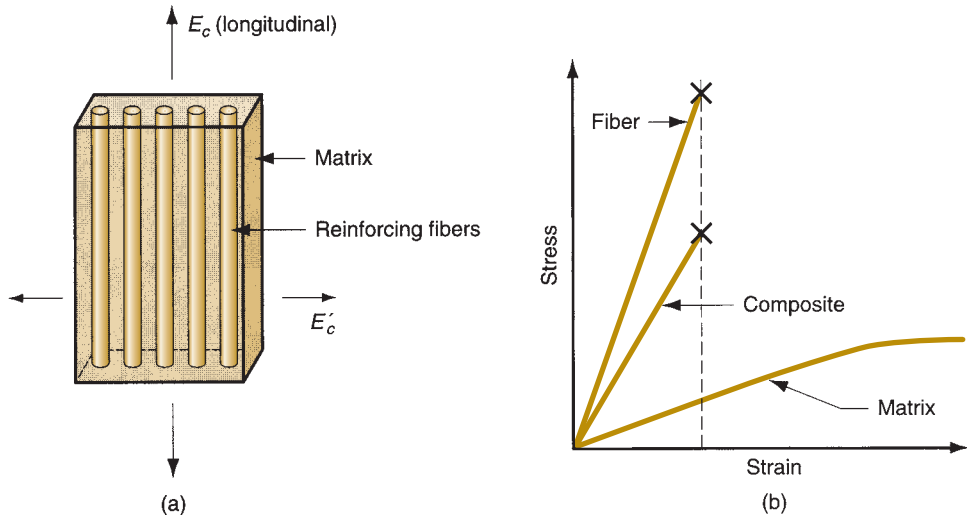


FIGURE 9.5 (a) Model of a fiber-reinforced composite material showing direction in which elastic modulus is being estimated by the rule of mixtures. (b) Stress-strain relationships for the composite material and its constituents. The fiber is stiff but brittle, while the matrix (commonly a polymer) is soft but ductile. The composite's modulus is a weighted average of its components' moduli. But when the reinforcing fibers fail, the composite does likewise.

where E_c , E_m , and E_r are the elastic moduli of the composite and its constituents, MPa (lb/in²); and f_m and f_r are again the volume fractions of the matrix and reinforcing phase. The effect of Equation (9.5) is seen in Figure 9.5(b).

Perpendicular to the longitudinal direction, the fibers contribute little to the overall stiffness except for their filling effect. The composite modulus can be estimated in this direction using the following:

$$E'_c = \frac{E_m E_r}{f_m E_r + f_r E_m} \quad (9.6)$$

where E'_c = elastic modulus perpendicular to the fiber direction, MPa (lb/in²). The two equations for E_c demonstrate the significant anisotropy of fiber-reinforced composites. This directional effect can be seen in Figure 9.6 for a fiber-reinforced polymer

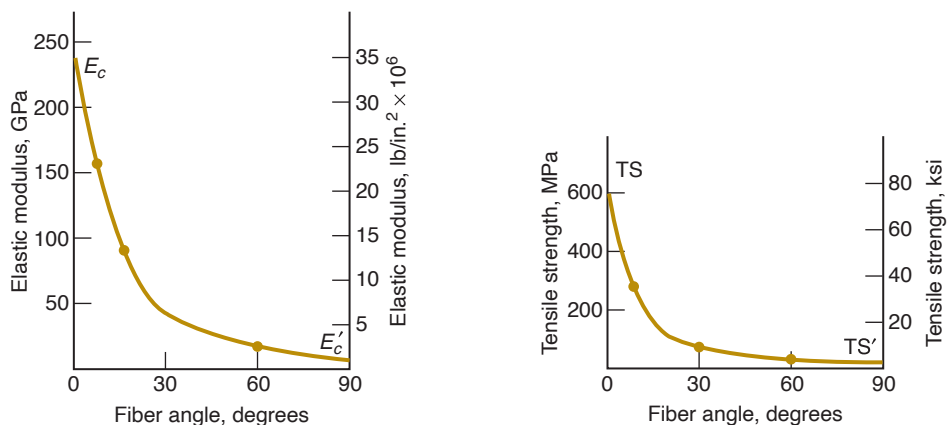


FIGURE 9.6 Variation in elastic modulus and tensile strength as a function of direction of measurement relative to longitudinal axis of carbon fiber-reinforced epoxy composite. (Source: [7]).

composite, in which both elastic modulus and tensile strength are measured relative to fiber direction.

Fibers illustrate the importance of geometric shape. Most materials have tensile strengths several times greater in a fibrous form than in bulk. However, applications of fibers are limited by surface flaws, buckling when subjected to compression, and the inconvenience of the filament geometry when a solid component is needed. By imbedding the fibers in a polymer matrix, a composite material is obtained that avoids the problems of fibers but utilizes their strengths. The matrix provides the bulk shape to protect the fiber surfaces and resist buckling; and the fibers lend their high strength to the composite. When a load is applied, the low-strength matrix deforms and distributes the stress to the high-strength fibers, which then carry the load. If individual fibers break, the load is redistributed through the matrix to other fibers.

9.1.4 OTHER COMPOSITE STRUCTURES

The model of a composite material described above is one in which a reinforcing phase is imbedded in a matrix phase, the combination having properties that are superior in certain respects to either of the constituents alone. However, composites can take alternative forms that do not fit this model, some of which are of considerable commercial and technological importance.

A **laminar composite structure** consists of two or more layers bonded together to form an integral piece, as in Figure 9.7(a). The layers are usually thick enough that this composite can be readily identified—not always the case with other composites. The layers are often of different materials, but not necessarily. Plywood is such an example; the layers are of the same wood, but the grains are oriented differently to increase overall strength of the laminated piece. A laminar composite often uses different materials in its layers to gain the advantage of combining the particular properties of each. In some cases, the layers themselves may be composite materials. It was mentioned that wood is a composite material; therefore, plywood is a laminar composite structure in which the layers themselves are composite materials. A list of examples of laminar composites is compiled in Table 9.3.

The **sandwich structure** is sometimes distinguished as a special case of the laminar composite structure. It consists of a relatively thick core of low-density material bonded on both faces to thin sheets of a different material. The low-density core may be a **foamed material**, as in Figure 9.7(b), or a **honeycomb**, as in (c). The reason for using a sandwich structure is to obtain a material with high strength-to-weight and stiffness-to-weight ratios.

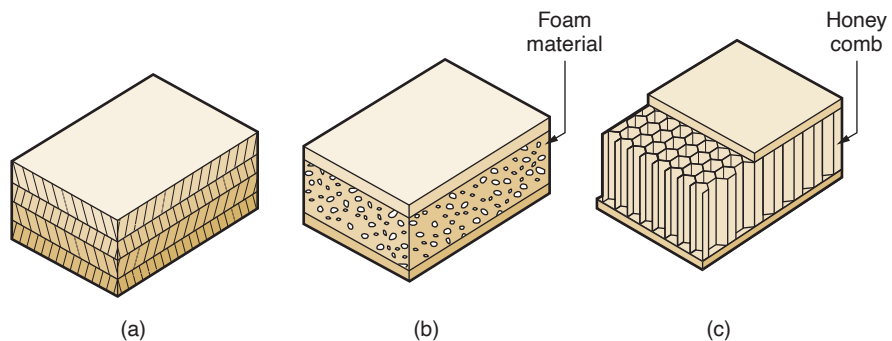


FIGURE 9.7 Laminar composite structures: (a) conventional laminar structure; (b) sandwich structure using a foam core, and (c) honeycomb sandwich structure.

TABLE • 9.3 Examples of laminar composite structures.

Laminar Composite	Description (reference in text if applicable)
Automotive tires	A tire consists of multiple layers bonded together; the layers are composite materials (rubber reinforced with carbon black), and the plies consist of rubber-impregnated fabrics (Chapter 14).
Honeycomb sandwich	A lightweight honeycomb structure is bonded on either face to thin sheets, as in Figure 9.7(c).
FRPs	Multilayered fiber-reinforced plastic panels are used for aircraft, automobile body panels, and boat hulls (Chapter 14).
Plywood	Alternating sheets of wood are bonded together at different orientations for improved strength.
Printed circuit boards	Layers of copper and reinforced plastic are used for electrical conductivity and insulation, respectively (Section 34.2).
Snow skis	Skis are laminar composite structures consisting of multiple layers of metals, particle board, and phenolic plastic.
Windshield glass	Two layers of glass on either side of a sheet of tough plastic (Section 12.3.1).

2 Metal Matrix Composites

Metal matrix composites (MMCs) consist of a metal matrix reinforced by a second phase. Common reinforcing phases include (1) particles of ceramic and (2) fibers of various materials, including other metals, ceramics, carbon, and boron. MMCs of the first type are commonly called *cermets*.

9.2.1 CERMETS

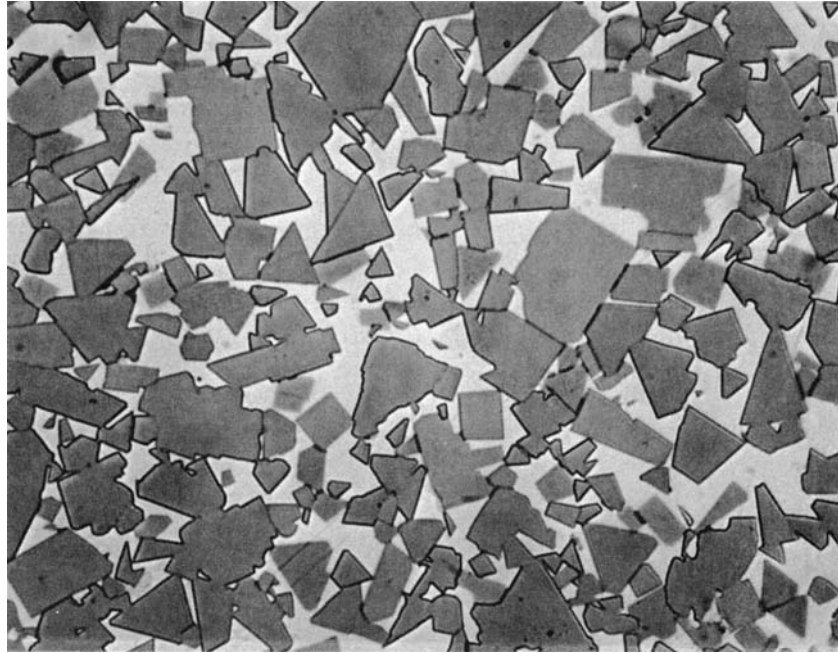
A *cermet*¹ is a composite material in which a ceramic is contained in a metallic matrix. The ceramic often dominates the mixture, sometimes ranging up to 96% by volume. Bonding can be enhanced by slight solubility between phases at the elevated temperatures used in processing these composites. Cermets can be subdivided into (1) cemented carbides and (2) oxide-based cermets.

Cemented Carbides *Cemented carbides* are composed of one or more carbide compounds bonded in a metallic matrix. The term *cermet* is not used for all of these materials, even though it is technically correct. The common cemented carbides are based on tungsten carbide (WC), titanium carbide (TiC), and chromium carbide (Cr₃C₂). Tantalum carbide (TaC) and others are also used but less commonly. The principal metallic binders are cobalt and nickel. The carbide ceramics (Section 7.3.2) are the principal ingredient in cemented carbides, typically ranging in content from 80% to 95% of total weight.

Cemented carbide parts are produced by particulate processing techniques (Section 16.3). Cobalt is the binder used for WC (see Figure 9.8), and nickel is a common binder for TiC and Cr₃C₂. Even though the binder constitutes only about 5% to 15%, its effect on mechanical properties is significant in the composite

¹The word “cermet” was first used in the English language around 1948.

FIGURE 9.8
Photomicrograph
(about 1500X) of
cemented carbide
with 85% WC and
15% Co. (Photo courtesy
of Kennametal Inc.)



material. Using WC–Co as an example, as the percentage of Co is increased, hardness is decreased and transverse rupture strength (TRS) is increased, as shown in Figure 9.9. TRS correlates with toughness of the WC–Co composite.

Cutting tools are the most common application of cemented carbides based on **tungsten carbide**. Other applications of WC–Co cemented carbides include wire drawing dies, rock-drilling bits and other mining tools, dies for powder metallurgy, indenters for hardness testers, and other applications where hardness and wear resistance are critical requirements.

Titanium carbide cermet are used principally for high temperature applications. Nickel is the preferred binder; its oxidation resistance at high temperatures is

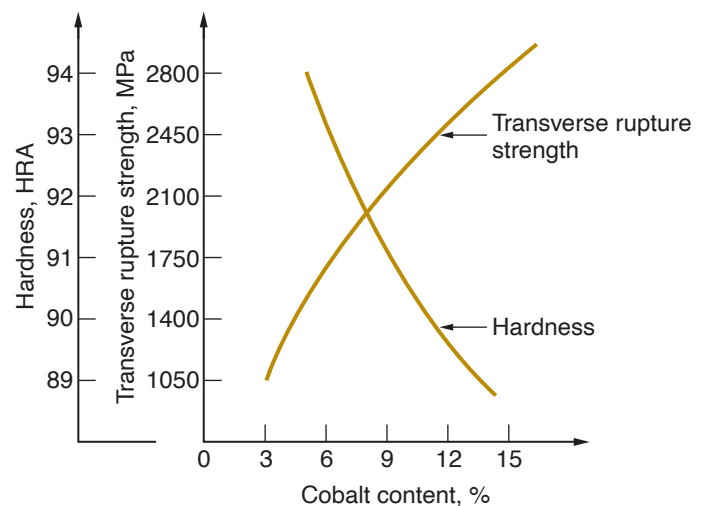


FIGURE 9.9 Typical
plot of hardness and
transverse rupture
strength as a function
of cobalt content.

superior to that of cobalt. Applications include gas-turbine nozzle vanes, valve seats, thermocouple protection tubes, torch tips, and hot-working spinning tools [11]. TiC–Ni is also used as a cutting tool material in machining operations.

Compared with WC–Co cemented carbides, nickel-bonded *chromium carbides* are more brittle, but have excellent chemical stability and corrosion resistance. This combination, together with good wear resistance, makes it suitable for applications such as gage blocks, valve liners, spray nozzles, and bearing seal rings [11].

Oxide-based Cermets Most of these composites utilize Al_2O_3 as the particulate phase; MgO is another oxide sometimes used. A common metal matrix is chromium, although other metals can also be used as binders. Relative proportions of the two phases vary significantly, with the possibility for the metal binder to be the major ingredient. Applications include cutting tools, mechanical seals, and thermocouple shields.

9.2.2 FIBER-REINFORCED METAL MATRIX COMPOSITES

These MMCs are of interest because they combine the high tensile strength and modulus of elasticity of a fiber with metals of low density, thus achieving good strength-to-weight and modulus-to-weight ratios in the resulting composite material. Typical metals used as the low-density matrix are aluminum, magnesium, and titanium. Some of the important fiber materials used in the composite include Al_2O_3 , boron, carbon, and SiC.

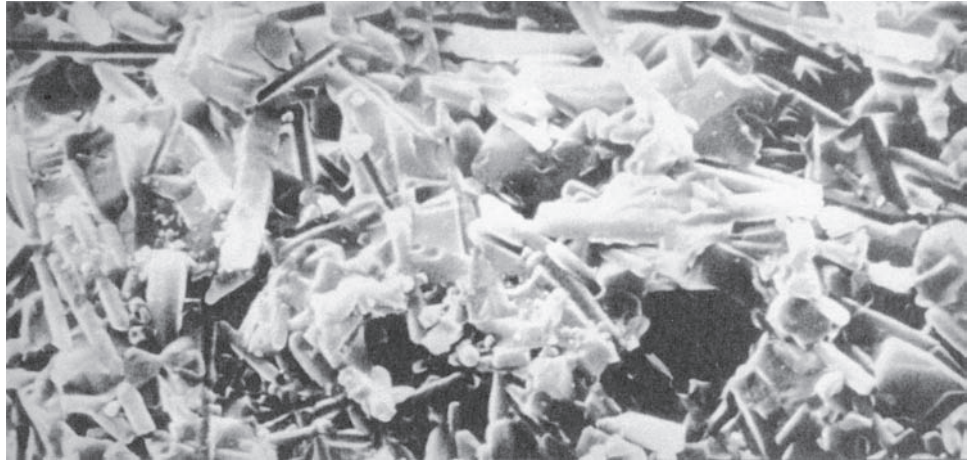
Properties of fiber-reinforced MMCs are anisotropic, as expected. Maximum tensile strength in the preferred direction is obtained by using continuous fibers bonded strongly to the matrix metal. Elastic modulus and tensile strength of the composite material increase with increasing fiber volume. MMCs with fiber reinforcement have good high-temperature strength properties; and they are good electrical and thermal conductors. Applications have largely been components in aircraft and turbine machinery, where these properties can be exploited.

3 Ceramic Matrix Composites

Ceramics have certain attractive properties: high stiffness, hardness, hot hardness, and compressive strength; and relatively low density. Ceramics also have several faults: low toughness and bulk tensile strength, and susceptibility to thermal cracking. Ceramic matrix composites (CMCs) represent an attempt to retain the desirable properties of ceramics while compensating for their weaknesses. CMCs consist of a ceramic primary phase imbedded with a secondary phase. To date, most development work has focused on the use of fibers as the secondary phase. Success has been elusive. Technical difficulties include thermal and chemical compatibility of the constituents in CMCs during processing. Also, as with any ceramic material, limitations on part geometry must be considered.

Ceramic materials used as matrices include alumina (Al_2O_3), boron carbide (B_4C), boron nitride (BN), silicon carbide (SiC), silicon nitride (Si_3N_4), titanium carbide (TiC), and several types of glass [10]. Some of these materials are still in the development stage as CMC matrices. Fiber materials in CMCs include carbon, SiC, and Al_2O_3 .

FIGURE 9.10 Highly magnified electron microscopy photograph (about 3000X) showing fracture surface of SiC whisker reinforced ceramic (Al_2O_3) used as cutting tool material. (Courtesy of Greenleaf Corporation.)



The reinforcing phase in current CMC technology consists of either short fibers, such as whiskers, or long fibers. Products with short fibers have been successfully fabricated using particulate processing methods, the fibers being treated as a form of powder in these materials. Although there are performance advantages in using long fibers as reinforcement in ceramic matrix composites, development of economical processing techniques for these materials has been difficult. One promising commercial application of CMCs is in metal-cutting tools as a competitor of cemented carbides, illustrated in Figure 9.10. The composite tool material has whiskers of SiC in a matrix of Al_2O_3 . Other potential applications are in elevated temperatures and environments that are chemically corrosive to other materials.

9.4 Polymer Matrix Composites

A **polymer matrix composite** (PMC) consists of a polymer primary phase in which a secondary phase is imbedded in the form of fibers, particles, or flakes. Commercially, PMCs are the most important of the three classes of synthetic composites. They include most plastic molding compounds, rubber reinforced with carbon black, and fiber-reinforced polymers (FRPs). Of the three, FRPs are most closely identified with the term composite. If one mentions “composite material” to a design engineer, FRP is usually the composite that comes to mind.

9.4.1 FIBER-REINFORCED POLYMERS

A **fiber-reinforced polymer** is a composite material consisting of a polymer matrix imbedded with high-strength fibers. The polymer matrix is usually a thermosetting plastic such as unsaturated polyester or epoxy, but thermoplastic polymers, such as nylons (polyamides), polycarbonate, polystyrene, and polyvinylchloride, are also used. In addition, elastomers are also reinforced by fibers for rubber products such as tires and conveyor belts.

Fibers in PMCs come in various forms: discontinuous (chopped), continuous, or woven as a fabric. Principal fiber materials in FRPs are glass, carbon, and Kevlar 49. Less common fibers include boron, SiC, and Al_2O_3 , and steel. Glass (in particular

E-glass) is the most common fiber material in today's FRPs; its use to reinforce plastics dates from around 1920.

The term **advanced composites** is sometimes used in connection with FRPs developed since the late 1960s that use boron, carbon, or Kevlar, as the reinforcing fibers [13]. Epoxy is the common matrix polymer. These composites generally have high fiber content ($\geq 50\%$ by volume) and possess high strength and modulus of elasticity. When two or more fiber materials are combined in the FRP composite, it is called a **hybrid composite**. Advantages cited for hybrids over conventional or advanced FRPs include balanced strength and stiffness, improved toughness and impact resistance, and reduced weight [11]. Advanced and hybrid composites are used in aerospace applications.

The most widely used form of the FRP itself is a laminar structure, made by stacking and bonding thin layers of fiber and polymer until the desired thickness is obtained. By varying the fiber orientation among the layers, a specified level of anisotropy in properties can be achieved in the laminate. This method is used to form parts of thin cross section, such as aircraft wing and fuselage sections, automobile and truck body panels, and boat hulls.

Properties There are a number of attractive features that distinguish fiber-reinforced plastics as engineering materials. Most notable are (1) high strength-to-weight ratio, (2) high modulus-to-weight ratio, and (3) low specific gravity. A typical FRP weighs only about one fifth as much as steel; yet strength and modulus are comparable in the fiber direction. Table 9.4 compares these properties for several FRPs, steels, and an aluminum alloy. Properties listed in Table 9.4 depend on the proportion of fibers in the composite. Both tensile strength and elastic modulus increase as the fiber content is increased, by Equation (9.5). Other properties and characteristics of fiber-reinforced plastics include (4) good fatigue strength; (5) good corrosion resistance, although polymers are soluble in various chemicals; (6) low thermal expansion for many FRPs, leading to good dimensional stability; and (7) significant anisotropy in properties. With regard to this last feature, the mechanical properties of the FRPs given in Table 9.4 are

TABLE • 9.4 Comparison of typical properties of fiber-reinforced plastics and representative metal alloys.

Material	Specific Gravity (SG)	Tensile Strength (TS)		Elastic Modulus (E)		Index ^a	
		MPa	lb/in ²	GPa	lb/in ²	TS/SG	E/SG
Low-C steel	7.87	345	50,000	207	30×10^6	1.0	1.0
Alloy steel (heat treated)	7.87	3450	500,000	207	30×10^6	10.0	1.0
Aluminum alloy (heat treated)	2.70	415	60,000	69	10×10^6	3.5	1.0
FRP: fiberglass in polyester	1.50	205	30,000	69	10×10^6	3.1	1.7
FRP: Carbon in epoxy ^b	1.55	1500	220,000	140	20×10^6	22.3	3.4
FRP: Carbon in epoxy ^c	1.65	1200	175,000	214	31×10^6	16.7	4.9
FRP: Kevlar in epoxy matrix	1.40	1380	200,000	76	11×10^6	22.5	2.1

Compiled from [3], [7], and other sources. Properties are measured in the fiber direction.

^aIndices are relative tensile strength-to-weight (TS/SG) and elastic modulus-to-weight (E/SG) ratios compared to low-C steel as the base (index = 1.0 for the base).

^bHigh tensile strength carbon fibers used in FRP.

^cHigh modulus carbon fibers used in FRP.

in the direction of the fiber. As previously noted, their values are significantly less when measured in a different direction.

Applications During the last three decades there has been a steady growth in the application of fiber-reinforced polymers in products requiring high strength and low weight, often as substitutions for metals. The aerospace industry is one of the biggest users of advanced composites. Designers are continually striving to reduce aircraft weight to increase fuel efficiency and payload capacity. Applications of advanced composites in both military and commercial aircraft have increased steadily. Much of the structural weight of today's airplanes and helicopters consists of FRPs. The new Boeing 787 Dreamliner features 50% (by weight) composite (carbon fiber-reinforced plastic). That's about 80% of the volume of the aircraft. Composites are used for the fuselage, wings, tail, doors, and interior. By comparison, Boeing's 777 has only about 12% composites (by weight).

The automotive industry is another important user of FRPs. The most obvious applications are FRP body panels for cars and truck cabs. A notable example is the Chevrolet Corvette that has been produced with FRP bodies for decades. Less apparent applications are in certain chassis and engine parts. Automotive applications differ from those in aerospace in two significant respects. First, the requirement for high strength-to-weight ratio is less demanding than for aircraft. Car and truck applications can use conventional fiberglass reinforced plastics rather than advanced composites. Second, production quantities are much higher in automotive applications, requiring more economical methods of fabrication. Continued use of low-carbon sheet steel in automobiles in the face of FRP's advantages is evidence of the low cost and processability of steel.

FRPs have been widely adopted for sports and recreational equipment. Fiberglass reinforced plastic has been used for boat hulls since the 1940s. Fishing rods were another early application. Today, FRPs are represented in a wide assortment of sports products, including tennis rackets, golf club shafts, football helmets, bows and arrows, skis, and bicycle wheels.

9.4.2 OTHER POLYMER MATRIX COMPOSITES

In addition to FRPs, other PMCs contain particles, flakes, and short fibers. Ingredients of the secondary phase are called **fillers** when used in polymer molding compounds (Section 8.1.5). Fillers divide into two categories: (1) reinforcements and (2) extenders. **Reinforcing fillers** serve to strengthen or otherwise improve mechanical properties of the polymer. Common examples include: wood flour and powdered mica in phenolic and amino resins to increase strength, abrasion resistance, and dimensional stability; and carbon black in rubber to improve strength, wear, and tear resistance. **Extenders** simply increase the bulk and reduce the cost-per-unit weight of the polymer, but have little or no effect on mechanical properties. Extenders may be formulated to improve molding characteristics of the resin.

Foamed polymers (Section 13.11) are a form of composite in which gas bubbles are imbedded in a polymer matrix. Styrofoam and polyurethane foam are the most common examples. The combination of near-zero density of the gas and relatively low density of the matrix makes these materials extremely light weight. The gas mixture also lends very low thermal conductivity for applications in which heat insulation is required.