FIBER-REINFORCED COMPOSITES

The most common examples of synthetic composite materials are those with micron-scale reinforcing fibers. Within this category are two distinct subgroups: (1) fiberglass generally using glass fibers with moderately high values of elastic modulus, and (2) advanced composites with even higher moduli fibers. We shall also compare these synthetic materials with an important natural, **fiber-reinforced composite**—wood.

Fiberglass is a classic example of a modern composite system. Reinforcing fibers are shown in Figure 12.12. A typical fracture surface of a composite (Figure 12.13) shows such fibers embedded in the polymeric matrix. Table 12.1 lists some common glass compositions used for fiber reinforcement. Each is the result of substantial development that has led to optimal suitability for specific applications. For example, the most generally used glass-fiber composition is

FIGURE 12.12 *Glass fibers to be used for reinforcement in a fiberglass composite. (Courtesy of Owens-Corning Fiberglas Corporation.)*

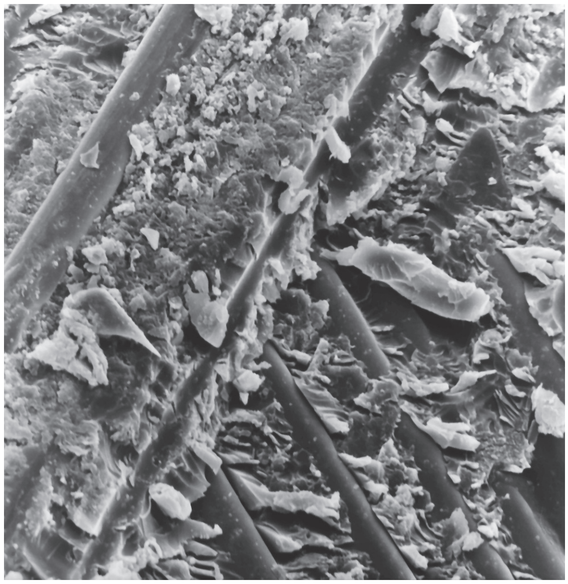


FIGURE 12.13 *The glass-fiber reinforcement in a fiberglass composite is clearly seen in a scanning electron microscope image of a fracture surface. (Courtesy of Owens-Corning Fiberglas Corporation.)*

TABLE 12.1

Compositions of Glass-Reinforcing Fibers

		Composition[a] (wt %)								
Designation	**Characteristic**	**SiO_2**	**(Al_2O_3 + Fe_2O_3)**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**B_2O_3**	**TiO_2**	**ZrO_2**
A-glass	Common soda–lime–silica	72	<1	10		14				
AR-glass	Alkali resistant (for concrete reinforcement)	61	<1	5	<1	14	3		7	10
C-glass	Chemical corrosion resistant	65	4	13	3	8	2	5		
E-glass	Electrical composition	54	15	17	5	<1	<1	8		
S-glass	High strength and modulus	65	25		10					

[a]Approximate and not representing various impurities.

Source: Data from J. G. Mohr and W. P. Rowe, *Fiber Glass,* Van Nostrand Reinhold Company, Inc., New York, 1978.

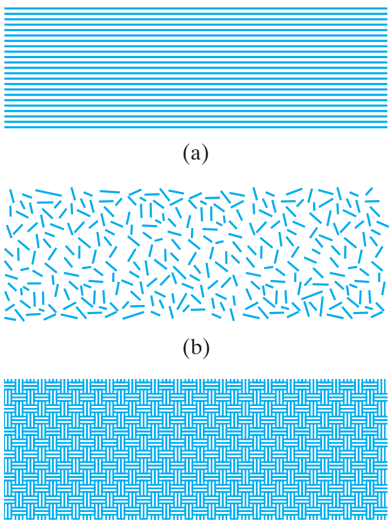
E-glass, in which E stands for "electrical type." The low sodium content of E-glass is responsible for its especially low electrical conductivity and its attractiveness as a dielectric. Its popularity in structural composites is related to the chemical durability of the borosilicate composition. Table 12.2 lists some of the common polymeric matrix materials. Three common fiber configurations are illustrated

TABLE 12.2

Polymeric Matrix Materials for Fiberglass

Polymer	Characteristics and applications
Thermosetting	
Epoxies	High strength (for filament-wound vessels)
Polyesters	For general structures (usually fabric reinforced)
Phenolics	High-temperature applications
Silicones	Electrical applications (e.g., printed-circuit panels)
Thermoplastic	
Nylon 66	
Polycarbonate	Less common, especially good ductility
Polystyrene	

Source: Data from L. J. Broutman and R. H. Krock, Eds., *Modern Composite Materials,* Addison-Wesley Publishing Co., Inc., Reading, MA, 1967, Chapter 13.



(a) (b) (c)

FIGURE 12.14 *Three common fiber configurations for composite reinforcement are (a) continuous fibers, (b) discrete (or chopped) fibers, and (c) woven fabric, which is used to make a laminated structure.*

in Figure 12.14. Parts (a) and (b) show the use of **continuous fibers** and **discrete (chopped) fibers**, respectively. Part (c) shows the **woven fabric** configuration, which is layered with the matrix polymer to form a **laminate**. The implications of these various geometries on mechanical properties will be covered in the discussion of property averaging. For now, we note that optimal strength is achieved by the aligned, continuous fiber reinforcement. Caution is necessary, however, in citing this strength because it is maximal only in the direction parallel to the fiber axes. In other words, the strength is highly **anisotropic**—it varies with direction.

Advanced composites include those systems in which reinforcing fibers have moduli higher than that of E-glass. For example, fiberglass used in most U.S. helicopter blades contains high modulus S-glass fibers (see Table 12.1). Advanced composites, however, generally involve fibers other than glass. Table 12.3 lists a variety of advanced composite systems. These systems include some of the most

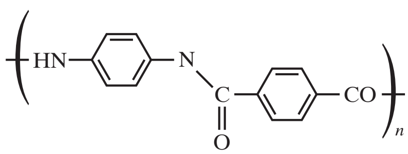
TABLE 12.3

Advanced Composite Systems Other Than Fiberglass	
Class	**Fiber**
Polymer matrix	Para-aramid (Kevlar[a])/epoxy
	Para-aramid (Kevlar[a])/polyester
	C (graphite)/epoxy
	C (graphite)/polyester
	C (graphite)/polyetheretherketone (PEEK)
	C (graphite)/polyphenylene sulfide (PPS)
Metal matrix	B/Al
	C/Al
	Al_2O_3/Al
	Al_2O_3/Mg
	SiC/Al
	SiC/Ti (alloys)
Ceramic matrix	Nb/$MoSi_2$
	C/C
	C/SiC
	SiC/Al_2O_3
	SiC/SiC
	SiC/Si_3N_4
	SiC/Li–Al–silicate (glass-ceramic)

[a]Trade name, DuPont.
Source: Data from K. K. Chawla, University of Alabama, Birmingham; A. K. Dhingra, the DuPont Company; and A. J. Klein, ASM International.

sophisticated materials developed for some of the most demanding engineering applications. The growth of the advanced composites industry began with the materials advances of World War II and accelerated rapidly with the space race of the 1960s and with subsequent growth in demand for commercial aviation and high-performance leisure-time products such as golf clubs and tennis rackets.

Carbon and Kevlar fiber reinforcements represent advances over traditional glass fibers for **polymer–matrix composites**. Carbon fibers typically range in diameter between 4 and 10 μm, with the carbon being a combination of crystalline graphite and noncrystalline regions. Kevlar is a Du Pont trade name for poly *p*-phenyleneterephthalamide (PPD-T), a para-aramid with the formula



(12.7)

Epoxies and polyesters (thermosetting polymers) are traditional matrices. Substantial progress has been made in developing thermoplastic polymer matrices, such as polyetheretherketone (PEEK) and polyphenylene sulfide (PPS). These materials have the advantages of increased toughness and recyclability. Carbon- and Kevlar-reinforced polymers are used in pressure vessels, and Kevlar reinforcement is widely used in tires. Carbon-reinforced PEEK and PPS demonstrate good temperature resistance and are, as a result, attractive for aerospace applications.

Metal–matrix composites have been developed for use in temperature, conductivity, and load conditions beyond the capability of polymer–matrix systems. For example, boron-reinforced aluminum was used in the Space Shuttle Orbiter, and carbon-reinforced aluminum is used in the Hubble Telescope. Alumina-reinforced aluminum is used in automobile engine components.

A primary driving force for the development of **ceramic–matrix composites** is superior high-temperature resistance. These composites, as opposed to traditional ceramics, represent the greatest promise to obtain the requisite toughness for structural applications such as high-efficiency jet-engine designs. An especially advanced composite system in this category is the **carbon–carbon composite**. This high-modulus and high-strength material is also quite expensive. The expense is significantly increased by the process of forming the large carbon chain molecules of the matrix by pyrolysis (heating in an inert atmosphere) of a polymeric hydrocarbon. Carbon–carbon composites are currently being used in high-performance automobiles as friction-resistant materials and in a variety of aerospace applications, such as ablative shields for reentry vehicles.

Metal fibers are frequently small-diameter wires. Especially high-strength reinforcement comes from **whiskers**; small, single-crystal fibers that can be grown with a nearly perfect crystalline structure. Unfortunately, whiskers cannot be grown as continuous filaments in the manner of glass fibers or metal wires. Figure 12.15 contrasts the wide range of cross-sectional geometries associated with reinforcing fibers.

During the 1980s, production of advanced composites in the United States doubled every 5 years. In the first three years of the 1990s, however, production suddenly declined by 20% due to the end of the Cold War and the resulting effect on defense budgets. Various trends have emerged in the advanced composites field in response to these changes. Emerging product applications include the marine market (e.g., high-performance powerboats), improved strength-to-weight ratio civil-engineering structures, and electric-car development. A fundamental challenge to the wider use of advanced composites in the general automotive industry is the need for reduced costs, which cannot occur until greater production capacity is in place. In turn, production capacity cannot be increased without greater demand in the automotive field. In recent decades, some small airplanes and rotorcrafts have utilized as much as 80 to 90 weight % advanced composites. A milestone has been reached with the introduction into commercial flight of the Boeing 787 aircraft in 2011 using 50 weight % advanced structural composites in its construction.

Specific technological developments are occurring in response to the new trend toward nondefense applications. A major thrust is reduced production costs. For this reason, nonautoclave curing of thermosetting resins is being developed for bridge construction. Similarly, resin transfer molding (RTM) involving textile preforms substantially reduces cure times. (The related technique of transfer molding for polymers is illustrated in Figure 12.24.)

Also, automated fiber-placement equipment produces a more rapid fabrication process. The addition of thermoplastics or elastomeric microspheres to thermosetting resins is among the various techniques being used to improve fracture toughness with a goal of reducing delamination and impact damage. Bismaleimide (BMI) resins are an advance over epoxies for heat resistance (over 300°C).

A single composite may contain various types of reinforcing fibers. **Hybrids** are woven fabrics consisting of two or more types of reinforcing fibers (e.g., carbon

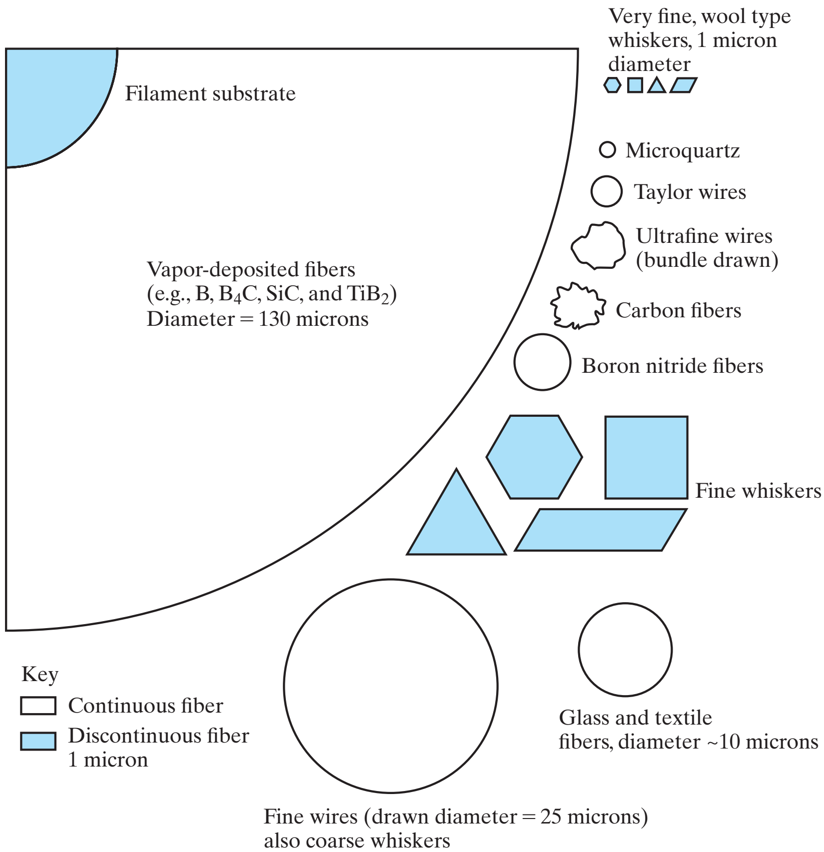


FIGURE 12.15 *Relative cross-sectional areas and shapes of a wide variety of reinforcing fibers. (After L. J. Broutman and R. H. Krock, Eds.,* Modern Composite Materials, *Addison-Wesley Publishing Co., Inc., Reading, MA, 1967, Chapter 14.)*

and glass or carbon and aramid). The combination is a design approach to optimize composite performance. For example, high-strength, noncarbon fibers can be added to carbon fibers to improve the impact resistance of the overall composite.

EXAMPLE 12.6

A fiberglass composite contains 70 vol % E-glass fibers in an epoxy matrix.

(a) Calculate the weight percent glass fibers in the composite.

(b) Determine the density of the composite. The density of E-glass is 2.54 Mg/m^3 ($= g/cm^3$) and for epoxy is 1.1 Mg/m^3.

SOLUTION

(a) For 1 m^3 composite, we would have 0.70 m^3 of E-glass and $(1.00 - 0.70)\ m^3 = 0.30\ m^3$ of epoxy. The mass of each component will be

$$m_{\text{E-glass}} = \frac{2.54\ \text{Mg}}{\text{m}^3} \times 0.70\ \text{m}^3 = 1.77\ \text{Mg}$$

and

$$m_{\text{epoxy}} = \frac{1.1\ \text{Mg}}{\text{m}^3} \times 0.30\ \text{m}^3 = 0.33\ \text{Mg},$$

giving

$$\text{wt \% glass} = \frac{1.77\ \text{Mg}}{(1.77 + 0.33)\ \text{Mg}} \times 100 = 84.3\%.$$

(b) The density will be given by

$$\rho = \frac{m}{V} = \frac{(1.77 + 0.33)\ \text{Mg}}{\text{m}^3} = 2.10\ \text{Mg/m}^3.$$

PRACTICE PROBLEM 12.6

In Example 12.6 we found the density of a typical fiberglass composite. Repeat the calculations for **(a)** 50 vol % and **(b)** 75 vol % E-glass fibers in an epoxy matrix.