Production rates for short-fiber composites (both aligned and randomly oriented) are rapid, and intricate shapes can be formed that are not possible with continuous fiber reinforcement. Furthermore, fabrication costs are considerably lower than for continuous and aligned; fabrication techniques applied to short-fiber composite materials include compression, injection, and extrusion molding, which are described for unreinforced polymers in Section 14.13.

15.6 THE FIBER PHASE

An important characteristic of most materials, especially brittle ones, is that a small-diameter fiber is much stronger than the bulk material. As discussed in Section 9.6, the probability of the presence of a critical surface flaw that can lead to fracture diminishes with decreasing specimen volume, and this feature is used to advantage in the fiber-reinforced composites. Also, the materials used for reinforcing fibers have high tensile strengths.

On the basis of diameter and character, fibers are grouped into three different classifications: *whiskers, fibers,* and *wires.* **Whiskers** are very thin single crystals that have extremely large length-to-diameter ratios. As a consequence of their small size, they have a high degree of crystalline perfection and are virtually flaw free, which accounts for their exceptionally high strengths; they are the strongest known materials. In spite of these high strengths, whiskers are not utilized extensively as a reinforcement medium because they are extremely expensive. Moreover, it is difficult and often impractical to incorporate whiskers into a matrix. Whisker materials include graphite, silicon carbide, silicon nitride, and aluminum oxide; some mechanical characteristics of these materials are given in Table 15.4.

Materials that are classified as **fibers** are either polycrystalline or amorphous and have small diameters; fibrous materials are generally either polymers or ceramics (e.g., the polymer aramids, glass, carbon, boron, aluminum oxide, and silicon carbide). Table 15.4 also presents some data on a few materials that are used in fiber form.

Fine wires have relatively large diameters; typical materials include steel, molybdenum, and tungsten. Wires are utilized as a radial steel reinforcement in automobile tires, in filament-wound rocket casings, and in wire-wound high-pressure hoses.

15.7 THE MATRIX PHASE

The **matrix phase** of fibrous composites may be a metal, polymer, or ceramic. In general, metals and polymers are used as matrix materials because some ductility is desirable; for ceramic-matrix composites (Section 15.10), the reinforcing component is added to improve fracture toughness. The discussion of this section will focus on polymer and metal matrices.

For fiber-reinforced composites, the matrix phase serves several functions. First, it binds the fibers together and acts as the medium by which an externally applied stress is transmitted and distributed to the fibers; only a very small proportion of an applied load is sustained by the matrix phase. Furthermore, the matrix material should be ductile. In addition, the elastic modulus of the fiber should be much higher than that of the matrix. The second function of the matrix is to protect the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels. Finally, the matrix separates the fibers and, by virtue of its relative softness and

Table 15.4 Characteristics of Several Fiber-Reinforcement Materials

Material	Specific Gravity	Tensile Strength [GPa (10⁶ psi)]	Specific Strength (GPa)	Modulus of Elasticity [GPa (10⁶ psi)]	Specific Modulus (GPa)
		Whiskers			
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
		Fibers			
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon[a]	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-Glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
		Metallic Wires			
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1

[a] The term "carbon" instead of "graphite" is used to denote these fibers, since they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.

plasticity, prevents the propagation of brittle cracks from fiber to fiber, which could result in catastrophic failure; in other words, the matrix phase serves as a barrier to crack propagation. Even though some of the individual fibers fail, total composite fracture will not occur until large numbers of adjacent fibers, once having failed, form a cluster of critical size.

It is essential that adhesive bonding forces between fiber and matrix be high to minimize fiber pull-out. In fact, bonding strength is an important consideration in the choice of the matrix–fiber combination. The ultimate strength of the composite depends to a large degree on the magnitude of this bond; adequate bonding is essential to maximize the stress transmittance from the weak matrix to the strong fibers.

15.8 POLYMER–MATRIX COMPOSITES

Polymer-matrix composites (*PMCs*) consist of a polymer resin[1] as the matrix, with fibers as the reinforcement medium. These materials are used in the greatest diversity of composite applications, as well as in the largest quantities, in light of their room-temperature properties, ease of fabrication, and cost. In this section the various classifications of PMCs are discussed according to reinforcement type (i.e., glass, carbon, and aramid), along with their applications and the various polymer resins that are employed.

GLASS FIBER-REINFORCED POLYMER (GFRP) COMPOSITES

Fiberglass is simply a composite consisting of glass fibers, either continuous or discontinuous, contained within a polymer matrix; this type of composite is produced in the largest quantities. The composition of the glass that is most commonly drawn into fibers (sometimes referred to as *E-glass*) is contained in Table 13.10; fiber diameters normally range between 3 and 20 μm. Glass is popular as a fiber reinforcement material for several reasons:

1. It is easily drawn into high-strength fibers from the molten state.
2. It is readily available and may be fabricated into a glass-reinforced plastic economically using a wide variety of composite-manufacturing techniques.
3. As a fiber, it is relatively strong, and when embedded in a plastic matrix, it produces a composite having a very high specific strength.
4. When coupled with the various plastics, it possesses a chemical inertness that renders the composite useful in a variety of corrosive environments.

The surface characteristics of glass fibers are extremely important because even minute surface flaws can deleteriously affect the tensile properties, as discussed in Section 9.6. Surface flaws are easily introduced by rubbing or abrading the surface with another hard material. Also, glass surfaces that have been exposed to the normal atmosphere for even short time periods generally have a weakened surface layer that interferes with bonding to the matrix. Newly drawn fibers are normally coated during drawing with a "size," a thin layer of a substance that protects the fiber surface from damage and undesirable environmental interactions. This size is ordinarily removed prior to composite fabrication and replaced with a "coupling agent" or finish that promotes a better bond between the fiber and matrix.

There are several limitations to this group of materials. In spite of having high strengths, they are not very stiff and do not display the rigidity that is necessary for some applications (e.g., as structural members for airplanes and bridges). Most fiberglass materials are limited to service temperatures below 200°C (400°F); at higher temperatures, most polymers begin to flow or to deteriorate. Service temperatures may be extended to approximately 300°C (575°F) by using high-purity fused silica for the fibers and high-temperature polymers such as the polyimide resins.

Many fiberglass applications are familiar: automotive and marine bodies, plastic pipes, storage containers, and industrial floorings. The transportation industries are utilizing increasing amounts of glass fiber-reinforced plastics in an effort to decrease

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[1] The term "resin" is used in this context to denote a high-molecular-weight reinforcing plastic.

vehicle weight and boost fuel efficiencies. A host of new applications are being used or currently investigated by the automotive industry.

CARBON FIBER-REINFORCED POLYMER (CFRP) COMPOSITES

Carbon is a high-performance fiber material that is the most commonly used reinforcement in advanced (i.e., nonfiberglass) polymer-matrix composites. The reasons for this are as follows:

1. Carbon fibers have the highest specific modulus and specific strength of all reinforcing fiber materials.
2. They retain their high-tensile modulus and high strength at elevated temperatures; high-temperature oxidation, however, may be a problem.
3. At room temperature carbon fibers are not affected by moisture or a wide variety of solvents, acids, and bases.
4. These fibers exhibit a diversity of physical and mechanical characteristics, allowing composites incorporating these fibers to have specific engineered properties.
5. Fiber and composite manufacturing processes have been developed that are relatively inexpensive and cost effective.

Use of the term "carbon fiber" may seem perplexing inasmuch as carbon is an element, and, as noted in Section 3.9, the stable form of crystalline carbon at ambient conditions is graphite, having the structure represented in Figure 3.17. Carbon fibers are not totally crystalline, but are composed of both graphitic and noncrystalline regions; these areas of noncrystallinity are devoid of the three-dimensional ordered arrangement of hexagonal carbon networks that is characteristic of graphite (Figure 3.17).

Manufacturing techniques for producing carbon fibers are relatively complex and will not be discussed. However, three different organic precursor materials are used—rayon, polyacrylonitrile (PAN), and pitch. Processing technique will vary from precursor to precursor, as will also the resultant fiber characteristics.

One classification scheme for carbon fibers is according to tensile modulus; on this basis the four classes are standard, intermediate, high, and ultrahigh moduli. Furthermore, fiber diameters normally range between 4 and 10 μm; both continuous and chopped forms are available. In addition, carbon fibers are normally coated with a protective epoxy size that also improves adhesion with the polymer matrix.

Carbon-reinforced polymer composites are currently being utilized extensively in sports and recreational equipment (fishing rods, golf clubs), filament-wound rocket motor cases, pressure vessels, and aircraft structural components—both military and commercial, fixed wing and helicopters (e.g., as wing, body, stabilizer, and rudder components).

ARAMID FIBER-REINFORCED POLYMER COMPOSITES

Aramid fibers are high-strength, high-modulus materials that were introduced in the early 1970s. They are especially desirable for their outstanding strength-to-weight ratios, which are superior to metals. Chemically, this group of materials is known as poly paraphenylene terephthalamide. There are a number of aramid materials; trade names for two of the most common are Kevlar and Nomex. For the former, there are several grades (viz. Kevlar 29, 49, and 149) which have different mechanical behaviors. During synthesis, the rigid molecules are aligned in the
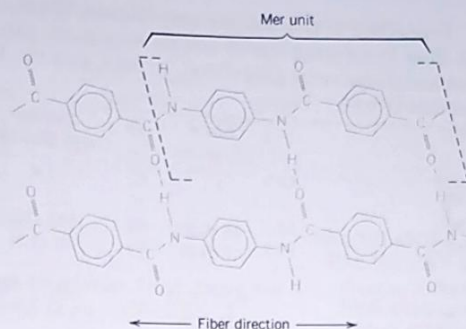
Mer unit

Fiber direction

FIGURE 15.10 Schematic representation of mer and chain structures for aramid (Kevlar) fibers. Chain alignment with the fiber direction and hydrogen bonds that form between adjacent chains are also shown. (From F. R. Jones, Editor, *Handbook of Polymer-Fibre Composites*. Copyright © 1994 by Addison Wesley Longman. Reprinted with permission.)

direction of the fiber axis, as liquid crystal domains (Section 13.16); the mer chemistry and mode of chain alignment are represented in Figure 15.10. Mechanically, these fibers have longitudinal tensile strengths and tensile moduli (Table 15.4) that are higher than other polymeric fiber materials; however, they are relatively weak in compression. In addition, this material is known for its toughness, impact resistance, and resistance to creep and fatigue failure. Even though the aramids are thermoplastics, they are, nevertheless, resistant to combustion and stable to relatively high temperatures; the temperature range over which they retain their high mechanical properties is between −200 and 200°C (−330 and 390°F). Chemically, they are susceptible to degradation by strong acids and bases, but they are relatively inert in other solvents and chemicals.

The aramid fibers are most often used in composites having polymer matrices; common matrix materials are the epoxies and polyesters. Since the fibers are relatively flexible and somewhat ductile, they may be processed by most common textile operations. Typical applications of these aramid composites are in ballistic products (bullet-proof vests), sporting goods, tires, ropes, missile cases, pressure vessels, and as a replacement for asbestos in automotive brake and clutch linings, and gaskets.

The properties of continuous and aligned glass-, carbon-, and aramid-fiber reinforced epoxy composites are included in Table 15.5. Thus, a comparison of the mechanical characteristics of these three materials may be made in both longitudinal and transverse directions.

OTHER FIBER REINFORCEMENT MATERIALS

Glass, carbon, and the aramids are the most common fiber reinforcements incorporated in polymer matrices. Other fiber materials that are used to much lesser degrees are boron, silicon carbide, and aluminum oxide; tensile moduli, tensile strengths, specific strengths, and specific moduli of these materials in fiber form are contained in Table 15.4. Boron fiber-reinforced polymer composites have been used in military aircraft components, helicopter rotor blades, and some sporting goods. Silicon carbide and alumina fibers are utilized in tennis rackets, circuit boards, and rocket nose cones.

POLYMER MATRIX MATERIALS

The roles assumed by the polymer matrix are outlined in Section 15.7. In addition, the matrix often determines the maximum service temperature, since it normally

Table 15.5 Properties of Continuous and Aligned Glass-, Carbon-, and Aramid-fiber Reinforced Epoxy-matrix Composites in Longitudinal and Transverse Directions. In All Cases the Fiber Volume Fraction is 0.60

Property	Glass (E-glass)	Carbon (High Strength)	Aramid (Kevlar 49)
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

Source: Adapted from R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989.

softens, melts, or degrades at a much lower temperature than the fiber reinforcement.

The most widely utilized and least expensive polymer resins are the polyesters and vinyl esters;[2] these matrix materials are used primarily for glass fiber-reinforced composites. A large number of resin formulations provide a wide range of properties for these polymers. The epoxies are more expensive and, in addition to commercial applications, are also utilized extensively in PMCs for aerospace applications; they have better mechanical properties and resistance to moisture than the polyesters and vinyl resins. For high-temperature applications, polyimide resins are employed; their continuous-use, upper-temperature limit is approximately 230°C (450°F). And finally, high-temperature thermoplastic resins offer the potential to be used in future aerospace applications; such materials include polyetheretherketone (PEEK), polyphenylene sulfide (PPS), and polyetherimide (PEI).

15.9 METAL–MATRIX COMPOSITES

As the name implies, for **metal-matrix composites** (*MMCs*), the matrix is a ductile metal. These materials may be utilized at higher service temperatures than their base metal counterparts; furthermore, the reinforcement may improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity, and dimensional stability. Some of the advantages of these materials over the polymer-matrix composites include higher operating temperatures, nonflammability, and greater resistance to degradation by organic fluids. Metal-matrix composites are much more expensive than PMCs, and, therefore, their (MMC) use is somewhat restricted.

The superalloys, as well as alloys of aluminum, magnesium, titanium, and copper, are employed as matrix materials. The reinforcement may be in the form of particulates, both continuous and discontinuous fibers, and whiskers; concentrations

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[2] The chemistry and typical properties of some of the matrix materials discussed in this section are included in Appendices B, D, and E.

Table 15.6 Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers

Fiber	Matrix	Fiber Content (vol%)	Density (g/cm³)	Longitudinal Tensile Modulus (GPa)	Longitudinal Tensile Strength (MPa)
Carbon	6061 Al	41	2.44	320	620
Boron	6061 Al	48	—	207	1515
SiC	6061 Al	50	2.93	230	1480
Alumina	380.0 Al	24	—	120	340
Carbon	AZ31 Mg	38	1.83	300	510
Borsic	Ti	45	3.68	220	1270

Source: Adapted from J. W. Weeton, D. M. Peters, and K. L. Thomas, *Engineers' Guide to Composite Materials,* ASM International, Materials Park, OH, 1987.

normally range between 10 and 60 vol%. Continuous fiber materials include carbon, silicon carbide, boron, alumina, and the refractory metals. On the other hand, discontinuous reinforcements consist primarily of silicon carbide whiskers, chopped fibers of alumina and carbon, and particulates of silicon carbide and alumina. In a sense, the cermets (Section 15.2) fall within this MMC scheme. In Table 15.6 are presented the properties of several common metal-matrix, continuous and aligned fiber-reinforced composites.

Some matrix–reinforcement combinations are highly reactive at elevated temperatures. Consequently, composite degradation may be caused by high-temperature processing, or by subjecting the MMC to elevated temperatures during service. This problem is commonly resolved either by applying a protective surface coating to the reinforcement or by modifying the matrix alloy composition.

Normally the processing of MMCs involves at least two steps: consolidation or synthesis (i.e., introduction of reinforcement into the matrix), followed by a shaping operation. A host of consolidation techniques are available, some of which are relatively sophisticated; discontinuous fiber MMCs are amenable to shaping by standard metal-forming operations (e.g., forging, extrusion, rolling).

Recently, some of the automobile manufacturers have introduced engine components consisting of an aluminum-alloy matrix that is reinforced with alumina and carbon fibers; this MMC is light in weight and resists wear and thermal distortion. Aerospace structural applications include advanced aluminum alloy metal-matrix composites; boron fibers are used as the reinforcement for the Space Shuttle Orbiter, and continuous graphite fibers for the Hubble Telescope.

The high-temperature creep and rupture properties of some of the superalloys (Ni- and Co-based alloys) may be enhanced by fiber reinforcement using refractory metals such as tungsten. Excellent high-temperature oxidation resistance and impact strength are also maintained. Designs incorporating these composites permit higher operating temperatures and better efficiencies for turbine engines.

15.10 Ceramic–Matrix Composites

As discussed in Chapter 13, ceramic materials are inherently resilient to oxidation and deterioration at elevated temperatures; were it not for their disposition to brittle fracture, some of these materials would be ideal candidates for use in high-temperature and severe-stress applications, specifically for components in automobile and aircraft gas turbine engines. Fracture toughness values for ceramic materials