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, 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 normally range between 10 and 60 vol%. Continuous-fiber materials include carbon, silicon carbide, boron, aluminum oxide, and the refractory metals. On the other hand, discontinuous reinforcements consist primarily of silicon carbide whiskers, chopped fibers of aluminum oxide and carbon, and particulates of silicon carbide and aluminum oxide. In a sense, the cermets (Section 16.2) fall within this MMC scheme. Table 16.9 presents 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).

Automobile manufacturers have recently begun to use MMCs in their products. For example, some engine components have been introduced consisting of an aluminum-alloy matrix that is reinforced with aluminum oxide and carbon fibers; this MMC is light in weight and resists wear and thermal distortion. Metal-matrix composites are also employed in driveshafts (that have higher rotational speeds and reduced vibrational noise levels), extruded stabilizer bars, and forged suspension and transmission components.

The aerospace industry also uses MMCs. 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 Space Telescope.

Table 16.9 Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers

Fiber	*Matrix*	*Fiber Content (vol%)*	*Density (g/cm^3)*	*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.

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.

16.10 CERAMIC-MATRIX COMPOSITES

As discussed in Chapters 12 and 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 are low and typically lie between 1 and 5 MPa$\sqrt{\text{m}}$ (0.9 and 4.5 ksi$\sqrt{\text{in.}}$); see Table 8.1 and Table B.5 in Appendix B. By way of contrast, K_{Ic} values for most metals are much higher [15 to greater than 150 MPa$\sqrt{\text{m}}$ (14 to $>$ 140 ksi$\sqrt{\text{in.}}$)].

ceramic-matrix composite

The fracture toughnesses of ceramics have been improved significantly by the development of a new generation of **ceramic-matrix composites** (*CMC*s)—particulates, fibers, or whiskers of one ceramic material that have been embedded into a matrix of another ceramic. Ceramic-matrix composite materials have extended fracture toughnesses to between about 6 and 20 MPa$\sqrt{\text{m}}$ (5.5 and 18 ksi$\sqrt{\text{in.}}$).

In essence, this improvement in the fracture properties results from interactions between advancing cracks and dispersed phase particles. Crack initiation normally occurs with the matrix phase, whereas crack propagation is impeded or hindered by the particles, fibers, or whiskers. Several techniques are used to retard crack propagation, which are discussed as follows.

One particularly interesting and promising toughening technique employs a phase transformation to arrest the propagation of cracks and is aptly termed *transformation toughening.* Small particles of partially stabilized zirconia (Section 12.7) are dispersed within the matrix material, often Al_2O_3 or ZrO_2 itself. Typically, CaO, MgO, Y_2O_3, and CeO are used as stabilizers. Partial stabilization allows retention of the metastable tetragonal phase at ambient conditions rather than the stable monoclinic phase; these two phases are noted on the ZrO_2–$CaZrO_3$ phase diagram in Figure 12.26. The stress field in front of a propagating crack causes these metastably retained tetragonal particles to undergo transformation to the stable monoclinic phase. Accompanying this transformation is a slight particle volume increase, and the net result is that compressive stresses are established on the crack surfaces near the crack tip that tend to pinch the crack shut, thereby arresting its growth. This process is demonstrated schematically in Figure 16.12.

Other recently developed toughening techniques involve the use of ceramic whiskers, often SiC or Si_3N_4. These whiskers may inhibit crack propagation by (1) deflecting crack tips, (2) forming bridges across crack faces, (3) absorbing energy during pullout as the whiskers debond from the matrix, and/or (4) causing a redistribution of stresses in regions adjacent to the crack tips.

In general, increasing fiber content improves strength and fracture toughness; this is demonstrated in Table 16.10 for SiC whisker-reinforced alumina. Furthermore, there is a considerable reduction in the scatter of fracture strengths for whisker-reinforced ceramics relative to their unreinforced counterparts. In addition, these CMCs exhibit improved high-temperature creep behavior and resistance to thermal shock (i.e., failure resulting from sudden changes in temperature).

Ceramic-matrix composites may be fabricated using hot pressing, hot isostatic pressing, and liquid-phase sintering techniques. Relative to applications, SiC

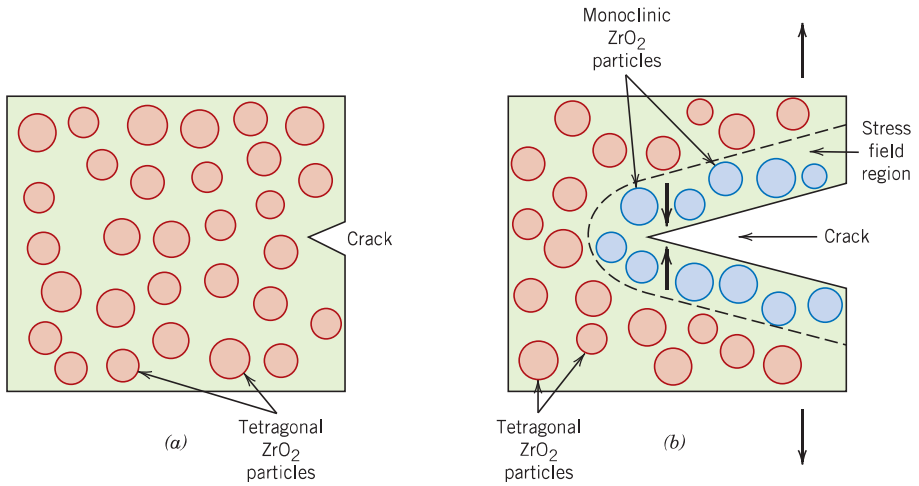

Figure 16.12 Schematic demonstration of transformation toughening. (*a*) A crack prior to inducement of the ZrO_2 particle phase transformation. (*b*) Crack arrestment due to the stress-induced phase transformation.

whisker-reinforced aluminas are being used as cutting-tool inserts for machining hard metal alloys; tool lives for these materials are greater than for cemented carbides (Section 16.2).

16.11 CARBON–CARBON COMPOSITES

carbon–carbon composite

One of the most advanced and promising engineering materials is the carbon fiber–reinforced carbon-matrix composite, often termed a **carbon–carbon composite;** as the name implies, both reinforcement and matrix are carbon. These materials are relatively new and expensive and, therefore, are not currently being used extensively. Their desirable properties include high-tensile moduli and tensile strengths that are retained to temperatures in excess of 2000°C (3630°F), resistance to creep, and relatively large fracture toughness values. Furthermore, carbon–carbon composites have low coefficients of thermal expansion and relatively high thermal conductivities; these characteristics, coupled with high strengths, give rise to a relatively low susceptibility to thermal shock. Their major drawback is a propensity to high-temperature oxidation.

The carbon–carbon composites are employed in rocket motors, as friction materials in aircraft and high-performance automobiles, for hot-pressing molds, in components for advanced turbine engines, and as ablative shields for re-entry vehicles.

Table 16.10 Room Temperature Fracture Strengths and Fracture Toughnesses for Various SiC Whisker Contents in Al_2O_3

Whisker Content (vol%)	*Fracture Strength (MPa)*	*Fracture Toughness ($MPa\sqrt{m}$)*
0	—	4.5
10	455 ± 55	7.1
20	655 ± 135	7.5–9.0
40	850 ± 130	6.0

Source: Adapted from *Engineered Materials Handbook,* Vol. 1, *Composites,* C. A. Dostal (Senior Editor), ASM International, Materials Park, OH, 1987.

The primary reason that these composite materials are so expensive is the relatively complex processing techniques that are employed. Preliminary procedures are similar to those used for carbon-fiber, polymer-matrix composites. That is, the continuous carbon fibers are laid down having the desired two- or three-dimensional pattern; these fibers are then impregnated with a liquid polymer resin, often a phenolic; the workpiece is next formed into the final shape, and the resin is allowed to cure. At this time the matrix resin is *pyrolyzed,* that is, converted into carbon by heating in an inert atmosphere; during pyrolysis, molecular components consisting of oxygen, hydrogen, and nitrogen are driven off, leaving behind large carbon-chain molecules. Subsequent heat treatments at higher temperatures will cause this carbon matrix to densify and increase in strength. The resulting composite, then, consists of the original carbon fibers that remained essentially unaltered, which are contained in this pyrolyzed carbon matrix.

16.12 HYBRID COMPOSITES

hybrid composite

A relatively new fiber-reinforced composite is the **hybrid,** which is obtained by using two or more different kinds of fibers in a single matrix; hybrids have a better all-around combination of properties than composites containing only a single fiber type. A variety of fiber combinations and matrix materials are used, but in the most common system, both carbon and glass fibers are incorporated into a polymeric resin. The carbon fibers are strong and relatively stiff and provide a low-density reinforcement; however, they are expensive. Glass fibers are inexpensive and lack the stiffness of carbon. The glass–carbon hybrid is stronger and tougher, has a higher impact resistance, and may be produced at a lower cost than either of the comparable all-carbon or all-glass reinforced plastics.

The two different fibers may be combined in a number of ways, which will ultimately affect the overall properties. For example, the fibers may all be aligned and intimately mixed with one another, or laminations may be constructed consisting of layers, each of which consists of a single fiber type, alternating one with another. In virtually all hybrids the properties are anisotropic.

When hybrid composites are stressed in tension, failure is usually noncatastrophic (i.e., does not occur suddenly). The carbon fibers are the first to fail, at which time the load is transferred to the glass fibers. Upon failure of the glass fibers, the matrix phase must sustain the applied load. Eventual composite failure concurs with that of the matrix phase.

Principal applications for hybrid composites are lightweight land, water, and air transport structural components, sporting goods, and lightweight orthopedic components.

16.13 PROCESSING OF FIBER-REINFORCED COMPOSITES

To fabricate continuous fiber–reinforced plastics that meet design specifications, the fibers should be uniformly distributed within the plastic matrix and, in most instances, all oriented in virtually the same direction. In this section several techniques (pultrusion, filament winding, and prepreg production processes) by which useful products of these materials are manufactured will be discussed.

Pultrusion

Pultrusion is used for the manufacture of components having continuous lengths and a constant cross-sectional shape (rods, tubes, beams, etc.). With this technique,