8.6 Graphite

Graphite is a crystalline form of carbon, and has a *layered structure*, with basal planes or sheets of close-packed carbon atoms (see Fig. 1.5); consequently, graphite is weak when sheared along the layers. This characteristic, in turn, gives graphite its low frictional properties, and explains its use as a lubricant, especially at elevated temperatures. However, its frictional properties are low only in an environment of air or moisture; in a vacuum, it is abrasive and thus a poor lubricant. Unlike with other materials, strength and stiffness of graphite increase with temperature. Amorphous graphite is known as **lampblack** (black soot) and is used as a pigment. Ordinary pencil "lead" is a mixture of graphite and clay; graphite deposits found in the early 16th century were first thought of as being a form of lead.

Although brittle, graphite has high electrical and thermal conductivity and good resistance to thermal shock and to high temperature, although it begins to oxidize at 500°C. It is an important material for applications such as electrodes, heating elements, brushes for motors, high-temperature fixtures and furnace parts, mold materials (such as crucibles for the melting and casting of metals), and seals (Fig. 8.6). A characteristic of graphite is its resistance to chemicals, thus it is used in filters for corrosive fluids; its low absorption cross-section and high scattering cross-section for thermal neutrons make graphite also suitable for nuclear applications.

Graphite Fibers. An important use of graphite is as *fibers* in reinforced plastics and composite materials, as described in Section 9.2.

Carbon and Graphite Foams. These foams have high service temperatures, chemical inertness, low thermal expansion, and thermal and electrical properties that can be tailored to specific applications. *Carbon foams* are available in either graphitic or nongraphitic structures. *Graphitic foams* (typically produced from petroleum, coal tar, and synthetic pitches) have low density, high thermal and electrical conductivity, but lower mechanical strength, and are much more expensive than nongraphitic foams (produced from coal or organic resins), which are highly amorphous.

These foams have a cellular microstructure, with interconnected pores, thus their mechanical properties depend on density (see also Section 8.3). Blocks of foam

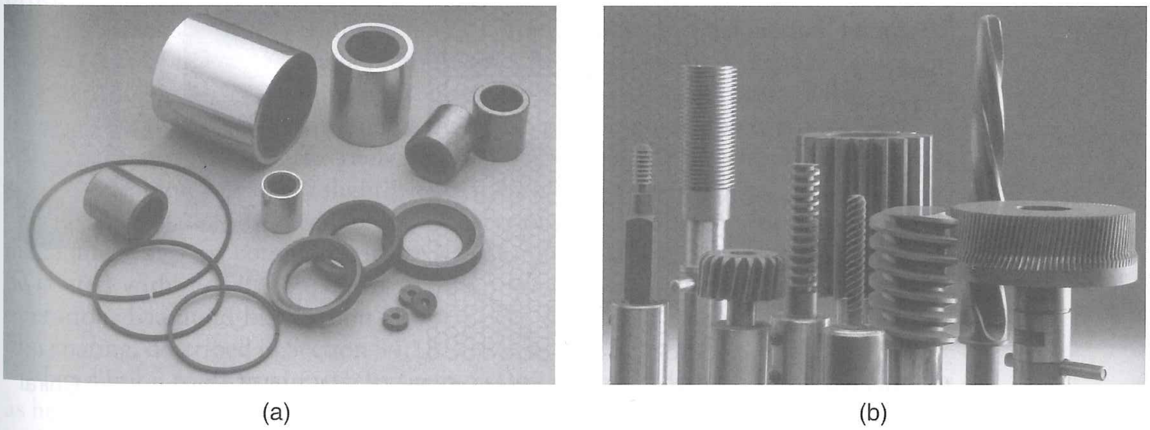
(a) (b)

FIGURE 8.6 (a) Various engineering components made of graphite. *Source:* Courtesy of Poco Graphite, Inc., a Unocal Co. (b) Examples of graphite electrodes for electrical discharge machining (Section 27.5). *Source:* Courtesy of Unicor, Inc.

can easily be machined into various complex shapes. Applications of carbon foams include their use as core materials for aircraft and ship interior panels, structural insulation, sound-absorption panels, substrates for spaceborne mirrors, lithium-ion batteries, and for fire and thermal protection.

8.6.1 Fullerenes

Carbon molecules (typically C60) are now produced in the shape of soccer balls, called *fullerenes* or **buckyballs**, after B. Fuller (1895–1983), the inventor of the geodesic dome. These chemically–inert spherical molecules are produced from soot, and act much like solid lubricant particles. When mixed with metals, fullerenes can become superconductors at low temperatures (around 40 K). Despite their promise, no commercial applications of buckyballs currently exist.

8.6.2 Nanotubes

Carbon nanotubes can be thought of as tubular forms of graphite, and are of interest for the development of nanoscale devices. (See also *nanomaterials*, Section 8.8.) *Nanotubes* are produced by laser ablation of graphite, carbon-arc discharge, and, most often, by chemical vapor deposition (CVD, Section 34.6.2). They can be single-walled (SWNT) or multi-walled (MWNT) and can be doped with various species.

Carbon nanotubes have exceptional strength, thus making them attractive as reinforcing fibers for composite materials; however, because they have very low adhesion with most materials, delamination with a matrix can limit their reinforcing effectiveness. It is difficult to disperse nanotubes properly because they have a tendency to clump, and this limits their effectiveness as a reinforcement. A few products have used carbon nanotubes, such as bicycle frames, specialty baseball bats, golf clubs, and tennis racquets. Nanotubes provide only a fraction of the reinforcing material (by volume), graphite fibers playing the major role.

An additional characteristic of carbon nanotubes is their very high electrical-current carrying capability. They can be made as semiconductors or conductors, depending on the orientation of the graphite in the nanotube (Fig. 8.7). Armchair nanotubes are theoretically capable of carrying a current density higher than 1,000

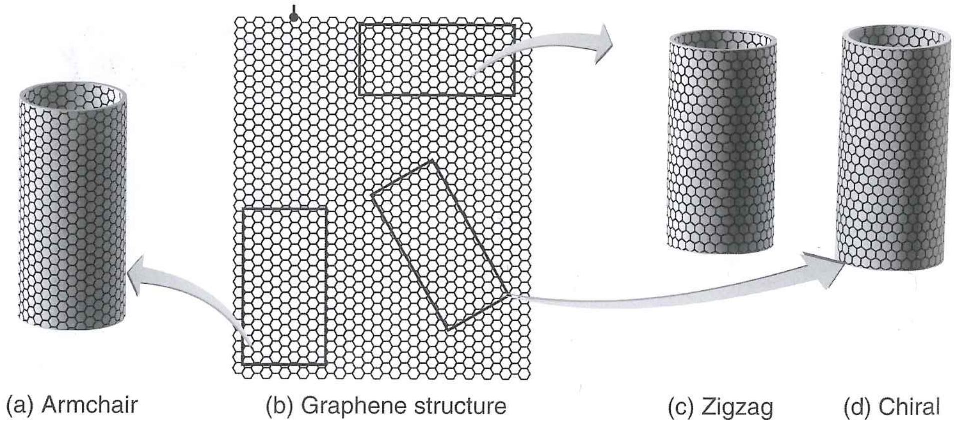

FIGURE 8.7 Forms of carbon nanotubes produced from a section of graphene: armchair, zigzag, and chiral. Armchair nanotubes are noteworthy for their high electrical conductivity, whereas zigzag and chiral nanotubes are semiconductors.

times that for silver or copper, thus making them attractive for electrical connections in nanodevices (Section 29.5). Carbon nanotubes have been incorporated into polymers to improve their static-electricity discharge capability, especially in fuel lines for automotive and aerospace applications.

Among the numerous proposed uses for carbon nanotubes are storage of hydrogen for use in hydrogen-powered vehicles, flat-panel displays, human tissue engineering, electrical cables for nano-scale circuitry, catalysts, and X-ray and microwave generators. Highly sensitive sensors using aligned carbon nanotubes are now being developed for detecting deadly gases, such as sarin.

8.6.3 Graphene

Graphene can be considered to be a single sheet of graphite, or an unwrapped nanotube, as shown in Fig. 8.7b. It is one of the most commonly encountered materials, but its direct observation in transmission electron microscopes dates only to the early 1960s. A number of methods have been developed for producing graphene, including epitaxy (Section 28.5) on silicon carbide or metal substrates and by chemical reduction of graphite. Research interest in graphene has grown considerably in the past few years, and applications of graphene as a transistor in integrated circuits (Chapter 28) and in solar cells have been suggested.

8.7 Diamond

Diamond is a form of carbon, with a covalently bonded structure. It is the hardest substance known (7000–8000 HK); however, it is brittle and begins to decompose in air at about 700°C, but resists higher temperatures in a nonoxidizing environment.

Synthetic or **industrial diamond** was first made in 1955. A common method of manufacturing it is to subject graphite to a hydrostatic pressure of 14 GPa and a temperature of 3000°C, referred to as *high-pressure, high-temperature* (HPHT) synthesis. An alternative is to produce diamonds through a chemical vapor deposition process (CVD; Section 34.6.2), depositing carbon onto a starting *seed* of diamond powder. The CVD process is used most often for synthetic gemstones. Synthetic diamond has identical, and sometimes slightly superior, mechanical properties as natural diamond, because of the presence of fewer and smaller impurities. The gemstones have a characteristic orange or yellow tint due to impurities, resulting from the CVD process, whereas laser treatment of the diamond can change the tint to pink or blue. However, since most of a gemstone's cost is attributed to grinding and finishing (Chapter 26) to achieve a desired shape, synthetic diamonds are only slightly less expensive than natural ones.

Synthetic diamond is available in a variety of sizes and shapes; for use in abrasive machining, the most common grit size is 0.01 mm in diameter. Diamond particles can be coated with nickel, copper, or titanium for improved performance in grinding operations **Diamond-like carbon** also has been developed and is used as a diamond film coating, described in Section 34.13.

In addition to its use in jewelry, gem-quality synthetic diamond has applications as heat sinks for computers, in telecommunications and integrated-circuit industries, and in high-power lasers. Its electrical conductivity is 50 times higher than that of natural diamond, and it is 10 times more resistant to laser damage.