9.4.1 Polymer Matrix Composites

There are a large and increasing number of processes for making PMC parts. Many are not very labor-intensive and can make near-net shape components. For thermoplastic matrices reinforced with discontinuous fibers, one of the most widely used processes is injection molding. However, as discussed in Section 9.3, the stiffness and strength of resulting parts are relatively low. This section focuses on processes for making composites with continuous fibers.

Many PMC processes combine fibers and matrices directly. However, a number use an intermediate material called a prepreg, which stands for preimpregnated material, consisting of fibers embedded in a thermoplastic or partially cured thermoset matrix. The most common forms of prepreg are unidirectional tapes and impregnated tows and fabrics.

Material consolidation is commonly achieved by application of heat and pressure. For thermosetting resins, consolidation involves a complex physical–chemical process, which is accelerated by subjecting the material to elevated temperature. However, some resins undergo cure at room temperature. Another way to cure resins without temperature is by use of electron bombardment. As part of the consolidation process, uncured laminates are often placed in an evacuated bag, called a vacuum bag, which applies atmospheric pressure when evacuated. The vacuum-bagged assembly is typically cured in an oven or autoclave. The latter also applies pressure significantly above the atmospheric level.

PMC parts are usually shaped by use of molds made from a variety of materials: steel, aluminum, bulk graphite, and also PMCs reinforced with E-glass and carbon fibers. Sometimes molds with embedded heaters are used.

The key processes for making PMC parts are filament winding, fiber placement, compression molding, pultrusion, prepreg lay-up, resin film infusion and resin transfer molding. The latter process uses a fiber preform which is placed in a mold.

9.4.2 Metal Matrix Composites

An important consideration in selection of manufacturing processes for MMCs is that reinforcements and matrices can react at elevated temperatures, degrading material properties. To overcome this problem, reinforcements are often coated with barrier materials. Many of the processes for making MMCs with continuous fiber reinforcements are very expensive. However, considerable effort has been devoted to development of relatively inexpensive processes that can make net shape or near-net shape parts that require little or no machining to achieve their final configuration.

Manufacturing processes for MMCs are based on a variety of approaches for combining constituents and consolidating the resulting material: powder metallurgy, ingot metallurgy, plasma spraying, chemical vapor deposition, physical vapor deposition, electrochemical plating, diffusion bonding, hot pressing, remelt casting, pressureless casting, and pressure casting. The last two processes use preforms.

Some MMCs are made by *in situ* reaction. For example, a composite consisting of aluminum reinforced with titanium carbide particles has been made by introducing a gas containing carbon into a molten alloy containing aluminum and titanium.

9.4.3 Ceramic Matrix Composites

As for MMCs, an important consideration in fabrication of CMCs is that reinforcements and matrices can react at high temperatures. An additional issue is that ceramics are very difficult to machine, so that it is desirable to fabricate parts that are close to their final shape. A number of CMC processes have this feature. In addition, some processes make it possible to fabricate CMC parts that would be difficult or impossible to create out of monolithic ceramics.

Key processes for CMCs include chemical vapor infiltration (CVI); infiltration of preforms with slurries, sol-gels, and molten ceramics; *in situ* chemical reaction; sintering; hot pressing; and hot isostatic processing. Another process infiltrates preforms with selected polymers that are then pyrolyzed to form a ceramic material.

9.4.4 Carbon/Carbon Composites

CCCs are primarily made by chemical vapor infiltration (CVI), also called chemical vapor deposition (CVD), and by infiltration of pitch or various resins. Following infiltration, the material is pyrolyzed, which removes most non-carbonaceous elements. This process is repeated several times until the desired material density is achieved.

9.5 APPLICATIONS

Composites are now being used in a large and increasing number of important mechanical engineering applications. In this section, we discuss some of the more significant current and emerging applications.

It is generally known that glass fiber-reinforced polymer (GFRP) composites have been used extensively as engineering materials for decades. The most widely recognized applications are probably boats, electrical equipment, and automobile and truck body components. It is generally known, for example, that the Corvette body is made of fiberglass and has been for many years. However, many materials that are actually composites, but are not recognized as such, also have been used for a long time in mechanical engineering applications. One example is cermets, which are ceramic particles bound together with metals; hence the name. These materials fall in the category of metal matrix composites. Cemented carbides are one type of cermet. What are commonly called "tungsten carbide" cutting tools and dies are, in most cases, not made of monolithic tungsten carbide, which is too brittle for many applications. Instead, they are actually MMCs consisting of tungsten carbide particles embedded in a high-temperature metallic matrix such as cobalt. The composite has a much higher fracture toughness than monolithic tungsten carbide.

Another example of unrecognized composites are industrial circuit breaker contact pads, made of silver reinforced with tungsten carbide particles, which impart hardness and wear resistance (Fig. 9.10). The silver provides electrical conductivity. This MMC is a good illustration of an application for which a new multifunctional material was developed to meet requirements for a combination of physical and mechanical properties.

In this section, we consider representative examples of composite usage in mechanical engineering applications, including aerospace and defense; electronic packaging and thermal control; machine components; internal combustion engines; transportation; process industries, high temperature and wear, corrosion and oxidation-resistant equipment; offshore and onshore oil exploration and production equipment; dimensionally stable components; biomedical applications; sports and leisure equipment; marine structures and miscellaneous applications. Use of composites is now so extensive that it is impossible to present a complete list. Instead, we have selected applications that, for the most part, are commercially successful and illustrate the potential for composite materials in various aspects of mechanical engineering.

9.5.1 Aerospace and Defense

Composites are baseline materials in a wide range of aerospace and defense structural applications, including military and commercial aircraft, spacecraft, and missiles. They are also used in aircraft gas turbine engine components, propellers, and helicopter rotors. Aircraft brakes are covered in another subsection.

PMCs are the workhorse materials for most aerospace and defense applications. Standard modulus and intermediate modulus carbon fibers are the leading reinforcements, followed by aramid and glass. Boron fibers are used in some of the original composite aircraft structures and special applications requiring high compressive strength. For low-temperature airframe and other applications, epoxies are the key matrix resin. For higher temperatures, bismaleimides, polyimides, and phenolics are employed. Thermoplastic resins increasingly are finding their way into new applications.

The key properties of composites that have led to their use in aircraft structures are high specific stiffness and strength and excellent fatigue resistance. For example, composites have largely replaced

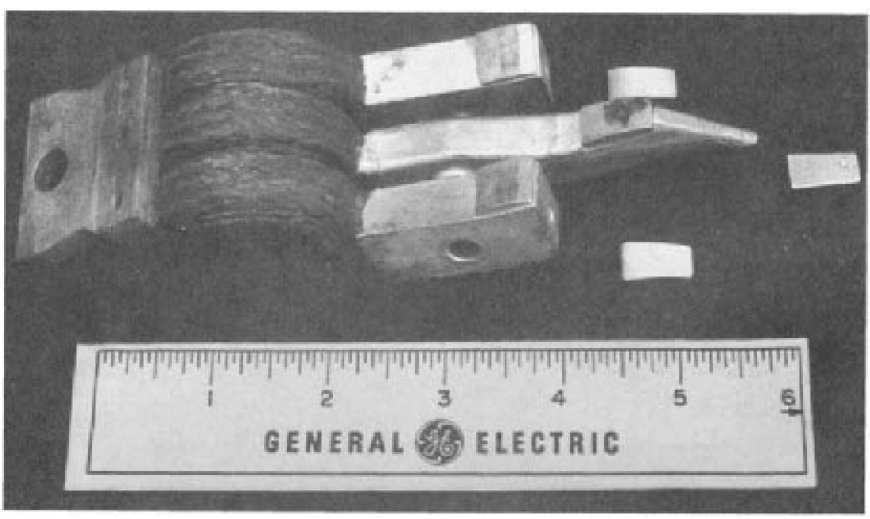

Fig. 9.10 Commercial circuit breaker uses tungsten carbide particle-reinforced silver contact pads.

monolithic aluminum in helicopter rotors because they extend fatigue life by factors of up to six times those of metallic designs.

The amount of composites used in aircraft structures varies by type of aircraft and the time at which they were developed. The B-2 "Stealth" Bomber makes extensive use of carbon fiber-reinforced PMCs (Fig. 9.11).

In general, aircraft that take off and land vertically (VTOL aircraft), such as helicopters and tilt wing vehicles, use the highest percentage of composites in their structures. For all practical purposes, most new VTOL aircraft have all-composite structures. The V-22 Osprey uses PMCs reinforced with carbon, aramid, and glass fibers in the fuselage, wings, empennage (tail section) and rotors (Fig. 9.12).

Use of composites in commercial passenger aircraft is limited by practical manufacturing problems in making very large structures and by cost. Still, use of composites has increased steadily. For example, the Boeing 777 has an all-composite empennage.

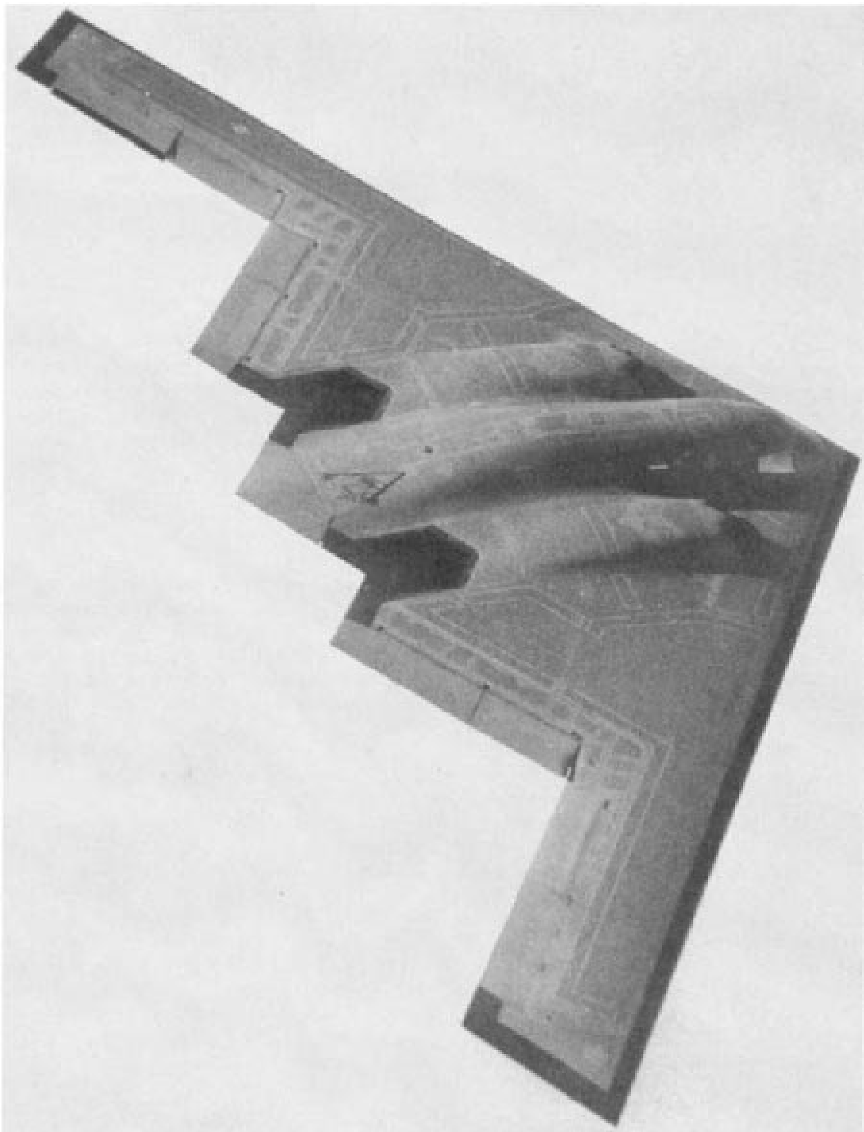

Fig. 9.11 The B-2 "Stealth" Bomber airframe makes extensive use of carbon fiber-reinforced polymer matrix composites (courtesy Northrop Grumman).

Fig. 9.12 The V-22 Osprey uses polymer matrix composites in the fuselage, wings, empennage, and rotors (courtesy Boeing).

Thrust-to-weight ratio is an important figure of merit for aircraft gas turbine engines and other propulsion systems. Because of this, there has been considerable work devoted to the development of a variety of composite components. Production applications include carbon fiber-reinforced polymer fan blades, exit guide vanes, and nacelle components; silicon carbide particle-reinforced aluminum exit guide vanes; and CMC engine flaps made of silicon carbide reinforced with carbon and with silicon carbide fibers.

There has been extensive development of MMCs with titanium and titanium aluminide matrices reinforced with silicon carbide fibers aimed at high-temperature engine and fuselage structures. Composites using intermetallic materials, such as titanium aluminide, are often called intermetallic matrix composites (IMCs).

The key design requirements for spacecraft structures are high specific stiffness and low thermal distortion, along with high specific strength for those components that see high loads during launch. The key reinforcements are high-stiffness PAN- and pitch-based carbon fibers. Figure 9.13 shows the NASA Upper Atmosphere Research Satellite structure, which is made of high-modulus PAN carbon/epoxy. For most spacecraft, thermal control is also an important design consideration, due in large part to the absence of convection as a cooling mechanism in space. Because of this, there is increasing interest in thermally conductive materials, including PMCs reinforced with ultrahigh-modulus pitch-based carbon fibers for structural components such as radiators, and for electronic packaging. MMCs are also being used for thermal control and electronic packaging applications. See Section 9.5.3 for a more detailed discussion of these applications.

The Space Shuttle Orbiters use boron fiber-reinforced aluminum struts in their center fuselage sections and CCC nose caps and wing leading edges.

The Hubble Space Telescope high-gain antenna masts, which also function as wave guides, are made of an MMC consisting of ultrahigh-modulus pitch-based carbon fibers in an aluminum matrix.

Missiles, especially those with solid rocket motors, have used PMCs for many years. In fact, high-strength glass was originally developed for this application. As for most aerospace applications, epoxies are the most common matrix resins. Over the years, new fibers with increasingly higher specific strengths—first aramid, then ultrahigh-strength carbon—have displaced glass in high-performance applications. However, high-strength glass is still used in a wide variety of related applications, such as launch tubes for shoulder-fired anti-tank rockets.

Carbon/carbon composites are widely used in rocket nozzle throat inserts.

9.5.2 Machine Components

Composites increasingly are being used in machine components because they reduce mass and thermal distortion and have excellent resistance to corrosion and fatigue.

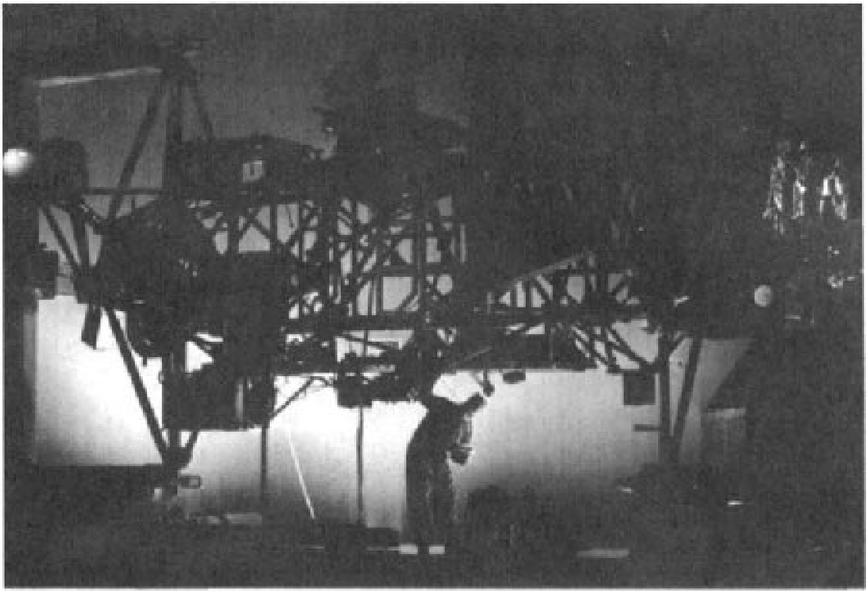

Fig. 9.13 The Upper Atmosphere Research Satellite structure is composed of lightweight high-modulus carbon fiber-reinforced epoxy struts, which provide high stiffness and strength and low coefficient of thermal expansion.

One of the most successful applications has been in rollers and shafts used in machines that handle rolls of paper, thin plastic film, fiber products, and audio tape. Figure 9.14 shows a chromium-plated carbon fiber-reinforced epoxy roller used in production of audio tape. The low rotary inertia of the composite part allows it to start and stop more quickly than the baseline metal design. This reduces the amount of defective tape resulting from differential slippage between roller and tape.

Rollers as long as 10.7 m (35 ft) and 0.43 m (17 in.) in diameter have been produced. In these applications, use of carbon fiber-reinforced polymers has resulted in reported mass reductions of 30% to 60%. This enables some shafts to be handled by one person instead of two (Fig. 9.15). It also reduces shaft rotary inertia, which, as for the audio machine roller discussed in the previous paragraph, allows machines to be stopped more quickly without damaging the plastic or paper. The higher critical speeds of composite shafts also allow them to be operated at higher speeds. In addition, the high stiffness of composite shafts reduces lateral displacement under load. PMC rollers can be coated with a variety of materials, including metals and elastomers.

PMCs also have been used in translating parts, such as tubes used to remove plastic parts from injection molding machines. In another application, use of a carbon fiber-reinforced epoxy robotic arm in a computer cartridge-retrieval system doubled the cartridge-exchange rate compared to the original aluminum design.

Specific strength is an important figure of merit for materials used in flywheels. Composites have received considerable attention for this reason (Fig. 9.16). Another advantage of composites is that their modes of failure tend to be less catastrophic than for metal designs. The latter, when they fail, often liberate large pieces of high-velocity, shrapnel-like jagged metal that are dangerous and difficult to contain.

The high specific stiffness and low coefficient of thermal expansion (CTE) of silicon carbide particle-reinforced aluminum has led to its use in machine parts for which low vibration, mass, and thermal distortion are important, such as photolithography stages (Fig. 9.17). The absence of out-gassing is another advantage of MMC components.

Figure 9.18 shows a developmental actuator housing made of silicon carbide particle-reinforced aluminum. Properties of interest here are high specific stiffness and yield strength. In addition, compared to monolithic aluminum, the composite offers a closer CTE match to steel than monolithic aluminum, and better wear resistance.

The excellent hardness, wear resistance, and smooth surface of a silicon carbide whisker-reinforced alumina CMC resulted in the adoption of this material for use in beverage can-forming equipment. Here, we find a CMC replacing what is in fact a metal matrix composite; a cemented carbide or cermet, consisting of tungsten carbide particles in a cobalt binder.

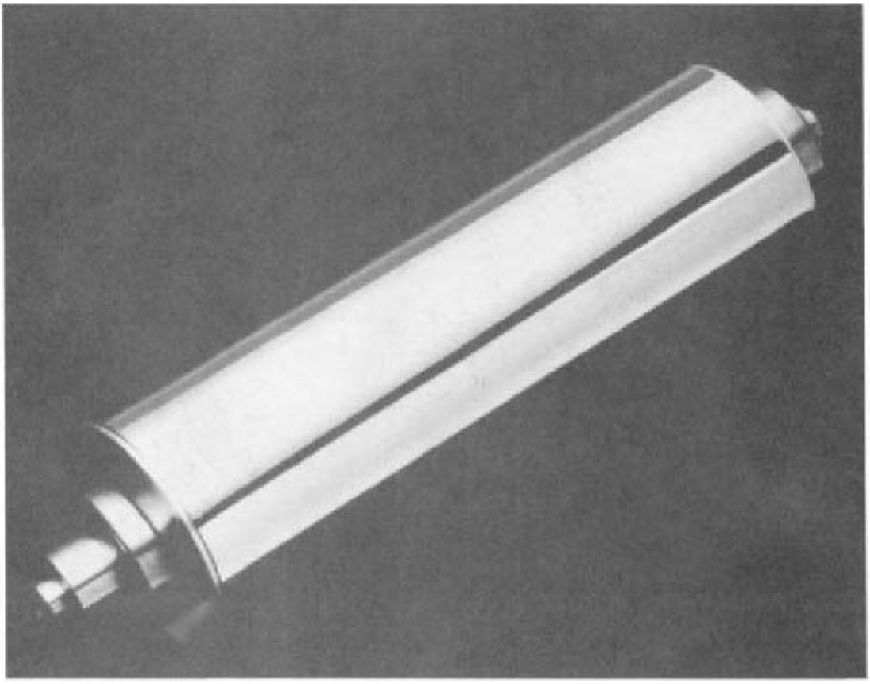

Fig. 9.14 Metal plated carbon/epoxy roller used in production of audio tape has a much lower rotary inertia than a metal roller, decreasing smearing during startup and shutdown (courtesy Tonen).

9.5.3 Electronic Packaging and Thermal Control

Composites increasingly are being used in thermal control and electronic packaging applications because of their high thermal conductivities, low densities, tailorable CTEs, and availability of net shape and near-net shape fabrication processes. The materials of interest are PMCs, MMCs, and CCCs.

Electronic Packaging

Electronic packaging is commonly divided into various levels, starting at the level of the integrated circuit and progressing upwards to the enclosure and support structure. Composites are used in all of these levels. Components made of composites include carriers, packages, heat sinks, enclosures, and support structures. Key production materials include silicon carbide particle-reinforced aluminum, beryllium oxide particle-reinforced beryllium, ultrahigh-thermal-conductivity (UHK) pitch-based carbon fiber-reinforced polymers, metals, and CCCs. Various types of composite components are used in electronic devices for cellular telephone ground telephone stations, electrical vehicles, aircraft, spacecraft, and missiles. Figure 9.19 shows a spacecraft electronics module housing made of beryllium oxide particle-reinforced beryllium. MMCs also have been successfully used in many aircraft electronic systems. For example, Figure 9.20 shows a printed circuit board heat sink (also called a cold plate or thermal plane) made of silicon carbide particle-reinforced aluminum.

Thermal Control

The key composite materials used in thermal control applications are UHK carbon fiber-reinforced polymers. For the most part, the applications include components that have structural as well as thermal control applications. Examples include the Boeing 777 aircraft engine nacelle honeycomb cores and spacecraft radiator panels and battery sleeves.

9.5.4 Internal Combustion Engines

There have been a number of historic uses of MMCs in automobile internal combustion engines. In the early 1980s, Toyota introduced an MMC diesel engine piston consisting of aluminum locally reinforced in the top ring groove region with discontinuous alumina-silica fibers and with discontin-

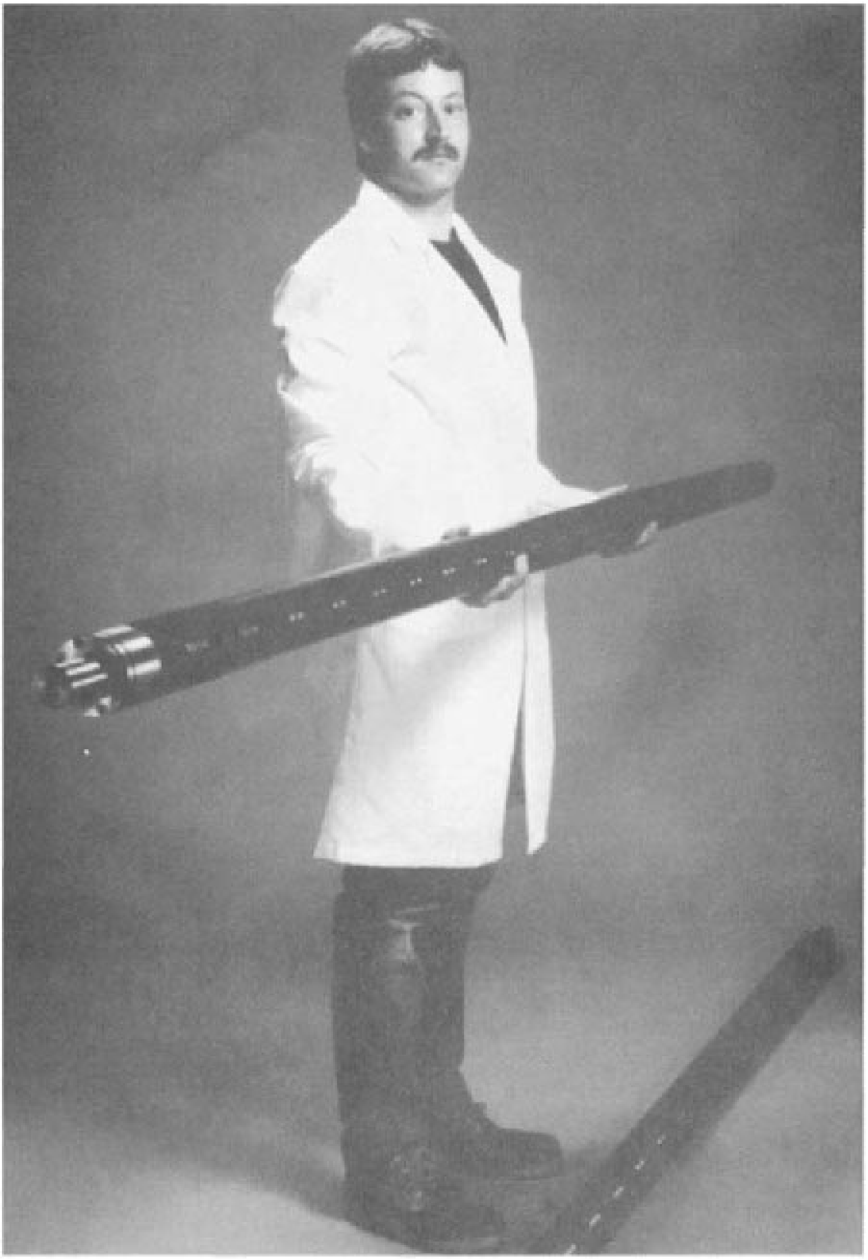

Fig. 9.15 The lower weight of carbon/epoxy rollers used in printing, paper, and conversion equipment facilitates handling. Lower rotary inertia results in reduced tendency to tear paper and plastic film during startup and shutdown (courtesy Du Pont).

uous alumina fibers. The pistons are made by pressure infiltration of a preform. Here, the ceramic fibers provide increased wear resistance, replacing a heavier nickel cast iron insert that was used with the original monolithic aluminum piston.

In the early 1990s, Honda began production of aluminum engine blocks reinforced in the cylinder wall regions with a combination of carbon and alumina fibers. Use of fiber reinforcement allowed the removal of cast iron cylinder liners that had been required because of the poor wear resistance

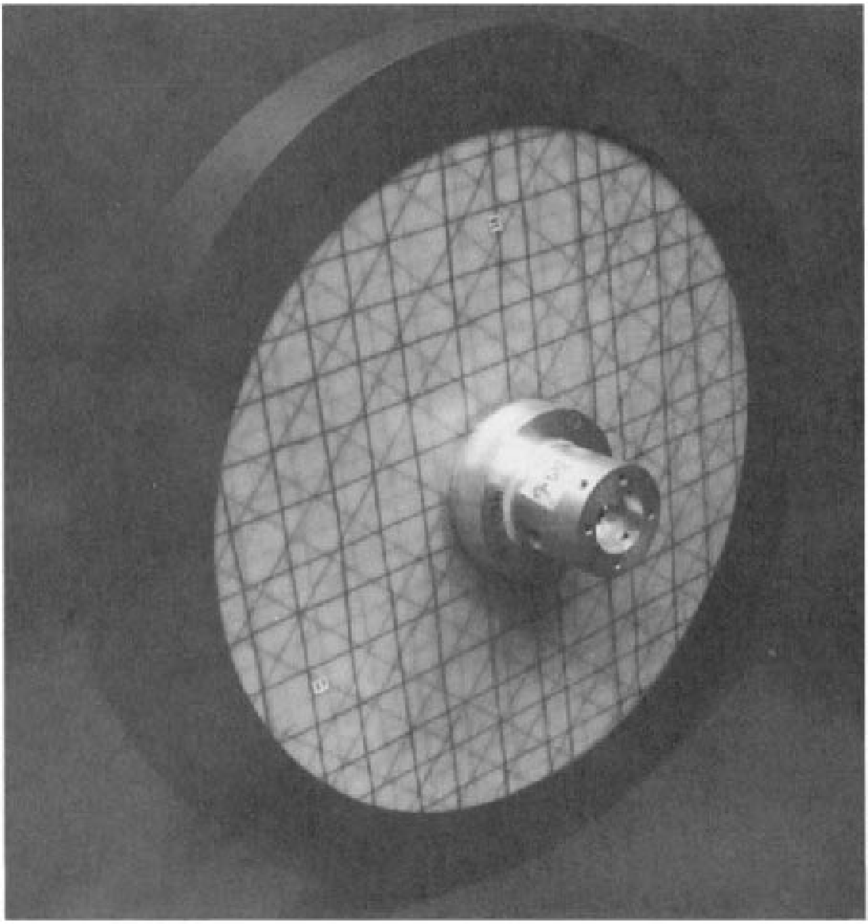

Fig. 9.16 Developmental flywheel for automobile energy storage combines a carbon/epoxy rim and a high-strength glass/epoxy disk.

of monolithic aluminum. As for the Toyota pistons, the engine blocks are made by a pressure infiltration process. The Honda engine uses hybrid fiber preforms consisting of discontinuous alumina and carbon fibers with a ceramic binder. The advantages of the composite design are greater bore diameter with no increase in overall engine size, higher thermal conductivity in the cylinder walls, and reduced weight. Figure 9.21 shows one of the engine blocks with a section cut away. The fiber-reinforced regions are clearly visible in a close-up view of the cylinder walls (Fig. 9.22).

Other engine components under evaluation are carbon/carbon pistons; MMC connecting rods and piston wrist pins; and CMC diesel engine exhaust valve guides.

9.5.5 Transportation

Composites are used in a wide variety of transportation applications, including automobile, truck, and train bodies; drive shafts; brakes; springs; and natural gas vehicle cylinders. There is also considerable interest in composite flywheels as a source of energy storage in vehicles. This subject is covered in Section 9.5.2.

Automobile, Truck, and Train Bodies

As mentioned in the introduction to this section, it is widely known that for many years, the GM Corvette has had a PMC body consisting of chopped glass fiber-reinforced thermosetting polyester. However, the body is semi-structural and primary loads are supported by a steel frame. A key reason for use of PMCs reinforced with chopped glass fibers in automotive components is that these materials

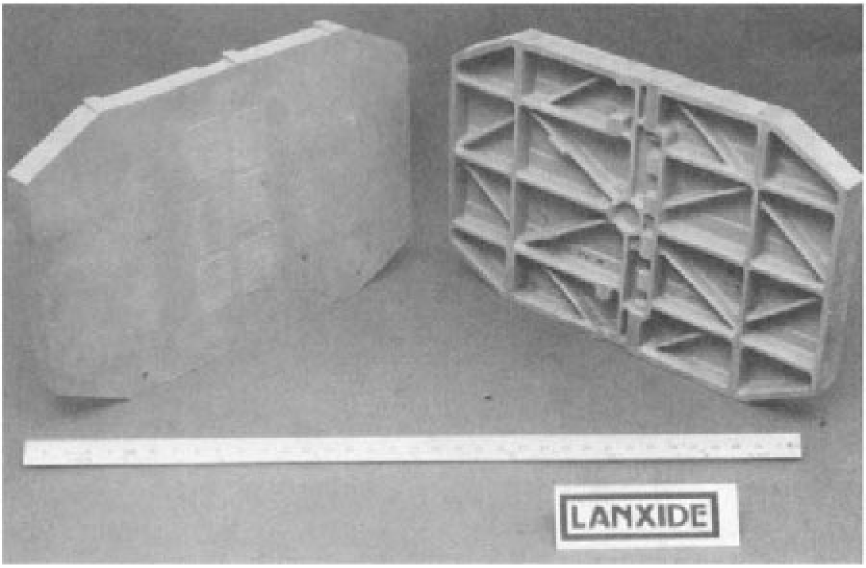

Fig. 9.17 Silicon carbide particle-reinforced aluminum photolithography stage has the same stiffness as the cast iron baseline, but is 60% lighter and has a much higher thermal conductivity, reducing thermal gradients and resulting distortion (courtesy Lanxide).

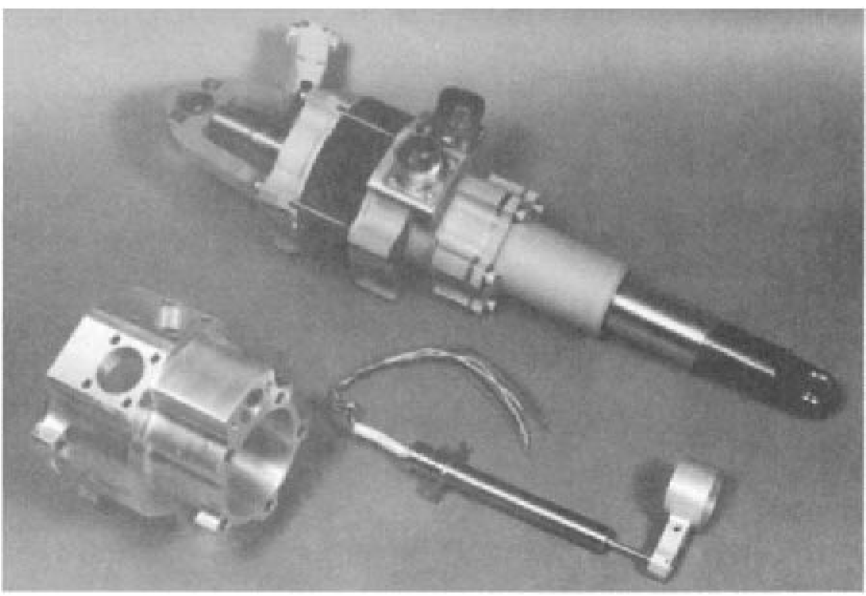

Fig. 9.18 Silicon carbide particle-reinforced aluminum actuator housings provide higher stiffness and wear resistance and lower coefficient of thermal expansion than aluminum (courtesy DWA Aluminum Composites).

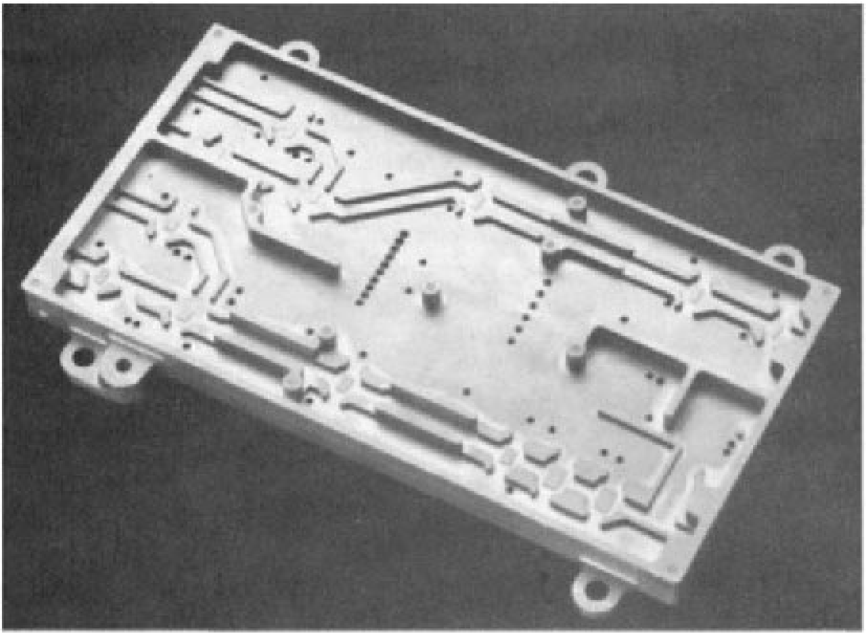

Fig. 9.19 Beryllium oxide particle-reinforced beryllium RF electronic housing provides reduced mass, high thermal conductivity, and coefficient of thermal expansion in the range of ceramic substrates and semiconductors (courtesy Brush Wellman).

allow complex shapes to be made in one piece, replacing numerous steel stampings that must be joined by welding or mechanical fastening, thereby reducing labor costs.

Drive Shafts

A critical design consideration for drive shafts is critical speed, which is the rotational speed that corresponds to the first natural frequency of lateral vibration. The latter is proportional to the square root of the effective axial modulus of the shaft divided by the effective shaft density; that is, shaft critical speed is proportional to the square root of specific stiffness. It has been found that in a variety of mechanical systems, the high specific stiffness of composites makes it possible to eliminate the need for intermediate bearings.

Composite production drive shafts are used in boats, cooling tower fans, and pickup trucks. In the last application, use of composites eliminates the need for universal joints, as well as center support bearings (Fig. 9.23). The lower mass of composite shafts also reduces vibrational loads on bearings, reducing wear. The excellent corrosion resistance of composites is an additional advantage in applications such as cooling tower fan drive shafts (see Section 9.5.6).

Another advantage of composites in drive shafts is that it is possible to vary the ratio of axial-to-torsional stiffness far more than is possible with metallic shafts. This can be accomplished by varying the number and orientation of the layers, and by appropriate use of material combinations. For example, it is possible to use carbon fibers in the axial direction to achieve high critical speed, and glass fibers at other angles to achieve low torsional stiffness, if desired.

The number of different designs and material combinations is limitless. In almost all cases, carbon fibers are used because of their high specific stiffness. Often, E-glass is used as an outer layer because of its excellent impact resistance and lower cost. In one case, carbon fibers are applied axially to a thin aluminum shaft. E-glass is used to electrically isolate the aluminum and carbon to prevent galvanic corrosion.

The high specific stiffness of silicon carbide particle-reinforced aluminum and the low cost and weldability of some material systems have resulted in their adoption in production automobile drive shafts.

Brakes for Automobiles, Trains, Aircraft, and Special Applications

Volumetric constraints and the need to reduce weight have led to the use of a variety of composites for automobile, train, aircraft, and special application brake components.

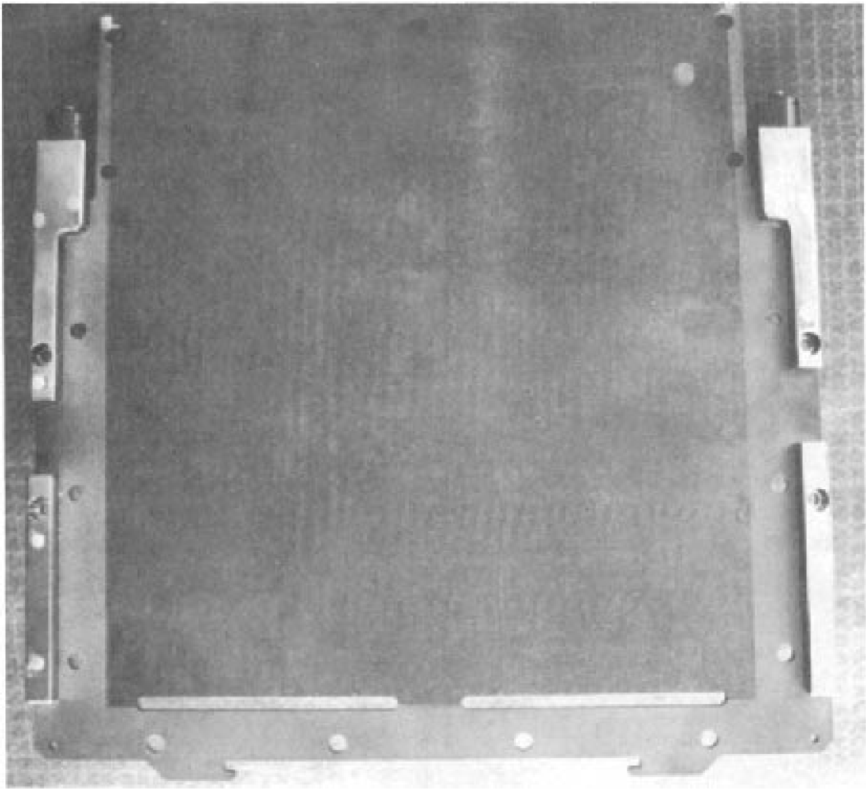

Fig. 9.20 Silicon carbide particle-reinforced aluminum printed circuit board heat sink is much lighter and has a higher specific stiffness than the copper–molybdenum baseline, and provides similar thermal performance (courtesy Lanxide Electronic Products).

Carbon/carbon composites have been used for some years in aircraft brakes in place of steel, resulting in a substantial weight reduction. Carbon/carbon has also been used in racing car and racing motorcycle brakes.

The wear resistance of monolithic aluminum generally is not good enough for brake rotors. However, introduction of ceramic particles, such as silicon carbide and alumina, results in materials with greatly improved resistance to wear. Ceramic particle-reinforced aluminum MMCs are being used in both automobile and railway car brake rotors in place of cast iron. In these applications, the high thermal conductivity of the composite is an advantage. However, the relatively low melting point of aluminum prevents the use of composites employing this metal as a matrix in rotors which see very high temperatures. The high specific stiffness and wear resistance of silicon carbide particle-reinforced aluminum have led to the evaluation of these MMCs in brake calipers. Figure 9.24 shows ceramic particle-reinforced aluminum brake rotors and caliper components.

Another interesting application for ceramic particle-reinforced aluminum MMCs is in amusement car rail brakes (see Section 9.5.12).

Automobile Springs

The Corvette uses structural GFRP leaf springs that are reinforced with continuous glass fibers. These have been used successfully for many years in what is a very demanding, cost-sensitive application.

Natural Gas Vehicle Cylinders

There is considerable interest in use of natural gas as a fuel for automobiles and trucks. Pressure vessels to contain the natural gas are required for the vehicles, refueling stations, and trucks to transport the fuel. The weight and cost of vehicle fuel tanks are major issues. A variety of composite designs that demonstrate weight savings over steel have been developed. They use steel, aluminum, or polymeric liners overwrapped with carbon fiber, glass fiber, or a combination of the two, embedded

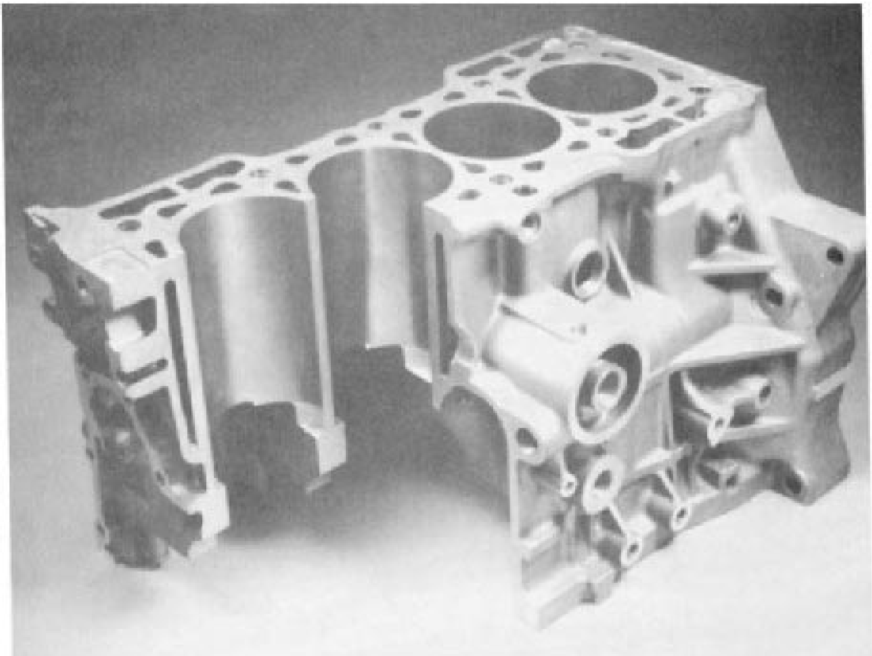

Fig. 9.21 Honda Prelude engine block has cylinder walls that are reinforced with a combination of alumina and carbon fibers, eliminating the need for cast iron sleeves. The result is an engine with better thermal performance and a higher power-to-weight ratio (courtesy Honda).

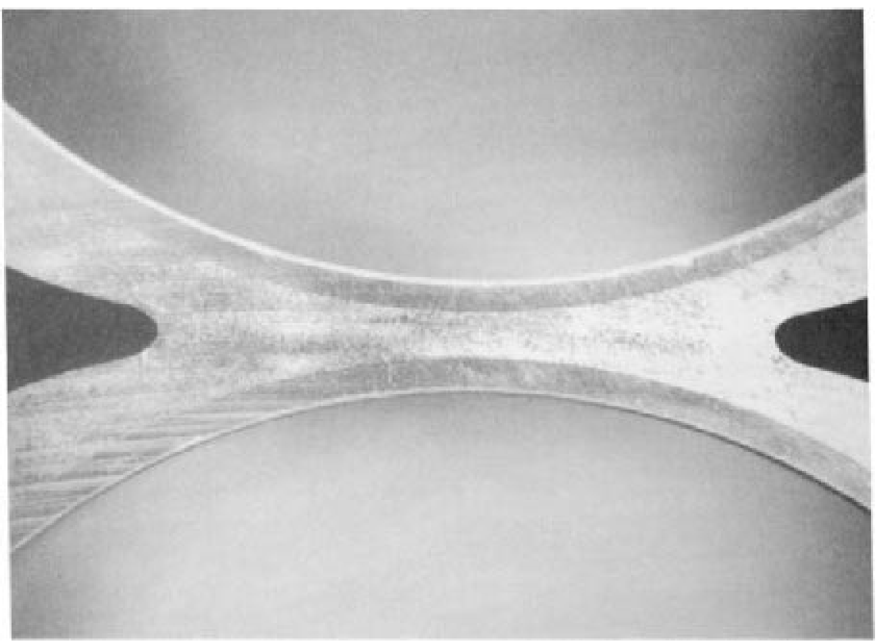

Fig. 9.22 Close-up of Honda Prelude cylinder walls showing region of fibrous reinforcement (courtesy Honda).

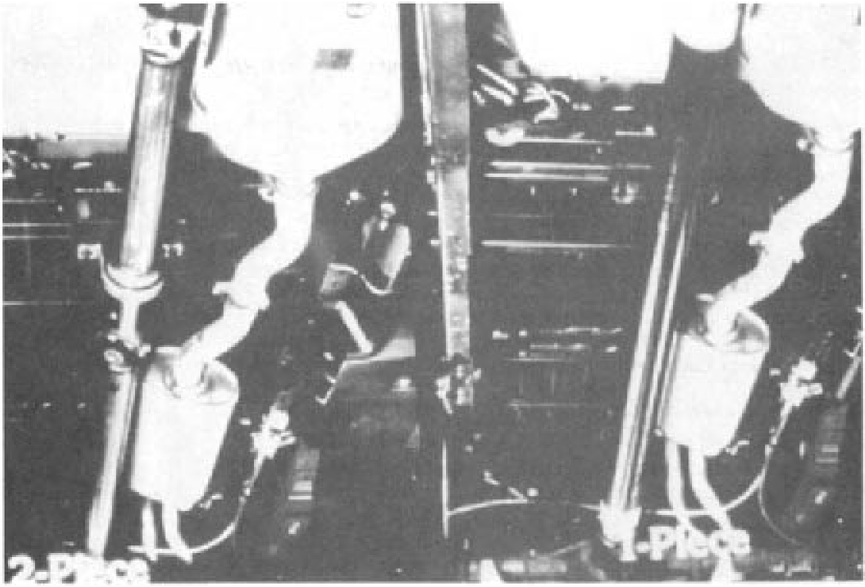

Fig. 9.23 One-piece pickup truck drive shaft consists of outer layers of carbon- and glass fiber-reinforced polymer that are pultruded over an inner aluminum tube. The composite drive shaft replaces a two-piece steel shaft that requires an intermediate support bearing and universal joint (courtesy MMFG).

Fig. 9.24 Silicon carbide particle-reinforced aluminum brake rotors, calipers, and other parts provide higher specific stiffness and better wear resistance than monolithic aluminum and are lighter than cast iron (courtesy Lanxide).

in a polymer matrix, typically epoxy. The durability and reliability of these tanks are key considerations for their use.

9.5.6 Process Industries, High-Temperature Applications, and Wear-, Corrosion-, and Oxidation-Resistant Equipment

The excellent corrosion resistance of many composite materials has led to their widespread use in process industries equipment. Undoubtedly, the most extensively used materials are PMCs consisting of thermosetting polyester and vinyl ester resins reinforced with E-glass fiber. These materials are relatively inexpensive and easily formed into products such as pipes, tanks, and flue liners. However, GFRP has its limitations. E-glass is susceptible to creep and creep rupture and is attacked by a variety of chemicals, including alkalies. For these reasons, E-glass fiber-reinforced polymers are typically not used in high-stress components. In addition, polyesters and vinyl esters are not suitable for high-temperature applications. Other types of composite materials overcome the limitations of GFRP and are finding increasing use in applications for which resistance to corrosion, oxidation, wear, and erosion are required, often in high-temperature environments. In this section, we consider representative applications of composites in a variety of process industries and related equipment.

High-Temperature Applications

The key materials of interest for high-temperature applications are CCCs, CMCs, and PMCs with high-temperature matrices. These materials, especially CMCs and CCCs, offer resistance to high-temperature corrosion and oxidation, as well as resistance to wear, erosion, and mechanical and thermal shock.

CCCs are being used in equipment to make glass products, such as bottles. Production and experimental components include GOB distributors, interceptors, pads, and conveyor machine wear guides. Use of carbon/carbon eliminates the need for water cooling, coatings, and lubricants required for steel parts. In some applications, the CCC parts have shown significant reduction in wear.

Carbon fiber-reinforced high-temperature thermoplastic composites are also being used in glass-handling equipment. The key advantages of this material are its low thermal conductivity, which reduces glass checking (microcracking), and its wear resistance, which reduces down time for part replacement.

A wide variety of ceramic matrix composites are being used in production and developmental high-temperature applications, including industrial gas turbine combustor liners and turbine rotor tip shrouds; radiant burner and immersion tubes; high-temperature gas filters; reverberatory screens for porous radiant burners; heat exchanger tubes and tube headers; and tube hangers for crude oil preheat furnaces. Figure 9.25 shows a number of developmental continuous fiber CMC parts made by polymer impregnation and pyrolisis: combustor liners, chemical pump components, high-temperature pipe hangers, and turbine seals. Figure 9.26 shows a CMC hot gas candle filter composed of alumina–boria–silica fibers in a silicon carbide matrix made by chemical vapor deposition.

In another high-temperature application, silicon carbide whisker-reinforced silicon nitride ladles are being used for casting molten aluminum.

Wear- and Erosion-Resistant Applications

PMCs, MMCs, CMCs, and CCCs are all being used in a variety of applications for which wear and erosion resistance is an important consideration in material selection.

Polymers are reinforced with a variety of materials to reduce coefficient of friction and wear and improve strength characteristics: carbon particles, molybdenum disulfide particles, carbon fibers, glass fibers, and aramid fibers.

As discussed in Sections 9.5.4 and 9.5.5, addition of ceramic reinforcements, such as aluminum oxide fibers, to aluminum significantly increases its wear resistance, allowing it to be used in wear-critical applications such as pistons and brake rotors and internal combustion engine blocks.

However, CMCs probably offer the greatest potential for applications requiring resistance to severe wear and erosion. One of the most important composites for these applications is silicon carbide particle-reinforced alumina [(SiC)p/Al_2O_3]. The material also contains some residual metal alloy. A significant benefit of this material is that the process used to make it, directed metal oxidation, allows the fabrication of large, complex components that are difficult to make out of monolithic ceramics.

CMCs are now being used in industries such as mining, mineral processing, metalworking, and chemical processing. Figure 9.27 shows components made of (SiC)p/Al_2O_3, including impellers, pipeline chokes and liners for pumps, chutes, and valves, and hydrocyclones.

Corrosion-Resistant Applications

As discussed earlier, E-glass-reinforced polyester and vinyl ester PMCs have been extensively used for decades in corrosion-resistant applications, such as chemical industry tanks, flue liners, pumps, and pipes. However, there are applications for which GFRP is not well suited. For example, carbon fibers are much more resistant than glass fibers to chemical attack, creep, and creep rupture, and

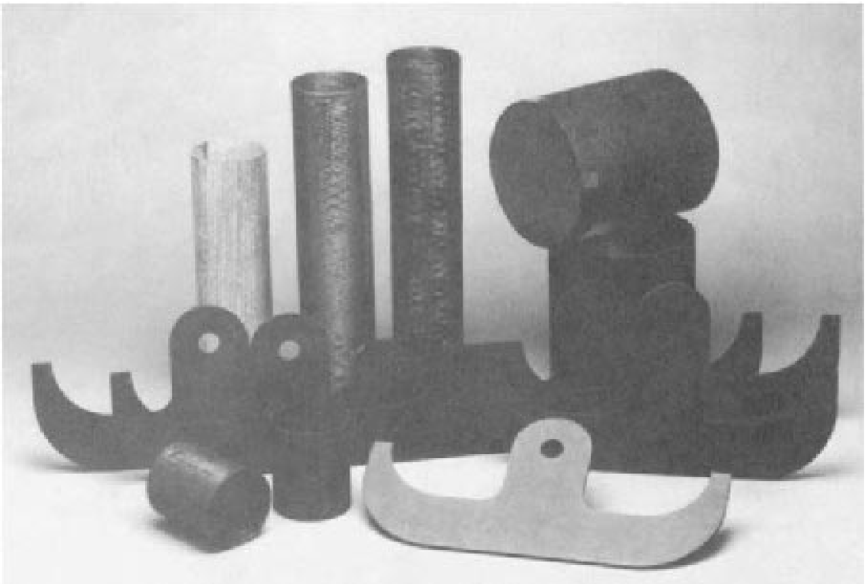

Fig. 9.25 Continuous fiber-reinforced ceramic matrix composite pipe hangers, combustor liners, chemical pump components, and other parts provide better thermal and mechanical shock resistance than monolithic ceramics and better oxidation and corrosion resistance than baseline metal designs (courtesy Dow Corning).

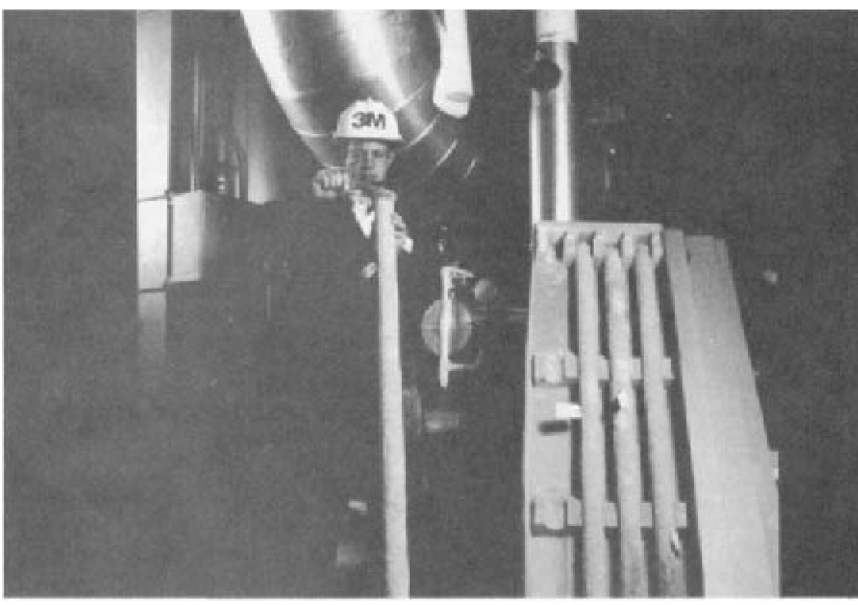

Fig. 9.26 Alumina–boria–silica fiber-reinforced silicon carbide ceramic matrix composite hot gas candle filter has better thermal and mechanical shock resistance than monolithic ceramics and is more resistant to corrosion and oxidation than metal filters (courtesy 3M).

Fig. 9.27 Silicon carbide particle-reinforced alumina ceramic matrix composite parts for wear-resistant applications, including impellers, pipeline chokes and liners for pumps, chutes, valves, and hydrocyclones (courtesy Lanxide).

have much higher specific stiffness. Carbon fiber-reinforced vinyl ester rods have been used in place of titanium in printed circuit production systems, where they are subjected to a variety of corrosive etchant materials. The high specific stiffness of the PMC rods results in less deflection than for titanium. Glass fiber-reinforced rods would deflect much more. Thermoplastics, such as polyether etherketone reinforced with carbon fibers, are being used in pump parts. In this application, carbon fibers provide increased corrosion resistance and reduced coefficient of friction compared to glass.

Epoxy-matrix drive shafts reinforced with carbon fibers, E-glass fibers, or a combination of these, are being used in corrosive environments to drive sewage pumps and cooling tower fans used in power plants, chemical manufacturing facilities and refineries. In some of these applications, composite shafts up to 6.1 m (20 ft) long replace stainless steel. Because of the high specific stiffness and strength of carbon fibers, the composite shafts have higher critical speeds and much lower masses, reducing static and vibratory bearing loads and often eliminating the need for intermediate support bearings. Figure 9.28 shows a carbon fiber-reinforced epoxy cooling tower drive shaft.

9.5.7 Offshore and Onshore Oil Exploration and Production Equipment

Oil exploration and production equipment requirements place severe demands on materials. To function successfully in these environments, materials must be durable and have good resistance to corrosion and fatigue. In addition, as offshore oil exploration moves to increasing depths, equipment mass is becoming more important. These needs are resulting in increasing interest in composite materials.

Sucker rods, which are used to raise oil to the surface, have been made of E-glass fiber-reinforced vinyl ester for many years (Fig. 9.29). Here, the composite offers corrosion resistance and weight savings over steel. Oil well drill pipe has been made using a combination of carbon and glass fibers.

The excellent corrosion resistance of GFRP has led to its successful use in gratings and railings for offshore oil platforms. Figure 9.30 shows E-glass fiber-reinforced phenolic grating, which is 80% lighter than steel, has much better corrosion resistance and lower thermal conductivity, and meets strength and fire-resistance requirements. The increasing water depth at which these platforms are being used is leading to increasing interest in other applications, such as mooring lines, drill pipes, and risers. Components using a combination of carbon fibers and glass fibers in vinyl ester and other resins are candidates to replace steel.

9.5.8 Dimensionally Stable Devices

The low CTE and low density of composite materials make them attractive for applications in which dimensional stability and mass are important. Examples include countless spacecraft optical and RF

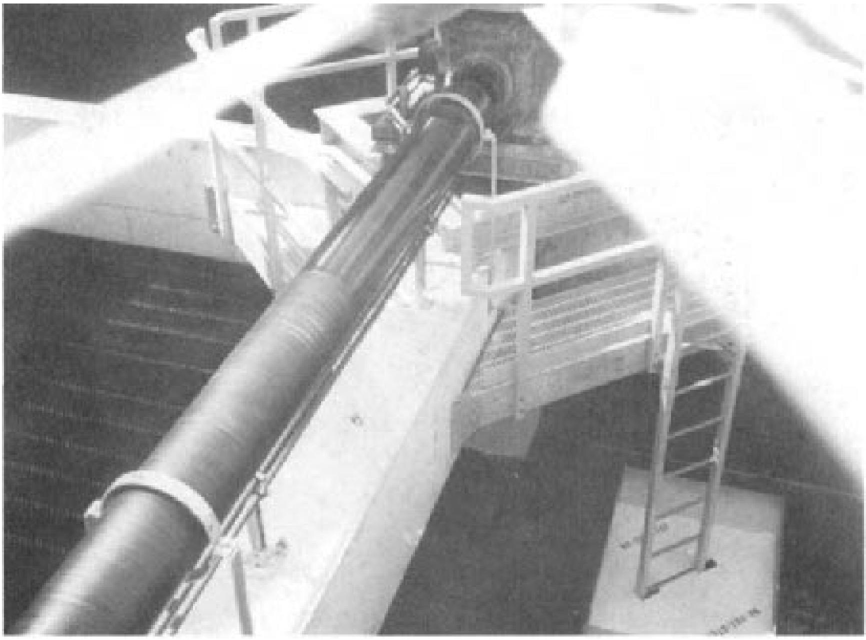

Fig. 9.28 Corrosion-resistant carbon fiber-reinforced epoxy cooling tower drive shaft eliminates requirement for intermediate support bearings (courtesy Addax).

systems, such as the Hubble Space Telescope metering truss, wave guides, antenna reflectors, electro-optical systems, and laser devices. Composites also have been used in commercial measuring equipment, such as coordinate measuring machines.

The key composites in these applications are carbon fiber-reinforced PMCs and silicon carbide particle-reinforced aluminum MMCs. Often, CFRPs are used in place of Invar®, a nickel–iron alloy that has a low CTE but a relatively high density, 8.0 g/cm^3 (0.29 Pci). Epoxies have been the traditional matrix materials, but they are being replaced with cyanate esters, which are less susceptible to moisture distortion and have less outgassing. Figure 9.31 shows a developmental electro-optical system gimbal composed of parts made from two types of carbon fiber-reinforced epoxy and from silicon carbide particle-reinforced aluminum. The MMC was used for parts that have complex shapes and are not well suited for carbon/epoxy. Use of composites substantially reduces mass and thermal distortion compared to the aluminum baseline.

A limited number of production mirrors have been made of silicon carbide particle-reinforced aluminum. Metal-coated carbon fiber-reinforced PMCs also are being investigated for lightweight, dimensionally stable mirrors.

9.5.9 Biomedical Applications

Composites are being used for an increasing number of biomedical applications, including x-ray equipment, prosthetics, orthotics, implants, dental restorative materials and wheelchairs. In addition to the usual requirements for stiffness, strength, and so on, materials used for implants must be compatible with the human body.

Carbon fiber-reinforced epoxy is widely used in x-ray film cassettes and tables and stretchers used to support patients in x-ray devices, such as tomography machines. Here, the high specific stiffness and strength of carbon/epoxy reduces the mass of the support equipment and cassettes, allowing the radiologist to lower the x-ray dosages to which patients are exposed.

Carbon fiber-reinforced polymers are extensively used in artificial fingers, arms, legs, hips and feet. They are also used in leg braces and wheelchairs. In all of these applications, the devices are lighter than metallic designs.

PMCs have been used for many years as dental restorative materials. Here, the reinforcements are glass and fumed silica particles, which provide hardness, wear resistance, and esthetic qualities, and reduce overall composite shrinkage during cure. Compositions with particle loadings as high as 80% are used. In recent years, titanium posts used to attach artificial replacement teeth to the jaw have been replaced by ones made of carbon fiber-reinforced epoxy.

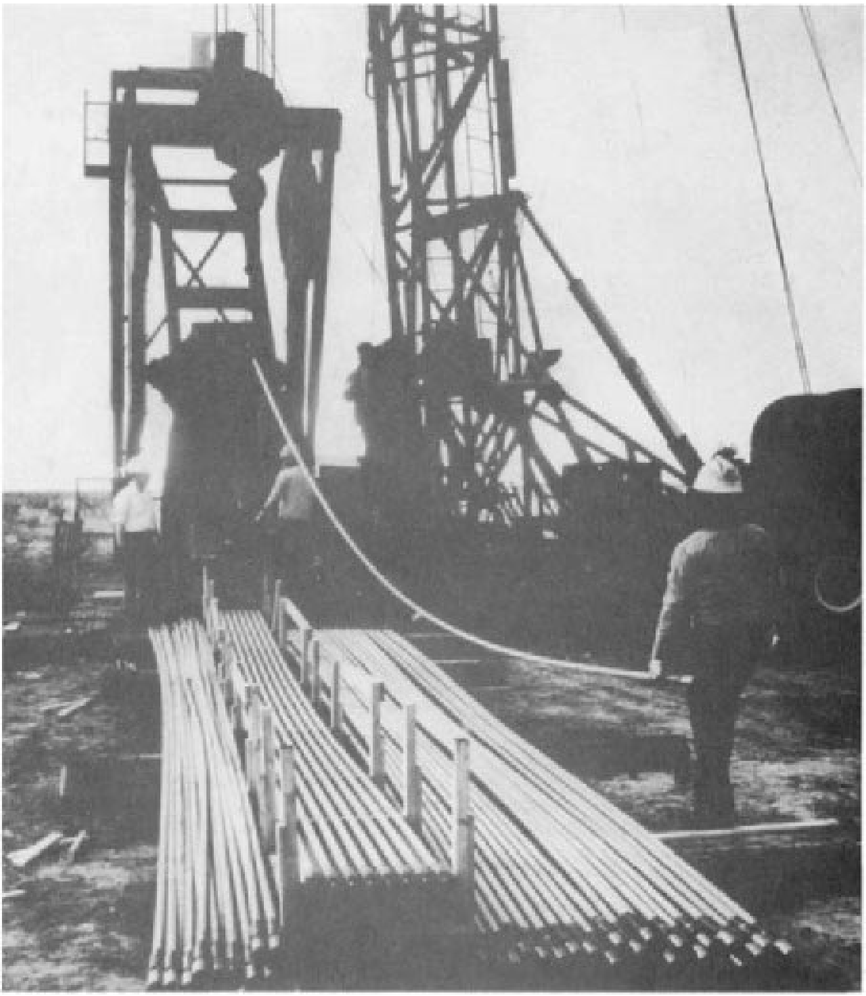

Fig. 9.29 Corrosion-resistant E-glass fiber-reinforced vinyl ester sucker rods used to pump oil (courtesy MMFG).

There is considerable research into development of PMC and CCC implant materials. One potential application is joint replacement. Here, work is under way to improve the resistance to wear and creep of ultrahigh-weight polyethylene, which has been used in a monolithic form for many years.

Another goal is to replace titanium and chromium alloys used for bone reinforcement and replacement. In these applications, the objective is to obtain materials with lower modulus than the incumbents. The reason for this is that the high stiffness of metals reduces stress in the adjacent bone, leading to mass loss. Candidate replacement materials are carbon fiber-reinforced polymers and CCCs.

9.5.10 Sports and Leisure Equipment

PMCs have been used successfully in sports equipment for many years. The key reinforcements are E-glass and, for high-performance products, carbon. The amount of carbon fiber used in golf club shafts alone rivals that used in the airframe industry. Boron and aramid fibers are used in specialized applications. Figure 9.32 shows an array of equipment made from carbon fibers, including golf club shafts, skis, tennis and other rackets, fishing rods, and others. PMCs also have been very successful in high-performance bicycle frames and wheels. There are numerous other PMC sports and leisure equipment applications, including surfboards, water skis, snowmobiles, and many others.

Fig. 9.30 Corrosion-resistant E-glass fiber-reinforced phenolic grating is 80% lighter than steel, has lower thermal conductivity, and meets strength and fire resistance requirements (courtesy MMFG).

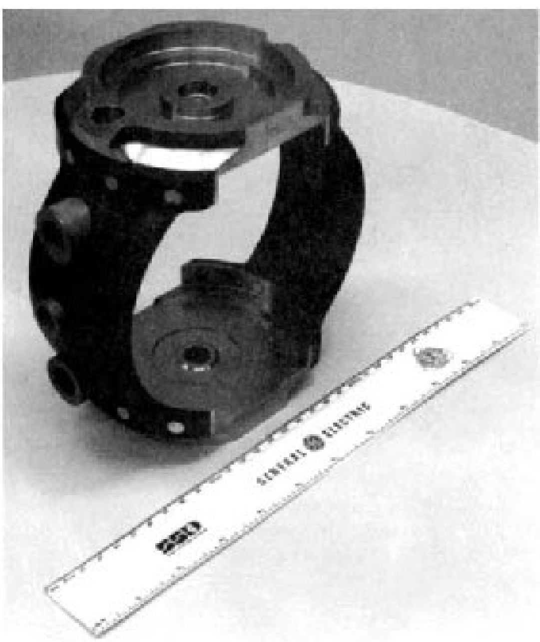

Fig. 9.31 Developmental lightweight, dimensionally stable electro-optical system gimbal composed of parts made from two types of carbon fiber-reinforced epoxy and from silicon carbide particle-reinforced aluminum.

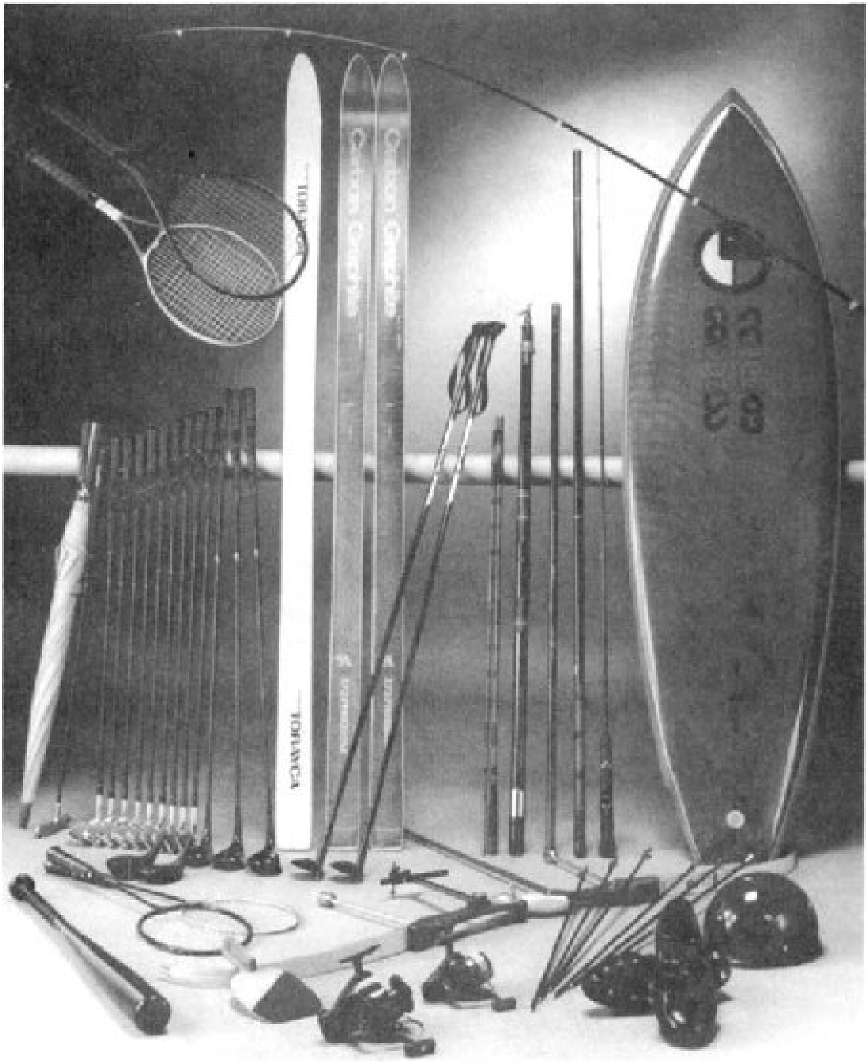

Fig. 9.32 Carbon fiber-reinforced polymer sports equipment (courtesy Toray).

MMCs have been used in a variety of specialized applications, such as mountain bike frames and wheels. Figure 9.33 shows developmental sports equipment using titanium carbide particle-reinforced titanium, including a golf club head, bat, and ice skate blade. In the latter application, the composite offers light weight and better wear resistance than monolithic titanium.

9.5.11 Marine Structures

Boats and ships were among the first important applications of polymer matrix composites. Applications range in size from canoes to mine hunters. The key materials are E-glass fibers and thermosetting polyester resins. However, in high-performance applications, such as Americas Cup sailboat hulls, booms, and masts, carbon and aramid fibers are used in place of glass, and epoxy resins frequently replace polyester. Carbon and aramid fibers are also used to reinforce sails to help maintain their aerodynamic shape. Figure 9.34 shows a catamaran that has a carbon fiber-reinforced PMC hull.

9.5.12 Miscellaneous Applications

In addition to the applications cited earlier in this section, there are countless other products using composite materials. We consider a few of these, including wind turbine blades, musical instruments, audio speakers, pressure vessels, and one other unique application.

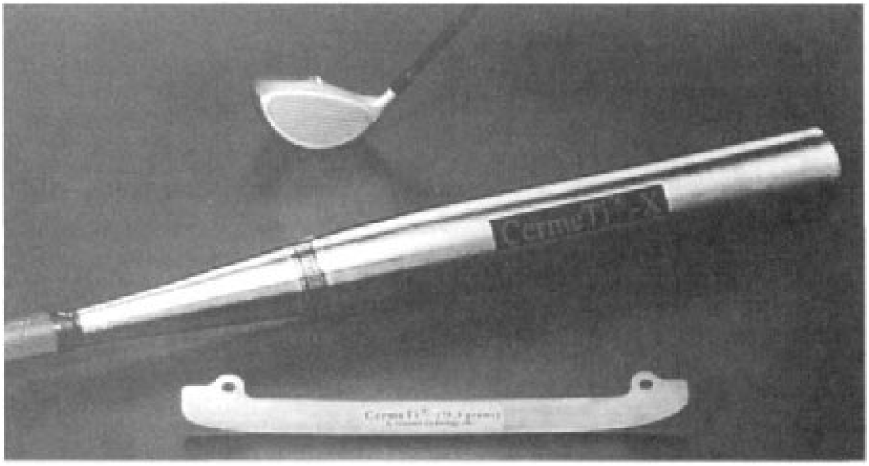

Fig. 9.33 Developmental sports equipment using titanium carbide particle-reinforced titanium, including a golf club head, bat, and ice skate blade (courtesy Dynamet Technology).

Wind turbines (i.e., windmills) have been used as a source of power for centuries. In the last few decades, there has been significant interest in use of wind turbines as renewable, nonpolluting source of electric power. Numerous devices have been installed in regions with high average annual wind speeds. Blades for many of these systems have been made of various polymers, notably epoxies and polyesters reinforced primarily with glass fibers, and in some instances carbon fibers. The reasons for use of composites are good fatigue and corrosion resistance, relative ease of fabrication, and cost-effectiveness.

Fig. 9.34 Catamaran with carbon fiber-reinforced hull (courtesy Toray).

Wood, an anisotropic fibrous material, has been used from time immemorial as a material of construction for musical instruments. In recent years, glass and carbon fiber-reinforced polymers, primarily epoxy, have been introduced in a wide range of instruments, including guitars, electric basses, banjos, mandolins, and violins. Carbon fiber reinforced plastics also have been used in violin bows. PMCs reinforced with aramid fibers are used in drum sticks and heads.

Audio speakers made of carbon fiber- and aramid fiber-reinforced epoxy have been used in a number of production applications (Fig. 9.35).

Pressure vessels used in natural gas vehicles were mentioned in Section 9.5.5. There have been many other applications of PMC pressure vessels, including firefighter breathing tanks, pressurization tanks for aircraft escape slides, and spacecraft pressure tanks. Reinforcements include high-strength glass, carbon, and aramid fibers. Epoxies are the leading matrix materials.

Figure 9.36 shows one of the more unusual applications for composites, a silicon carbide particle-reinforced aluminum brake rail mounted on a vehicle used in a theme park ride. Here the composite provides much better wear resistance than monolithic aluminum, with a negligible increase in weight.

9.6 DESIGN AND ANALYSIS

The most widely used materials of construction in mechanical engineering applications, monolithic metals and ceramics, are typically considered to be isotropic for purposes of design and analysis. Particle-reinforced composites also tend to be relatively isotropic. However, composites reinforced with fibers, especially continuous fibers, are typically strongly anisotropic and require special design and analysis methods. In this section, we consider how the special characteristics of composites influence the design process. We concentrate on composites reinforced with continuous fibers, which includes reinforcement forms such as fabrics and braids, because these are the most efficient materials.

As discussed in earlier sections, there are four key classes of composites: polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and carbon/carbon composites (CCCs). We consider all four, but focus on PMCs, which are the most widely used class of composites at this time and are likely to remain so for some time to come. Much of the discussion of PMC design and analysis, especially that dealing with consideration of the importance of elastic property anisotropy, applies to all fiber-reinforced composites.

The design process is an iterative one. After the critical step of establishing requirements, the engineer develops a preliminary design, which is then analyzed to determine whether it meets requirements. If analysis shows that safety margins are too large or too small, the design is refined, and the process repeated.

For a composite component, the designer selects the overall configuration; reinforcement types, forms, and volume fractions; matrix material; and the number of layers, along with their thicknesses and orientations.

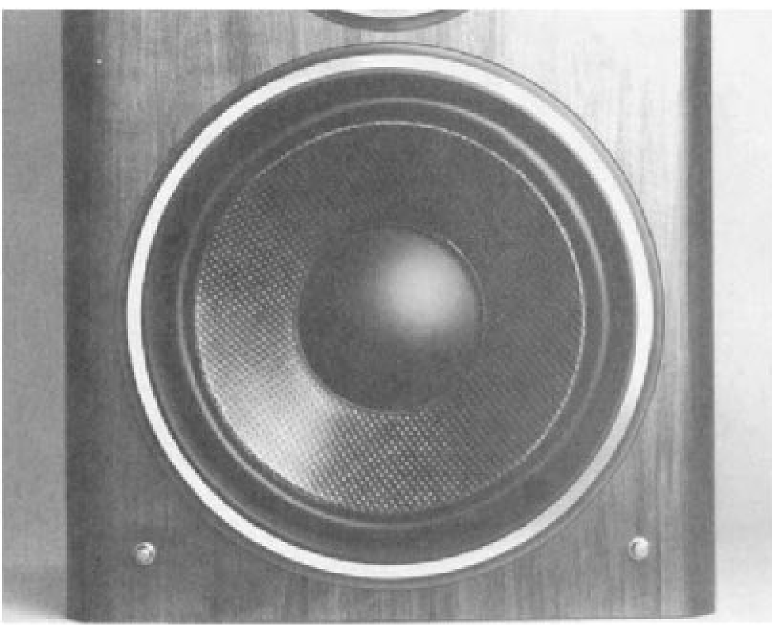

Fig. 9.35 Carbon fiber-reinforced epoxy audio speaker (courtesy Tonen).

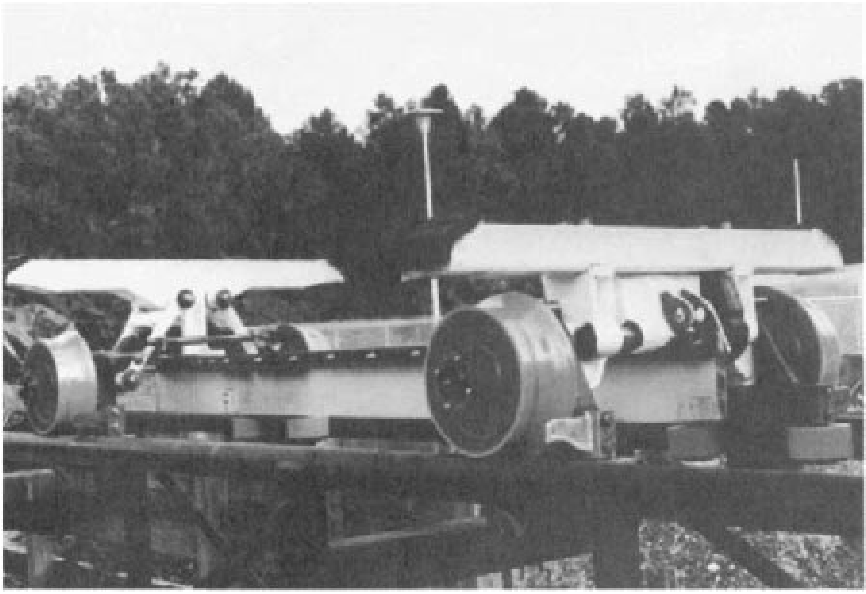

Fig. 9.36 Theme park ride vehicle uses a silicon carbide particle-reinforced aluminum brake rail (courtesy DWA Aluminum Composites).

An important consideration is selection of the manufacturing process, which, as discussed in previous section, has critical effects on material properties and cost. Experience has shown that in developing composite components, it is particularly important to involve manufacturing, quality assurance, and procurement personnel from the start.

In the next section, we discuss the design process for a PMC component. We then examine special considerations for MMCs, CMCs, and CCCs. Because design and analysis of composite components is very complex, it is not possible to cover the subject in detail.

9.6.1 Polymer Matrix Composites

As discussed in Sections 9.1 and 9.3, PMCs, which derive their strength and stiffness from the fibrous reinforcement phase, are, like wood, typically strongly anisotropic. PMCs are weak and have low stiffness in directions that are perpendicular to fiber directions and planes which are not intersected by fibers. We call these matrix-dominated directions and properties. Examples are transverse directions in unidirectional composites and interlaminar planes in laminates. As a consequence of the low transverse and through-thickness strengths of PMCs, unidirectional laminates are rarely used in structural applications.

Because PMC laminates are strongly anisotropic, isotropic analytical methods generally cannot be used. Anisotropy affects virtually all aspects of design and analysis, including deflections, natural frequencies, buckling loads, and failure modes. Fortunately, analytical methods for anisotropic structures are well developed. This is true for both closed-form anisotropic solutions and finite elements methods.

As a simple illustration of the differences between isotropic plates and anisotropic laminates, consider elastic constants. For isotropic materials, there are only two independent elastic constants. For example, the extensional modulus (E), shear modulus (G), and Poisson's ratio, (v) are related by the formula $E = 2G(1 + v)$. This is generally not valid for anisotropic laminates, for which there are four independent inplane elastic constants. In common engineering, they are usually Ex, Ey, Gxy, and vxy. Here, Ex and Ey are the extensional moduli in the x- and y-directions, Gxy is the inplane shear modulus, and vxy is the major inplane Poisson's ratio. The latter is defined as the ratio of the magnitude of the strain in the y-direction divided by the magnitude of the strain in the x-direction when an extensional stress is applied in the x-direction.

When a tensile stress is applied to an isotropic material, it produces an extensional strain in the direction of the applied load and a lateral, Poisson, contraction in the perpendicular direction. There is no shear distortion. Conversely, when a shear stress is applied to an isotropic material, it produces only shear strain, and not extensional strain. However, for an arbitrary anisotropic material, application of an extensional load produces not only extensional strains in the directions parallel and perpendicular to the applied load, but shear strains, as well. This is called tension-shear coupling. When a shear stress is applied, it produces extensional as well as shear strains.

When anisotropic materials are laminated and subjected to an inplane tensile stress, the general laminate response is much more complex than that of a plate made of an isotropic material. In the most general case of an arbitrary laminate, the tensile stress will produce not only extension in the direction of the load and lateral contraction, but also bending, twisting, and inplane shear deformation.

To minimize coupling, laminates are designed to be balanced and symmetric. A balanced laminate is one for which the directions of the layers above the mid-plane are a mirror image of those below it. A symmetric laminate is one for which for every layer having an orientation of $+\theta$ direction with respect to a reference axis, there exists an identical laminate in the $-\theta$ direction.

Although coupling is undesirable in most cases, there have been a few designs where selected coupling has been used to advantage. Examples are aircraft with forward swept wings and bicycle cranks.

It is important to note that the properties of laminates are very sensitive to laminate geometry. Further, anisotropic laminates can have characteristics very different from those of monolithic materials. Often, these properties are counter-intuitive. For example, the Poisson's ratio of laminates having fibers in the $+45°$ and $-45°$ directions can be much greater than 0.5, compared to about 0.3 for most metals. Addition of fibers at 90° can reduce this value significantly.

Theoretically the designer can select from an infinite number of laminate geometries to meet requirements for a particular component. In practice, however, it is common to choose laminates from discrete families with fibers in a few directions. The most common family has fibers in four directions: 0°, +45°, −45°, and 90°. The designer selects laminates having various percentages of layers in the four directions, usually making sure that they are balanced and symmetric. To assure adequate strength in all directions, many organizations use the "10% Rule." Using this convention, at least 10% of the layers in a laminate are placed in each of the four key directions.

A critical design consideration for laminated PMCs is minimization of through-thickness stresses. This is very different from the situation for monolithic structures, for which these stresses are typically considered to be of secondary importance and are ignored. Interlaminar stresses arise from a variety of sources: out-of-plane loads; curvature; stress waves from impact loads; and free-edge effects. Interlaminar stresses in curved regions are caused by mechanical loads, and by differential thermal and moisture expansion in the inplane and through-thickness directions.

Computer programs based on laminated plate theory are widely used in design and analysis. These programs are used to predict laminate properties and to define laminate response and layer stresses and strains resulting from applied loads, moments, and changes in temperature and moisture level. Laminated plate analysis is also used to generate carpet plots for properties of laminated plates which are used in preliminary design.

The stress-strain curves for PMCs are essentially linear to failure, although, as discussed in Sections 9.2 and 9.3, composites reinforced with carbon and aramid fibers do display some nonlinearity. As a consequence of the lack of plastic deformation, under static loading, PMC laminates are sensitive to stress concentrations, such as those that arise at joints and cutouts. However, composite stress concentrations are relatively insensitive to fatigue loading. In fact, fatigue loading often results in local microdamage that reduces the effect of the stress concentration. This is the opposite of monolithic metals, which are relatively insensitive to static stress concentrations because of plasticity, but sensitive to stress concentrations under fatigue loading, which causes propagation of through-thickness cracks.

Prediction of laminate failure under applied load is commonly based on a variety of failure theories that are applied to stresses or strains on a layer-by-layer basis. Layer stresses and strains are determined using finite element analysis combined with laminated plate theory. Failure theories are based on maximum stress, maximum strain, or numerous interaction formulas for stress or strain components.

The joining of composites is a critical design issue because of their sensitivity to stress concentrations. Joining is accomplished by adhesive bonding, mechanical fasteners, or a combination of these. As a rule, adhesive joints are the most efficient structurally, but are sensitive to manufacturing processes and environmental degradation. Mechanically fastened joints are used for very highly loaded structures, especially those subjected to fatigue loading and for which environmental degradation is a concern. However, because mechanical joints are less efficient, there is typically a weight penalty associated with their use. Stresses arising from differences in Poisson's ratios and coefficients of thermal expansion (CTEs) are important considerations when composites are joined to metals or other laminates. Stresses caused by moisture expansion also should be considered.

Galvanic corrosion is an important issue whenever dissimilar materials are joined. This is especially true for carbon and aluminum. The problem can be overcome by electrically isolating the two materials or by using compatible materials.

As for all materials, design allowables for PMCs should take into account the loading conditions and environment, including temperature to which they will be subjected.

9.6.2 Metal Matrix Composites

As discussed in Sections 9.3 and 9.5, the leading types of reinforcements for MMCs are continuous fibers, discontinuous fibers, and particles. Continuous fibers provide materials with the highest strength and stiffnesses. Discontinuous fibers are primarily used to increase wear resistance and elevated temperature static and fatigue strengths. Particles provide isotropic materials with high specific modulus and yield strength, improved elevated temperature strength properties and wear resistance, and reduced CTE.

For all MMCs, an important consideration is degradation of properties resulting from interactions between the reinforcement and matrix at elevated temperature, which can occur during manufacture or in service. This is defined experimentally.

In contrast to PMCs, the high transverse strength of many MMCs allows use of unidirectional laminates in structures. A good example are the Space Shuttle Orbiter boron–aluminum struts cited in Section 9.5. An important consideration for MMCs reinforced with continuous fibers is that they display elastic-plastic characteristics.

As discussed in Section 9.5, fiber orientation has a critical influence on composite properties. A critical consideration for MMCs reinforced with discontinuous fibers is to assure that the manufacturing process results in components which have fiber volume fractions and orientations that meet design requirements.

The isotropic nature of particle-reinforced MMCs significantly simplifies design. Major considerations for these materials are that they tend to have lower elongations and fracture toughnesses than the base metal.

9.6.3 Ceramic Matrix Composites

As for MMCs, interactions between matrix and reinforcement at elevated temperatures is an important consideration. In addition, formation of matrix cracking exposes reinforcements to the environment, which can degrade the properties of the interphase or the fiber itself, resulting in embrittlement and weakening of the material.

Another design consideration for CMCs is that, like PMCs, they have relatively weak properties in fiber-dominated directions. They also are sensitive to stress concentrations that arise at joints and cutouts.

9.6.4 Carbon/Carbon Composites

The comments for CMCs generally apply to CCCs, although the problem of fiber-matrix interaction is not a serious consideration for the latter. A major consideration for CCCs is that they typically have even weaker matrix-dominated properties than PMCs and CMCs.

A critical issue for CMCs is elevated temperature oxidation, which, as discussed in Section 9.3, can be reduced by use of coatings and oxidation inhibitors in the matrix.

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