Chapter 5
Polymer Matrix Composites

Polymer matrix composites (PMCs) have established themselves as engineering structural materials, not just as laboratory curiosities or cheap stuff for making chairs and tables. This came about not only because of the introduction of high-performance fibers such as carbon, boron, and aramid but also because of some new and improved matrix materials (see Chap. 3). Nevertheless, glass fiber reinforced polymers represent the largest class of PMCs. Carbon fiber reinforced PMCs are perhaps the most important structural composites; especially in the aerospace field. In this chapter, we discuss polymer composite systems containing glass, aramid, polyethylene, boron, and carbon fibers.

5.1 Processing of PMCs

Many techniques, originally developed for making glass fiber reinforced polymer matrix composites can also be used with other fibers. Glass fiber reinforced polymer composites represent the largest class of PMCs. As we saw in Chap. 3, polymeric matrix materials can be conveniently classified as thermosets and thermoplastics. Recall that thermosets harden on curing. Curing or cross-linking occurs in thermosets by appropriate chemical agents and/or application of heat and pressure. Conventionally, thermal energy (heating to 200 °C or above) is provided for this purpose. This process, however, brings in the problems of thermal gradients, residual stresses, and long curing times. Residual stresses can cause serious problems in nonsymmetric or very thick PMC laminates, where they may be relieved by warping of the laminate, fiber waviness, matrix microcracking, and ply delamination. We mentioned electron beam curing in Chap. 3. Electron beam curing offers an alternative that avoids these problems. It is a nonthermal curing process that requires much shorter cure time cycles. Curing by electron beam occurs by electron-initiated reactions at a selectable cure temperature. We describe different methods of fabrication of polymer matrix composites—first thermoset-based composites and then thermoplastic-based composites.

5.1.1 Processing of Thermoset Matrix Composites

There are many processing methods for composites with thermoset matrix materials including epoxy, unsaturated polyester, and vinyl ester.

5.1.1.1 Hand Layup and Spray Techniques

Hand layup and spray techniques are perhaps the simplest polymer processing techniques. Fibers can be laid onto a mold by hand and the resin (unsaturated polyester is one of the most common) is sprayed or brushed on. Frequently, resin and fibers (chopped) are sprayed together onto the mold surface. In both cases, the deposited layers are densified with rollers. Figure 5.1 shows schematics of these processes. Accelerators and catalysts are frequently used. Curing may be done at room temperature or at a moderately high temperature in an oven.

5.1.1.2 Filament Winding

Filament winding (Shibley 1982; Tarnopol'skii and Bail' 1983) is another very versatile technique in which a continuous tow or roving is passed through a resin impregnation bath and wound over a rotating or stationary mandrel. A roving consists of thousands of individual filaments. Figure 5.2a shows a schematic of this process, while Fig. 5.2b shows a pressure vessel made by filament winding. The winding of roving can be polar (hoop) or helical. In polar winding, the fiber tows do not cross over, while in the helical they do. The fibers are, of course, laid on the mandrel in a helical fashion in helical windings; the helix angle depends on the shape of the object to be made. Successive layers are laid on at a constant or varying angle until the desired thickness is attained. Curing of the thermosetting resin is done at an elevated temperature and the mandrel is removed. Very large cylindrical (e.g., pipes) and spherical (e.g., for chemical storage) vessels are built by filament winding. Glass, carbon, and aramid fibers are routinely used with epoxy, polyester, and vinyl ester resins for producing filament wound shapes.

There are two types of filament winding processes: wet winding and prepreg winding. In wet winding, low-viscosity resin is applied to the filaments during the winding process. Polyesters and epoxies with viscosity less than 2 Pa s (2,000 cP) are used in wet winding. In prepreg winding, a hot-melt or solvent-dip process is

a

Reinforcement

Resin   Hand Roller

Laminate

Contact Mold   Gel Coat

b

Laminate

Chopped Roving

Catalyzed Resin

Chopper /
Spray Gun

Contact Mold
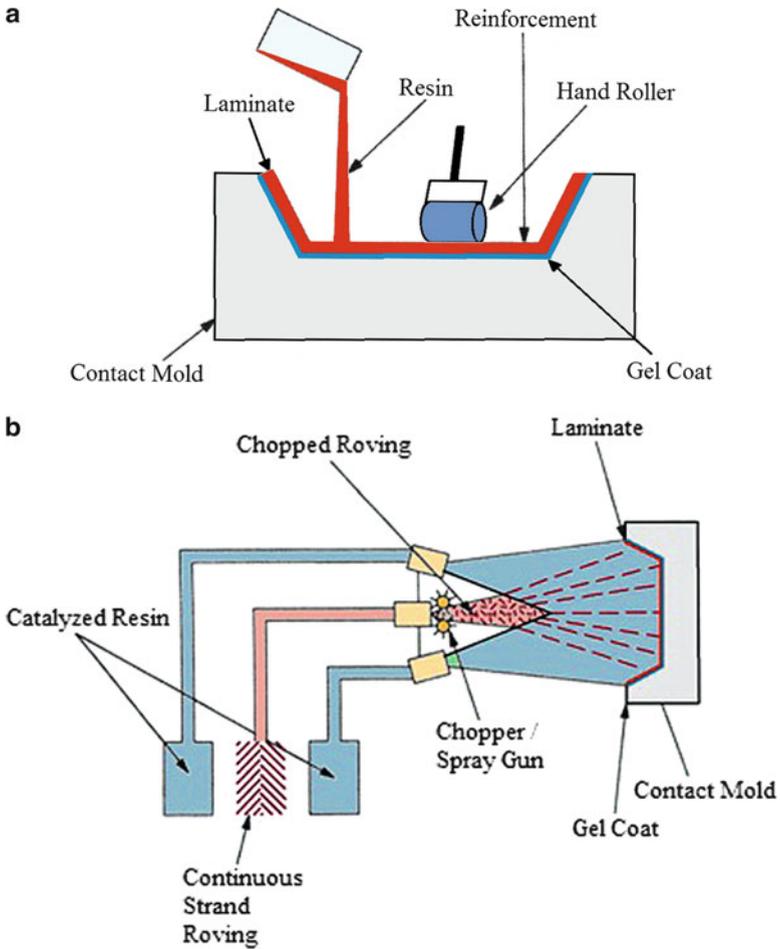
Gel Coat

Continuous
Strand
Roving

Fig. 5.1 (a) In hand layup, fibers are laid onto a mold by hand, and the resin is sprayed or brushed on. (b) In spray-up, resin and fibers (chopped) are sprayed together onto the mold surface

used to preimpregnate the fibers. Rigid amines, novolacs, polyimides, and higher-viscosity epoxies are generally used for this process. In filament winding, the most probable void sites are roving crossovers and regions between layers with different fiber orientations.
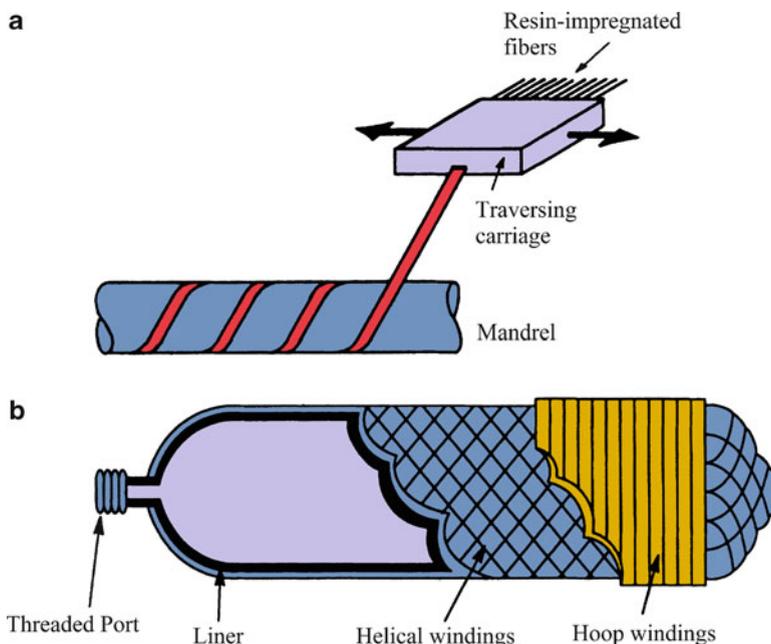
Fig. 5.2 (a) Schematic of filament winding process. (b) Schematic of a filament wound pressure vessel with a liner; helical and hoop winding are shown

5.1.1.3 Pultrusion

In this process continuous sections of polymer matrix composites with fibers oriented mainly axially are produced. Figure 5.3a shows a schematic of this process. Continuous fiber tows come from various creels. Mat or biaxial fabric may be added to these to provide some transverse strength. These are passed through a resin bath containing a catalyst. After this, the resin-impregnated fibers pass through a series of wipers to remove any excess polymer and then through a collimator before entering the heated die. A thorough wet-out of the rovings is very important. Stripped excess resin is recirculated to the resin bath. The heated die has the shape of the finished component to be produced. The resin is cured in the die and the composite is pulled out. At the end of the line the part is cut by a flying saw to a fixed length. Typically, the process can produce continuously at a rate of 10–200 cm/min. The exact speed depends on the resin type and the cross-sectional thickness of the part being produced. Pultruded profiles as wide as 1.25 m with more than 60 % fiber volume fraction can be made routinely. An example of a product obtained by pultrusion is shown in Fig. 5.3b. The hollow trapezoidal-shaped product shown is a helicopter windshield post made of carbon fiber mat and tows in a high-temperature vinyl ester resin matrix.

Note that the pultrusion process has a continuous molding cycle. This requires that the fiber distribution be constant and that the cross-sectional shapes not vary, i.e., no bends or tapers are allowed. Main advantages of the process are low labor cost and product consistency. Shapes such as rods, channels, and angle and flat stock are easily produced. Fibrous reinforcements in different forms can be used. Roving, i.e., continuous fibers are most commonly used. It is easy to saturate such a bundle of fibers with the resin. Continuous strand mat consisting of continuous fiber lengths with random orientation can also be used. They are used to obtain reinforcement action in the transverse direction. Other forms of materials used include chopped strand mat consisting of short (chopped) fibers that can be bonded or stitched to a carrier material, commonly a unidirectional tape, and woven fabrics and braided tapes. Such forms provide reinforcement at $0°$, $90°$, or an arbitrary angle θ to the loading direction. Common resins used in pultrusion are polyester, vinyl ester, and epoxy. Meyer (1985) provides the details regarding this process.
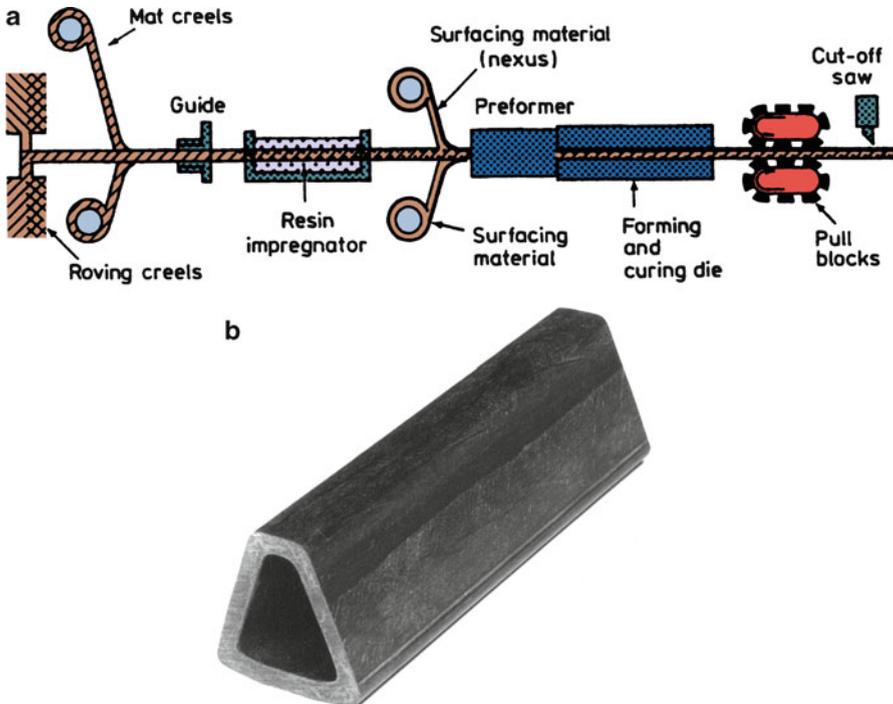

Fig. 5.3 (**a**) Schematic of the pultrusion process (courtesy of Morrison Molded Fiber Glass Co.). (**b**) A helicopter windshield post made of carbon fibers/vinyl ester resin by pultrusion. The post is 1.5 m long (courtesy of Morrison Molded Fiber Glass Co.)

5.1.1.4   Resin Transfer Molding

Resin transfer molding (RTM) is a closed-mold, low-pressure process. A preform made of the desired fiber (carbon, glass, or aramid) is placed inside a mold, and liquid resin such as epoxy or polyester is injected into the mold by means of a pump. Reinforcements can be stitched, but more commonly they are made into a preform that maintains its shape during injection of the polymer matrix. The resin is allowed to cure and form a solid composite. The polymer viscosity should be low (<1 Pas) enough for the fibers to be wetted easily. Additives to enhance the surface finish, flame retardancy, weather resistance, curing speed, etc. may be added to the resin. Thermoplastics have too high a melting point and too high viscosities (>1 Pas or 1,000 cP) to be processed with RTM. In RTM processing, Darcy's law, which describes the permeability of a porous medium, is of great importance. Darcy's law for single-phase fluid flow says that the volume current density, J, i.e., volume/(area $\times$ time), of a fluid is given by:

$$J = -\frac{k}{\eta}\nabla P,$$

where k is the permeability of the porous medium, η is the fluid viscosity, ∇P represents the pressure gradient that drives the fluid flow. It can be recognized that Darcy's law is an analog of Ohm's law for electrical conduction, i.e., hydraulic permeability is an analog of electrical conductivity. Note that the permeability, k, is a function of the properties of the porous medium, i.e., its microstructure; it does not depend on properties of the fluid.

Among the advantages of RTM, one can cite the following:

- Large, complex shapes and curvatures can be obtained.
- A higher level of automation is possible than in many other processes.
- Layup is simpler and the process is speedier than manual operations.
- By using woven, stitched, or braided preforms, fiber volume fractions as high as 65 % can be achieved.
- The process involves a closed mold; therefore styrene emissions can be reduced to a minimum. In general, RTM produces much fewer emissions compared to hand layup or spray-up techniques.

Mold design is a critical element in the RTM process. Generally, the fibrous preform is preheated. The mold has built-in heating elements to accelerate the process of resin curing. Resin flow into the mold and heat transfer are analyzed numerically to obtain an optimal mold design.

The automotive industry has found RTM to be a cost-effective, high volume process for large scale processing. Use of RTM to make automotive parts can result in significant weight reduction. For example, composite parts made by RTM resulted in 90 kg reduction in the weight of Dodge Viper automobile.

5.1.1.5 Automated Tape Placement and Automated Fiber Placement

In general, automation in most any field results in productivity gains. For example, a completely automated process, i.e., no human being is required, has a great attraction for use in radioactive or clean environments. In the area of fabrication of composites, it has led to two very important techniques: automatic tape placement (ATL) and automatic fiber placement (AFP). Another significant advantage is that rather large structures can be made by this process. The hand layup process is limited by the extent of a worker's reach. Clearly, such a restriction would be absent in any automatic process. Most automated machines are large, sophisticated and represent a major capital investment. Resin choices for tapes can be grouped by processing characteristics. These are commonly thermoset resins such as epoxies; they are cured to B-stage, i.e., tacky, and later fully cured. The second group comprises of nontacky solid resins that melt and flow prior to curing to a thermoset polymer, e.g., bismaleimides and nontacky thermoplastic resins processed entirely by melting and freezing, e.g., polyether ether ketone, (PEEK), and polyphenylene sulfide, (PPS).

Capital expenditures for computer-controlled, automated equipment can be significant, however. Understandably, such equipment initially found applications in defense related applications, e.g., the wing skin panels of F-22 *Raptor* fighter jet. With Boeing 787 and Airbus A380 and other advanced aircrafts, automated processing techniques have moved into civilian aircraft construction as well.

Automated Tape Placement

In this technique, resin preimpregnated high performance reinforcement fibers in the form of a tape are placed in specific directions. It is easy to see that part weight will be minimized by placing fibers only along the directions needed. Automated tape placement (ATP) has gained wide acceptance for part fabrication in the aerospace industry; examples include aircraft wings, body skins, and control surfaces. In ATP, prepregged tape, rather than single fiber tows, is laid down continuously to form parts. It is often used for parts with highly complex contours or angles. Tape layup is versatile; it allows breaks in the process and easy changes in direction. Although, the process is commonly used with thermosets, it can be adapted for thermoplastic materials as well.

In principle, the ATL works as follows. The customer's computer aided design (CAD) is the starting point. Using the CAD system, the product or component to be manufactured, say a curved part, is developed mathematically onto a flat surface. This is further broken down into layers to be fabricated by laying strips of tape side by side. Sophisticated software is used to translate strips in each layer via a series of numerical control steps to develop the final product shape. A spool of tape (consisting of, say, carbon fiber preimpregnated with a thermosetting resin, commonly epoxy), covered with a protective paper on the top and protective film

underneath, is unwound; the film and the paper are peeled off, and the tape suspended in mid air is cut to correct shape by cutting blades. The cutting blades are very fast; they can make 6,000 cuts per minute. A laser beam in the tape laying head is used to accurately lay the tape on the mold.

Automated tape laying machines (ATL) are used to make aircraft parts such as wing stringers, spars, skins and elevators, tail skins and horizontal planes, engine cowls, fuselage skins and belly fairings. These automated tape laying machines are capable of laying preimpregnated tapes of 75-, 150- or 300-mm width at any orientation and can build up the product consisting of any number of plies. Modern ATL machines have heads that integrate ultrasonic cutting of the laminate, cutter depth-setting, and dockable inkjet marking. Low-rail gantry platforms are available in medium and large size ranges that can be matched to customer part size and floor space requirements. The machines feature tape-deposit speeds of up to 50 m/min and a high degree of placement accuracies on complex contours.

Automated Fiber Placement

Automated fiber placement (AFP) involves the use of individual fiber tows. Multiple resin preimpregnated fiber tows are placed onto a mandrel at high speed, using a numerically controlled placement head to dispense, clamp, cut and restart each tow during placement. Minimum cut length (the shortest tow length a machine can lay down) is the essential ply-shape determinant. The fiber placement heads can be attached to a 5-axis gantry or retrofitted to a filament winder. Machines are available with dual mandrel stations to increase productivity. Advantages of fiber placement fabrication include speed, reduced material scrap and labor costs, part consolidation and improved part-to-part uniformity. The process is employed when producing large thermoset parts with complex shapes.

The fiber tows, preimpregnated with the resin, from spools are fed into the fiber placement head where they are collimated into a single band and laminated onto the work surface. Typically, each tow is about 3 mm wide strand of continuous fibers. A strand, in its turn, may consist of 12,000 individual filaments impregnated with an epoxy resin.

Different fiber tows can be delivered at different speeds, thus conforming to a complex structural shape. For example, when a curved surface is to be laminated, the outer tows of the band pull more strand length than the inner tows. It is possible to cut individual tows and restart without stopping the motion of the head. This allows in-process control of the band width, avoiding excess resin build-up and to fill in any gaps. A compaction roller or shoe consolidates the tape pressing it onto the work surface. This pressing action serve to removes any trapped air and any minor gaps between individual tows. Figure 5.4 shows a schematic of the automatic fiber placement process.
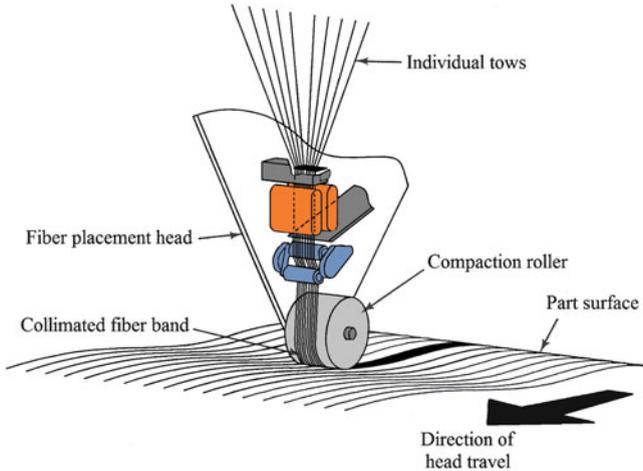
Fig. 5.4 Schematic of automatic fiber placement process

High speed, automatic processing has become very popular with the coming of large-sized civilian aircraft. As an example of a commercially produced AFP machine, we mention VIPER made by MAG Cincinnati (Hebron, Ky.). Such machines are used for automated fabrication of composite fuselage panels for the commercial aircraft. The VIPER 6000 series AFP machines can produce fuselage panels up to 6.3 m in diameter. The VIPERs will produce 92 % of the fuselage for the A350 XWB. According to MAG Cincinnati, the company that manufactures the VIPER machines, such machines enable independent control over feed, clamp, cut and start for up to 32 individual tows or slit tape. Multistrands of carbon fiber/ epoxy can be placed around a mandrel to make a single finished part without seams and rivets.

5.1.1.6 Autoclave-Based Methods

Autoclave-based methods or bag molding processes (Slobodzinsky 1982) are used to make large parts. Before we describe this important process, we should digress and describe an important term, although we have used it earlier, viz., prepreg. The term *prepreg* is a short form of preimpregnated fibers. Generally, a prepreg is in the form of a thin sheet or lamina of unidirectional (or occasionally woven) fiber/ polymer composite protected on both sides with easily removable separators. Figure 5.5a shows schematic of a prepreg. Prepregs thus represent an intermediate stage in the fabrication of a polymeric composite component. The prepreg generally has the resin in a partially cured state with a moderately self-adhesive tack. This can easily be obtained with epoxies whose cure can be separated into two stages (see Chap. 3). Some composite systems have thermoset matrix materials that do not go through a two-stage cure, such as polyesters and polyimides; in such systems,

the tack in the prepreg can be achieved by the addition of liquid rubbers or resins. In prepregs made with a thermoplastic matrix, such a tack is conspicuous by its absence. The reason for this is that thermoplastics do not undergo a curing reaction like thermosets (see Chap. 3). As a consequence, prepregs made with a thermoplastic matrix are quite stiff or *boardy*. A typical unidirectional prepreg is in the form of a long roll, 300−1,500 mm wide roll and 0.125 mm thick. The length of the roll can be anything, but it is generally 50–250 m. The fiber content, by volume, in a unidirectional prepreg is typically about is about 65 %. It is not uncommon to use 50 or more such plies or laminae in an autoclave processed composite.

Prepregs can be made by a number of techniques. In a process called *solution dip,* the resin ingredients are dissolved in a solvent to 40–50 % solids level. The fiber (in the form of a yarn or a fabric) is passed through the solution, and it picks up an amount of solids that depends on the speed of throughput and the amount of solids in the solution. In another process, *solution spray,* a specified amount of solid resin is sprayed onto the fiber yarn or fabric. In both solution dip and solution spray, the impregnated fiber is put through a heat cycle to remove the solvents and the chemical reaction in the resin proceeds to give the desired tack. In *direct hot-melt,* the resin formulation is incorporated as a high temperature coat on the fiber. At high temperature, the viscosity is low enough for coating the fiber directly. *Film calendaring* involves casting the resin formulation into a film from either hot-melt or solution. The fiber yarn is sandwiched between two films and calendared so that the film is worked onto the fiber.

Autoclave-based processing of PMCs results in a very high quality product. That is the reason it is used to make components in the aerospace field. An *autoclave* is a closed vessel (round or cylindrical) in which processes (physical and/or chemical) occur under simultaneous application of high temperature and pressure. Heat and pressure are applied to appropriately stacked prepregs. The combined action of heat and pressure consolidates the laminae, removes the entrapped air, and helps cure the polymeric matrix. Autoclave processing of composites thus involves a number of phenomena: chemical reaction (curing of the thermoset matrix), flow of the resin, and heat transfer. Figure 5.5b shows schematically the setup in an autoclave to make a laminated composite. Bags containing prepregs in predetermined orientations (this is discussed in Chap. 11) are placed in an autoclave (typically a cylindrical oven in which pressure and heat can be applied to part). The bags consist of thin and flexible membranes made of rubber that separate the layup from the gas used to compress. Densification and curing are achieved by pressure differential across the bag walls. One can use vacuum, in which case the bag contents are evacuated and atmospheric pressure consolidates the composite. Figure 5.5c shows a schematic of the layup of plies with different fiber orientations obtained after consolidation. Optical micrographs of actual carbon fiber/epoxy laminated composite made in an autoclave are shown in Fig. 5.5d, e. Note the different fiber orientation in different layers.

Autoclave-based processing with prepregs is quite versatile. One may use more than one type of reinforcement fiber to produce what is called a *hybrid* composite. A prepreg with fibers running parallel to the long dimension is called a 0° lamina or ply. A prepreg cut with fibers perpendicular to the long dimension is designated as

a

Polyethylene film

Silicone release paper

Unidirectional composite

b

High Autoclave Pressure

Bagging Film

To Vacuum Pump

Sealing Strip   Prepreg and Breather   Tool

c

A = 0°
B = 90°
X = -45°
Y = +45°
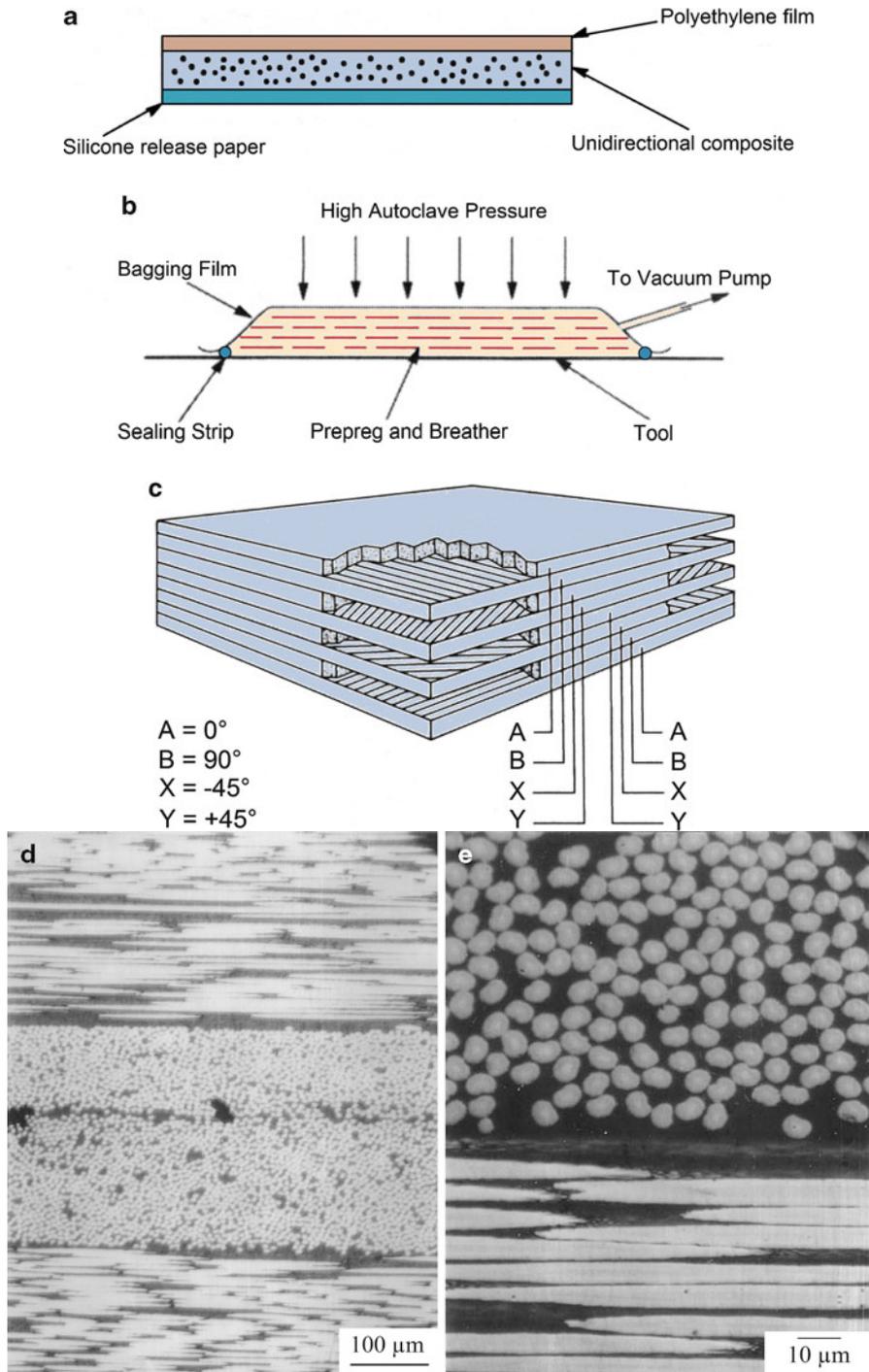
A
B
X
Y

A
B
X
Y

d

100 μm

e

10 μm

Fig. 5.5 (a) Schematic of a prepreg. (b) Setup in an autoclave to make a laminated composite. (c) Layup of plies with different fiber orientations. (d) Micrograph of carbon fiber/epoxy laminated composite made in an autoclave. (e) A higher magnification picture of (e). Note the different fiber orientation in different layers

Fig. 5.6   A large autoclave that is used to make the wings of Boeing 787. An idea of the size of the autoclave can be had from the height of the person standing inside the autoclave (courtesy of ASC Process Systems Inc., Sylmar, California)

a 90° lamina, while a prepreg with fibers running at an intermediate angle θ is designated a θ-ply. The exact orientation sequence of plies in the laminate is determined from theory of elasticity (see Chap. 11) to obtained appropriate magnitudes and directions of stress and to avoid unwanted twisting and/or torsion. Such laminate construction, mostly done by hand, can result in high fiber volume fractions (60–65 %). A nice example of an autoclave, one the largest in the world which is used to make the wings of the Boeing 787 plane is shown in Fig. 5.6. An idea of the physical dimensions can be had from the man standing in the cylindrical body of the autoclave. One of the end pieces is shown on the left hand side in the picture.

5.1.2   Thermoplastic Matrix Composites

Thermoplastic matrix composites have several advantages and disadvantages over thermoset matrix composites. We first list these and then we will describe some of the important processes used to form thermoplastic matrix composites.

The advantages of thermoplastic matrix composites include:

- Refrigeration is not necessary with a thermoplastic matrix.
- Parts can be made and joined by heating.
- Parts can be remolded, and any scrap can be recycled.

- Thermoplastics have better toughness and impact resistance than thermosets. This can generally also be translated into thermoplastic matrix composites.

  The disadvantages include:

- The processing temperatures are generally higher than those with thermosets.
- Thermoplastics are stiff and boardy, i.e., they lack the tackiness of the partially cured epoxies.

A good quality laminate must be void-free. This implies that there must be sufficient flow of the thermoplastic matrix between layers as well as within individual tows. Generally, a pressure of 6–12 MPa, a temperature between 275 and 350 °C, and dwell times of up to 30 min are appropriate for thermoplastics such as polysulfones and polyetheretherketone (PEEK). Because no time is needed for any curing reaction, the time length of the molding cycle with a thermoplastic matrix is less than that with a thermoset matrix.

A brief description of processing methods for thermoplastic matrix composites follows.

5.1.2.1 Film Stacking

Laminae of thermoplastic matrix containing fibers with very low resin content (~15 w/o) are used in this process. Low resin content is used because these are very boardy materials. The laminae are stacked alternately with thin films of pure polymer matrix material. This stack of laminae consists of fibers impregnated with insufficient matrix and polymer films of complementary weight to give the desired fiber volume fraction in the end product. These are then consolidated by simultaneous application of heat and pressure.

The impregnation of thermoplastic matrix takes place under the simultaneous application of heat and pressure; the magnitude of pressure and temperature must be sufficient to force the polymeric melt to flow into and through the reinforcement preform. The rate of penetration of a fluid into the fibrous preform structure is described by Darcy's law (see Sect. 5.1.1.4). Darcy's law says that flow rate is directly proportional to the applied pressure and inversely proportional to the viscosity. Thus, increasing the applied pressure and decreasing the viscosity of the molten polymer (i.e., increasing the temperature) helps in the processing.

5.1.2.2 Diaphragm Forming

This process involves the sandwiching of freely floating thermoplastic prepreg layers between two diaphragms (Cogswell 1992). The air between the diaphragms is evacuated and thermoplastic laminate is heated above the melting point of the matrix. Pressure is applied to one side, which deforms the diaphragms and makes them take the shape of the mold. The laminate layers are freely floating and very

flexible above the melting point of the matrix, thus they readily conform to the mold shape. After the completion of the forming process, the mold is cooled, the diaphragms are stripped off, and the composite is obtained. One of the advantages of this technique is that components with double curvatures can be formed. The diaphragms are the key to the forming process, and their stiffness is a very critical parameter. Compliant diaphragms do the job for simple components. For very complex shapes requiring high molding pressures, stiff diaphragms are needed. At high pressures, a significant transverse squeezing flow can result, and this can produce undesirable thickness variations in the final composite.
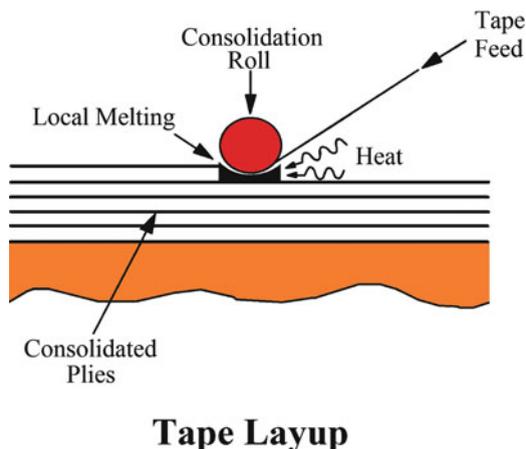

Fig. 5.7   Schematic of a thermoplastic tape laying machine (courtesy of Cincinnati Milacron)

5.1.2.3   Thermoplastic Tape Laying

Thermoplastic tape laying machines are also available, although they are not as common as the thermosetting tape laying machines. Figure 5.7 shows the schematic of one such machine. A controllable tape head has the tape dispensing and shim dispensing/take-up reels and heating shoes. The hot head dispenses thermoplastic tape from a supply reel. There are three heating and two cooling/compaction shoes. The hot shoes heat the tape to molten state. The cold shoes cool the tape instantly to a solid state.

5.1.2.4   Commingled Fibers

The thermoplastic matrix can be provided in the form of a fiber. The matrix fiber and the reinforcement fiber are commingled to produce a yarn that is a blend of the thermoplastic matrix and reinforcement yarn. Such a commingled yarn can be

woven, knit, or filament wound. The yarn formed into the appropriate shape is then subjected to heat and pressure to melt the thermoplastic matrix component, wet out the reinforcement fibers, and obtain a composite.

There are many commingled fibers available commercially for processing into a composite. As examples, we cite the following. Vectran is the trade name of a liquid crystal thermoplastic aromatic polyester fiber. The multifilament yarn is produced by melt spinning. It has a low melting point, and thus when commingled with a reinforcement fiber, it can provide the matrix component in the composite. It is available in the form of multifilament yarn that can be commingled with glass or other reinforcement fibers. Twintex is another commercial name that involves commingled polypropylene fibers and glass fibers.

5.1.2.5 Thermoforming and Injection Molding

As pointed out earlier, thermoplastics soften on heating, and therefore melt flow techniques of forming can be used. Such techniques include injection molding, extrusion, and thermoforming. Thermoforming involves the production of a sheet, which is heated and stamped, followed by vacuum or pressure forming. Generally, discontinuous fibrous (principally glass) reinforcement is used, which results in an increase of melt viscosity. Short fiber reinforced thermoplastic resin composites can also be produced by a method called *reinforced reaction injection molding* (RRIM) (Lockwood and Alberino 1981). RRIM is actually an extension of the *reaction injection molding* (RIM) of polymers. In RIM, two liquid components are pumped at high speeds and pressures into a mixing head and then into a mold where the two components react to polymerize rapidly. An important example is a urethane RIM polymer. In RRIM, short fibers (or fillers) are added to one or both of the components. The equipment for RRIM must be able to handle rather abrasive slurries. The fiber lengths that can be handled are generally short, owing to viscosity limitations. Because a certain minimum length of fiber, called the critical length (see Chap. 10), is required for effective fiber reinforcement, more often than not RRIM additives are fillers rather than reinforcements. Most RIM and RRIM applications are in the automotive industry.

5.1.2.6 Long Fiber Thermoplastic Compression Molding

The most common way of making thermoplastic composites involves mixing of short length of fibers (about 2–3 mm or less) with a thermoplastic matrix and injection molding the composite (see above). The properties of these short fiber reinforced composites are better than those of the unreinforced matrix material, but the full potential of the reinforcing fiber is not achieved. We treat the important subject of critical length of fiber for load transfer in Chap. 10. Suffice it here to state that increasing the length of fibers to greater than 10 mm would result in improvements in a variety of properties of the composites. In the literature the

acronym LFT is used to refer to composites with a thermoplastic matrix containing fibers greater than 10 mm in length. Figure 5.8 shows variation of some mechanical characteristics of a composite as a function of fiber length in a schematic manner. Note the increase in stiffness and strength as well as improvement in impact properties with increasing fiber length. This has led to innovations in processing of long fiber thermoplastic matrix composites, commonly referred to as LFT composites.

The basic process is illustrated in Fig. 5.9. The critical step in processing LFTs is the production of continuous fiber reinforced rods or tapes from which long fiber pellets are cut (Vaidya and Chawla 2008). In this process, continuous fiber tows pass through a bath of molten matrix and the impregnated tows pass through a die for shaping into a rod or ribbon, followed by passage through a chiller to cool. The last stage involves a puller/chopper; the puller pulls the tow at the desired speed while the chopper cuts the continuous, impregnated tow to desired length of pellets suitable for use in an extruder and compression molding. The long fiber pellets are suitable for the conventional injection molding process, injection compression molding as well as the extrusion compression molding process. The LFT pellets made by hot melt impregnation are fed into a plasticator where they are metered in a barrel, heated above the melting point of the thermoplastic resin, and the mixture of polymer plus fiber flows through a low shear plasticator to form a molten charge. The molten charge (it looks like cotton candy) coming out of the plasticator is quickly transferred to a heated mold where it is compressed in a closed tool (generally, a high tonnage press). The part is then removed after sufficient cooling.
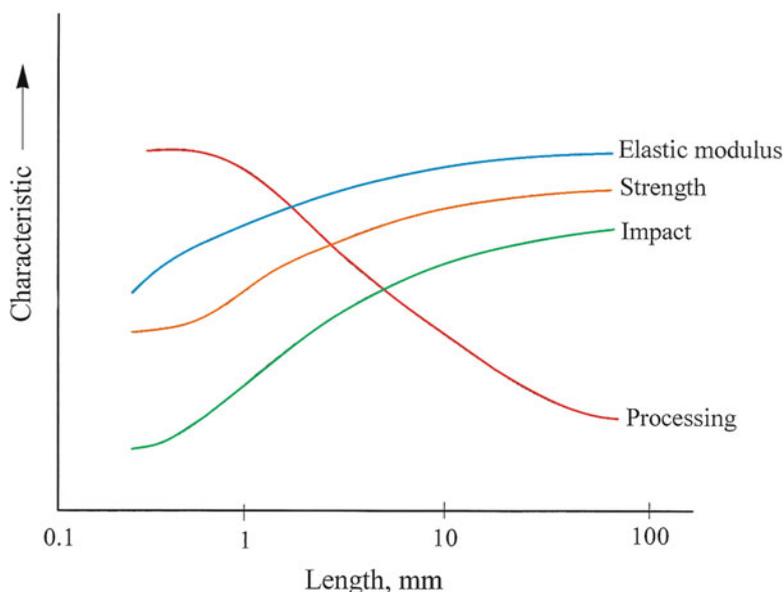

Fig. 5.8 Variation of some mechanical properties of a composite as a function of fiber length
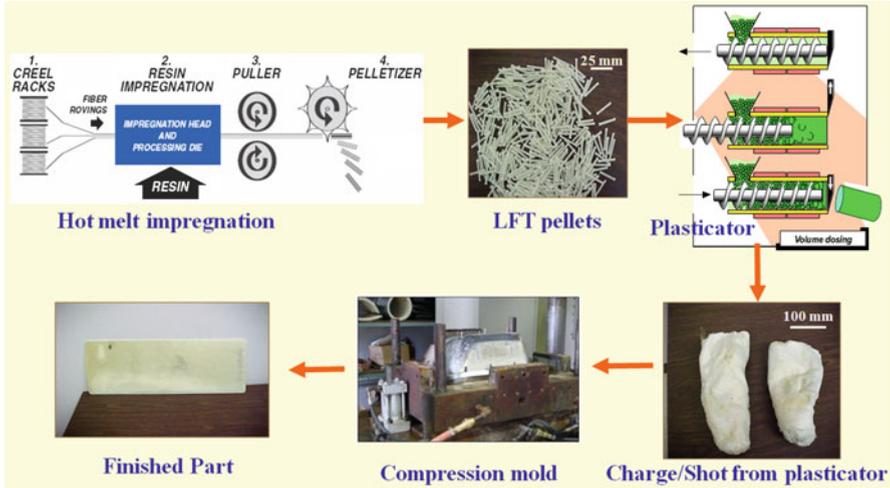
Fig. 5.9 Extrusion/compression molding process for making long fiber reinforced thermoplastic (LFT) composites. Hot melt impregnation of fibers is used to produce tapes, rods or long pellets of LFT. Pelletized LFT material is fed into an extruder or plasticator. Plasticized LFT charge is compression molded to different product forms

Another commercial process called, LFT-D-ILC, has been used to make LFT composites consisting of styrene copolymers/glass fibers. Polypropylene has also been used as a thermoplastic matrix in this process. Essentially, it is an extrusion/compression molding process. The distinctive feature of the LFT-D-ILC process is that the long fiber composite is produced directly from the basic materials. The polymer matrix material and any modifiers/additives are mixed and melted in a compounding extruder. This mixture is mixed with the reinforcing fibers in a twin screw extruder (Krause et al. 2003). The special screw-design disperses the fibers in the matrix and further fiber breakage is avoided. The extruder machines work continuously and produce a continuous long fiber reinforced extrudate, which is cut into pieces with the desired length and is then directly compression molded.

5.1.3   Sheet Molding Compound

There are some common PMCs that do not contain long, continuous fibers; hence, we describe them separately in this section. *Sheet molding compound* (SMC) is the name given to a composite that consists of a polyester resin containing short glass fibers plus some additives called fillers. The additives generally consist of fine calcium carbonate particles and mica flakes. Sometimes calcium carbonate powder is substituted by hollow glass microspheres, which results in a lower density, but makes it more expensive. Figure 5.10 shows a schematic of the SMC processing. Polyester resin can be replaced by vinyl ester to further reduce the weight, but again

with a cost penalty. SMC is used in making some auto body parts, such as bumper beams, radiator support panels, and many others. It has been used in the Corvette sports car for many decades. Polypropylene resin can be reinforced with calcium carbonate particles, mica flakes, or glass fibers. Such composites, though structurally not as important as, say, carbon fiber/epoxy composites, do show improved mechanical properties vis à vis unreinforced resin. Characteristics such as strength, stiffness, and service temperature are improved. These materials are used in automotive parts, appliances, electrical components, and so forth.
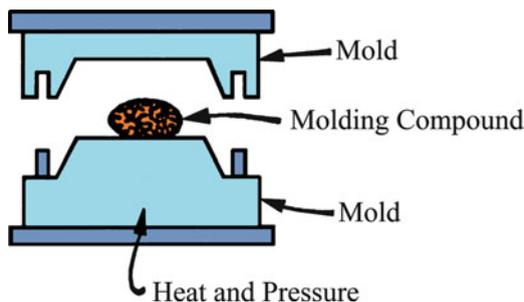

Fig. 5.10 Schematic of SMC processing

## *5.1.4   Carbon Fiber Reinforced Polymer Composites*

Carbon fiber reinforced polymer matrix composites can be said to have had their beginning in the 1950s and to have attained the status of a mature structural material in the 1980s. Not unexpectedly, earlier applications in the defense-related aerospace industry were the main driving force for the carbon fiber reinforced polymer matrix composites, followed by the sporting goods industry. The availability of a large variety of carbon fibers (Chap. 2), coupled with a steady decline in their prices over the years, and an equally large variety of polymer matrix materials (Chap. 3) made it easier for carbon fiber polymer composites to assume the important position that they have: applications in civilian aircraft, automotive, and civil infrastructure.. Epoxy is the most commonly used polymer matrix with carbon fibers. Polyester, vinyl ester, polysulfone, polyimide, and thermoplastic resins are also used. Carbon fibers are the major load-bearing components in most such composites. There is, however, a class of carbon fiber composites wherein the excellent thermal and, to some extent, electrical conductivity characteristics of carbon fibers are exploited; for example, in situations where static electric charge accumulation occurs, parts made of thermoplastics containing short carbon fibers are frequently used. Carbon fibers coated with a metal, e.g., nickel, are used for shielding against electromagnetic interference. Mesophase pitch-based carbon fibers show excellent thermal conductivity and thus find applications in thermal management systems.

5.2   Interface in PMCs

We provide below a summary of some important features of the interface region in PMCs with glass, carbon, aramid, and polyethylene fibers.

5.2.1   *Glass Fiber/Polymer*

The reader would recall from the description given in Chaps. 2 and 3 that inorganic, silica-based glasses are analogous to many organic polymers in that they are amorphous. Recall also that pure, crystalline silica melts at 1,800 °C and can be worked in the range of 1,600–1,800 °C. However, by adding some metal oxides, one can break the Si–O bonds and obtain a series of amorphous glasses with low glass transition temperatures so that they can be processed at much lower temperatures than pure silica. In general, the atomic or molecular arrangement in any material is different at the surface than in the interior. In particular, in the case of silica-based glasses containing a variety of oxides, a complex hydroxyl layer is formed rather easily. Nonhygroscopic oxides absorb water as hydroxyl groups while hygroscopic oxides become hydrated. The activity of a glass surface is thus a function of the hydroxyl content and the cations just below the surface. That is, the surface activity of E-glass will be different from that of fused silica. Invariably, glass fibers are surface treated by applying a *size* on the freshly drawn glass fibers to protect them from the environment, for handling ease, and to avoid introducing surface defects. Common sizes are starch gum, hydrogenated vegetable oil, gelatin, polyvinyl alcohol (PVA), and a variety of nonionic emulsifiers. The size is generally incompatible with the matrix resin and is therefore removed before putting the glass fibers in a resin matrix by heat cleaning at ~350 °C for 15–20 h in air, followed by washing with detergent or solvent and drying. After cleaning, organometallic or organosilane coupling agents are applied; an aqueous solution of silane is commonly used for this purpose. The organosilane compounds have the chemical formula

$$R - Si - X_3,$$
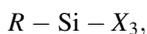
where R is a resin-compatible group and X represents groups capable of interacting with hydroxylated silanols on the glass surface. Typically, a silane coupling agent will have the following general chemical structure:

$$X_3Si(CH_2)_nY,$$

where n can have a value between 0 and 3, X is a hydrolyzable group on silicon, and Y is an organofunctional group that is resin-compatible. Silane coupling agents are generally applied to glass from an aqueous solution. Hydrolyzable groups are

essential for generating intermediate silanols. Examples of coupling agents commonly used are organometallic or organosilane complexes. It is thought by some researchers (Knox 1982) that the coupling agents create a chemical bridge between the glass surface and the resin matrix. Other researchers (Kardos 1985) do not subscribe to this view.

The *chemical bridge theory* goes as follows. Silane molecules, as mentioned earlier, are multifunctional groups with a general chemical formula of $R–SiX_3$, where X stands for hydrolyzable groups bonded to Si. For example, X can be an ethoxy group—OC_2H_5—and R is a resin-compatible group. They are hydrolyzed in aqueous size solutions to give trihydroxy silanols (Fig. 5.11a). These trihydroxy silanols get attached to hydroxyl groups at the glass surface by means of hydrogen bonding (Fig. 5.11b). During the drying of sized glass fibers, water is removed and a condensation reaction occurs between silanol and the glass surface and between adjacent silanol molecules on the glass surface, leading to a polysiloxane layer bonded to the glass surface (Fig. 5.11c). Now we can see that the silane coating is anchored at one end, through the R group, to the uncured epoxy or polyester matrix, and at the other end to the glass fiber through the hydrolyzed silanol groups. On curing, the functional groups R either react with the resin or join the resin molecular network (Fig. 5.11d).

Appealing though this chemical bridge model of silane coupling is, there are certain shortcomings. The interface model shown in Fig. 5.11d will result in such a
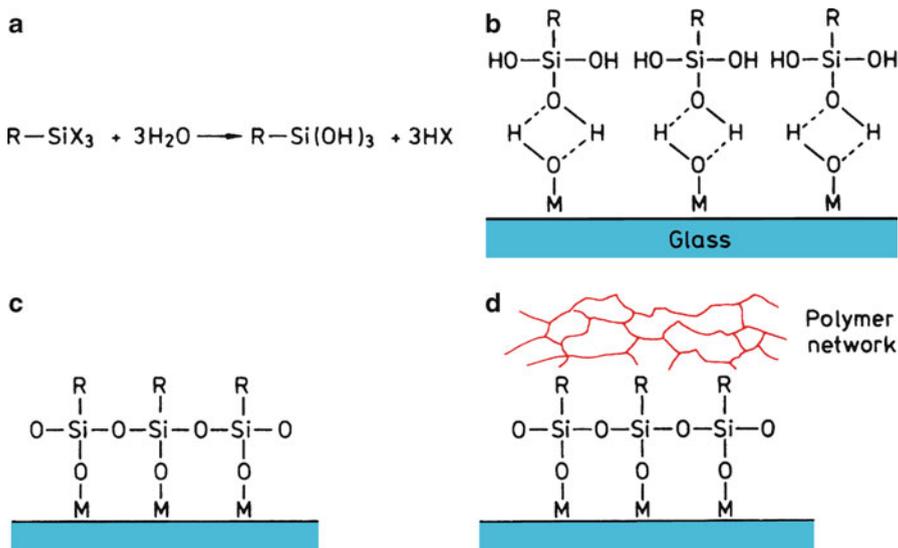

Fig. 5.11 Chemical bridge theory of a silane coupling agent: (**a**) hydrolysis of silane to silanol; (**b**) hydrogen bonding between hydroxy groups of silanol and a glass surface; (**c**) polysiloxane bonded to a glass surface; and (**d**) resin-compatible functional groups R form part of the polymer matrix [from Hull (1981), reprinted with permission]

strong bond that it will fail because of the strains encountered during the curing of the resin and resulting from differential thermal contraction (see below). Also, under conditions of industrial application of silanes from aqueous solution, a covalent reaction to the glass fiber surface does not occur unless a primary or secondary amine is present (Kardos 1985; Kaas and Kardos 1971).

5.2.1.1 Reversible Bond Model

During the processing of PMCs, most polymeric matrix materials will shrink on curing, while the reinforcement fiber remains unaffected. This can lead to large stresses at the fiber/polymer interface. Stresses can also result on cooling due to differences in coefficients of thermal expansion of glass (about $5 \times 10^{-6} \, \text{K}^{-1}$) and rigid polymer ($\sim 50–100 \times 10^{-6} \, \text{K}^{-1}$). The chemical bridge model provides a rigid bond at the glass/polymer interface that will not be able to withstand the strains involved because of the curing and shrinkage. A clean glass surface under ordinary atmospheric conditions can readily pick up a molecular layer of water. Water can reach the glass/polymer interface by diffusion through the polymer, by penetrating through cracks or by capillary migration along the fibers. Note that hydrophobic mineral fibers such as carbon or silicon carbide are less sensitive to water than glass fiber because there is little tendency for water molecules to cluster at the interface. Thus, the silane coupling agents at the glass/resin interface also have the important function of allowing the composite to accommodate internal stresses.

Plueddemann (1974) pointed out that a silane coupling agent provides a reversible hydrolytic bond between a polymer matrix and an inorganic fiber. Hydrated silanol bonds to the oxides on the glass surface, (i.e., –MOH, where M stands for Si, Al, Fe, and so on), with the elimination of water. The dynamic equilibrium mechanism of bonding requires water at a hydrophilic interface to allow relaxation of thermal stresses generated during cooling. Plueddemann's model is shown in Fig. 5.12. In the presence of water at the interface (it can diffuse in from the resin), the covalent M–O bond hydrolyzes as shown in Fig. 5.12a. If a shear parallel to the interface occurs, the polymer and glass fiber can glide past each other without a permanent bond rupture (Fig. 5.12b). Ishida and Koenig (1978) used infrared spectroscopy to obtain experimental evidence for this reversible bond mechanism. The interface is not a static sandwich of polymer–water–glass. Instead, a dynamic equilibrium prevails that involves making and breaking of bonds, which allows relaxation of internal stresses at a molecular scale. Water is therefore necessary to bond rigid polymers to inorganic surfaces such as glass.
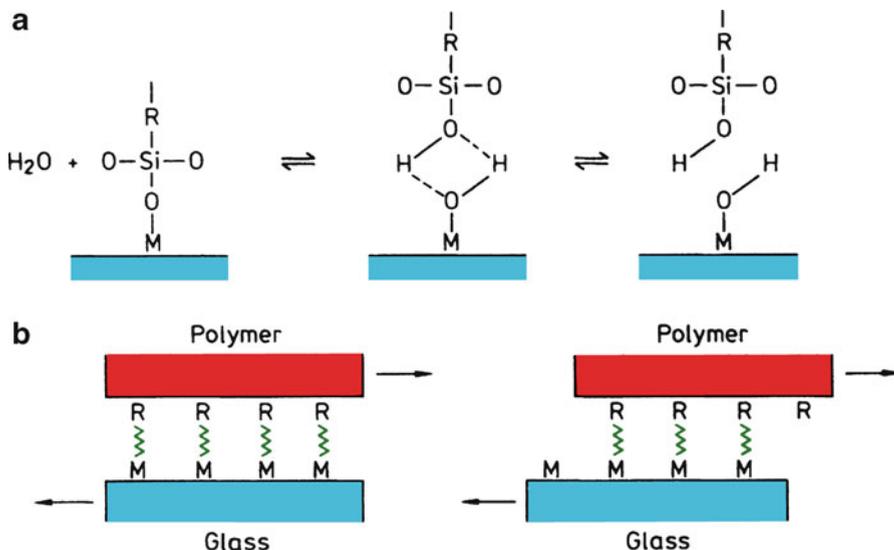
Fig. 5.12 (**a**) Plueddemann's reversible bond associated with hydrolysis. (**b**) Shear displacement at a glass/polymer interface without permanent bond rupture [from Hull (1981), reprinted with permission]

5.2.2 Carbon Fiber/Polymer Interface

As in any other composite, the carbon fiber/polymer matrix interface is very important in determining the final properties of the composite. Carbon fiber is a highly inert material. This makes it difficult to have a strong adhesion between carbon fiber and a polymer matrix. One solution is to make the fiber surface rough by oxidation or etching in an acid. This results in an increased specific surface area and improved wetting, which in turn results in improved interlaminar shear strength because of the mechanical keying effect at the fiber/matrix interface. Recall that the carbon fiber microstructure is inhomogeneous through its cross section. Specifically, in the surface layer, the basal planes are better aligned parallel to the surface. This graphitic layer is very smooth and weak in shear and hard to bind with a matrix. That is the reason that a surface treatment is given to carbon fibers. A variety of surface treatments can be used to accomplish the following:

(a) Increase the surface roughness
(b) Increase the surface reactivity

The interface region between a carbon fiber and the polymer matrix is quite complex. It is therefore not surprising that a unified view of the interface in such composites does not exist. As pointed out in Chap. 2, the carbon fiber structure, at

submicrometer level, is not homogeneous through its cross section. The orientation of the basal planes depends on the precursor fiber and processing conditions. In particular, the so-called onion-skin structure is frequently observed in PAN-based fibers, wherein basal planes in a thin surface layer are aligned parallel to the surface while the basal planes in the core are less well-aligned. Figure 5.13 shows the structure of a carbon fiber/epoxy composite (Diefendorf 1985). The onion-skin zone (C in Fig. 5.13) has a very graphitic structure and is quite weak in shear. Thus, failure is likely to occur in this thin zone. Additionally, the skin can be hard to bind with a polymeric matrix because of the high degree of preferred orientation of the basal planes, thus, facilitating interfacial failure (zone D). The matrix properties in zone E (close to the interface) may be different from those of the bulk epoxy (zone B). Carbon fibers meant for polymer reinforcement invariably receive some form of surface treatment from the manufacturer to improve their compatibility with the polymer matrix and their handleability. Organic *sizes* are commonly applied by passing the fibers through a sizing bath. Common sizes include polyvinyl alcohol, epoxy, polyimide, and titanate coupling agents.

Carbon fibers, especially high-modulus carbon fibers that have undergone a high-temperature graphitization, are quite smooth. They have a rather low specific area, varying from 0.1 to 2 m^2/g. Invariably, there is a microscopic scale of roughness; mostly as longitudinal striations (see Fig. 2.20). Carbon fibers are also generally chemically inert; that is, interfacial interactions in carbon fiber-based composites would be rather weak. Generally, a short beam bending test is conducted to measure what is called *interlaminar shear strength,* ILSS (see Chap. 4). Admittedly, such a test is not entirely satisfactory, but for lack of any better, quicker, or more convenient test, the ILSS test value is taken as a measure of bond strength.
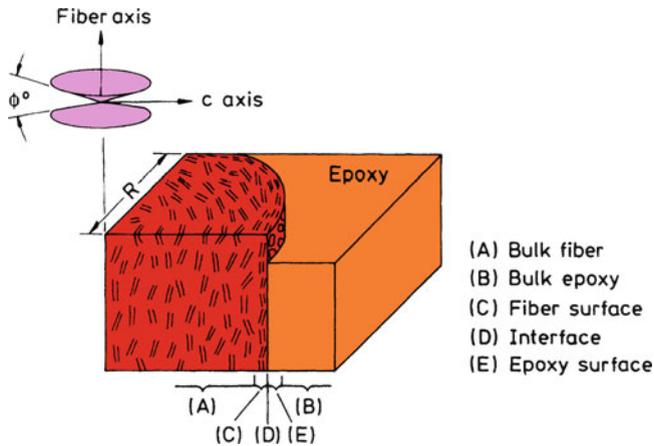

Fig. 5.13 Schematic structure of a carbon fiber/epoxy composite showing carbon fiber, interface, and epoxy matrix [from Diefendorf (1985), used with permission]

Ehrburger and Donnet (1980) point out that there are two principal ways of improving interfacial bonding in carbon fiber composites: increase the fiber surface roughness, and thus the interfacial area, and increase the surface reactivity. Many surface treatments have been developed to obtain improved interfacial bonding between carbon fibers and the polymer matrix (Donnet and Bansal 1984; McKee and Mimeault 1973). A brief description of these follows.

5.2.2.1   Chemical Vapor Deposition

Silicon carbide and pyrocarbon have been deposited on carbon fibers by chemical vapor deposition (CVD). Growing whiskers (~2 μm in diameter) on the carbon fiber surface, called *whiskerization* in the literature, can result in a two- to threefold increase of ILSS. The improvement in ILSS is mainly due to the increase in surface area. Whiskerization involving the growth of single-crystal SiC whiskers perpendicular to the fiber results in an efficient mechanical keying effect with the polymer matrix. The CVD method of doing this is expensive, and handling of whiskerized fibers is difficult. Although this treatment results in an increase in ILSS, there also occurs a weakening of the fibers. Ehlert et al. (2010) have developed a solution-based technique of growing ZnO nanorods perpendicular to the carbon fiber which seems to be quite promising inasmuch as it is claimed not to result in a decrease in strength while improving the interfacial strength by mechanical interlocking.

5.2.2.2   Oxidative Etching

Treating carbon fibers with several surface-oxidation agents leads to significant increases in the ILSS of composites. This is because the oxidation treatment increases the fiber surface area and the number of surface groups (Ehrburger and Donnet 1980). Figure 5.14 shows a linear relationship between the fiber surface roughness as measured by AFM and interlaminar shear strength in a series of carbon fiber/epoxy composites (Jangehud et al. 1993). Yet another reason for increased ILSS may be the removal of surface defects, such as pores, weakly bonded carbon debris, and impurities (Donnet and Bansal 1984). Oxidation treatments can be carried out by a gaseous or a liquid phase. Gas phase oxidation can be done with air or oxygen diluted with an inert gas (Clark et al. 1974). Gas flow rates and the temperature are the important parameters in this process. Oxidation results in an increase in the fiber surface roughness by pitting and increased longitudinal striations (Donnet and Bansal 1984). Too high an oxidation rate will result in nonuniform etching of the carbon fibers and a loss of fiber tensile strength. Since oxidation results in a weight loss, we can conveniently take the amount of weight loss as an indication of the degree of oxidation. Figure 5.15 shows ILSS vs. weight loss for high-strength and high-modulus carbon fiber

composites (Clark et al. 1974). Weight loss being a measure of the oxidation of carbon fiber, the maximum ILSS in Fig. 5.15 corresponds to less than a 10 % weight loss in both cases. Overoxidation results in a loss of fiber strength and lower ILSS.

Fig. 5.14 Linear relationship between the carbon fiber surface roughness as measured by AFM and interlaminar shear strength in a series of carbon fiber/ epoxy composites [Jangehud et al. (1993)]
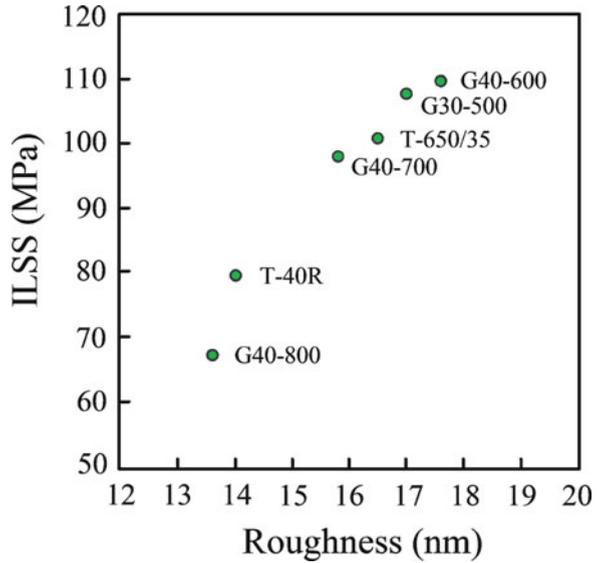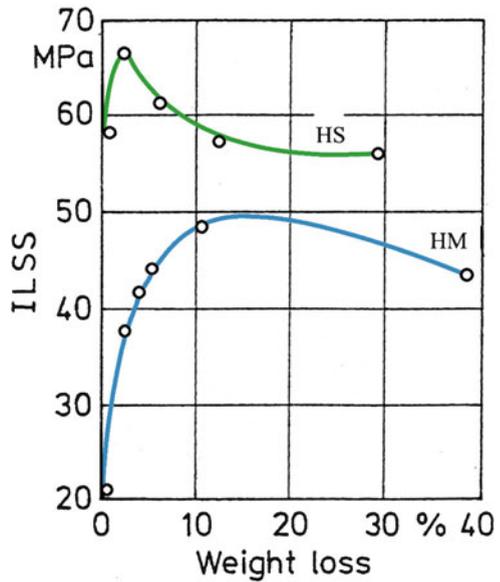

Fig. 5.15 Interlaminar shear strength (ILSS) as a function of weight loss on oxidation. A high-weight loss corresponds to a high degree of oxidation. Note that the maximum ILSS corresponds to less than 10 % weight loss in both cases. [from Clark et al. (1974), used with permission]

5.2.2.3   Liquid Phase Oxidation

Liquid phase oxidation involves treatments in nitric acid, sodium hypochlorite, potassium permanganate, and anodic etching (Donnet and Bansal 1984). Liquid phase oxidation by nitric acid and sodium hypochlorite results in an increase in the interfacial area and formation of oxygenated surface groups due to fiber etching. Wetting of the carbon fibers by the polymer is enhanced by these changes.

Graphitic oxides are lamellar compounds having large amounts of hydroxylic and carboxylic groups. The formation of a graphitic oxide layer increases the number of acidic groups on the carbon fibers.

Anodic etching or electrochemical oxidation using dilute nitric acid or dilute sodium hydroxide solutions results in no significant decrease in tensile strength of the carbon fibers, according to Ehrburger and Donnet (1980). The fiber weight loss is less than 2 % and no great change in surface area or fiber roughness occurs, the major change being an increase in the acidic surface groups. Oxidative treatments produce functional groups (e.g., $-CO_2H$, $-C-OH$, and $-C=O$) on carbon fiber surfaces. They form at the edges of basal planes and at defects. These functional groups form chemical bonds with unsaturated resins.

According to Drzal et al. (1983a, b) various carbon fiber surface treatments promote adhesion to epoxy materials through a two-pronged mechanism: (a) the surface treatment removes a weak outer layer that is present initially on the fiber and (b) chemical groups are added to the surface which increase interaction with the matrix. When a fiber finish is applied, according to Drzal and coworkers, the effect is to produce a brittle but high modulus interphase layer between the fiber and the matrix. As amine content is reduced, the modulus of epoxy goes up accompanied by lower fracture strength and strain. That is, the interphase being created between the fiber and the matrix has high modulus but low toughness. This promotes matrix fracture as opposed to interfacial fracture.

5.2.2.4   Aramid Fiber/Polymer Interface

Most polymers show rather poor adhesion to aramid fibers. This is evidenced by the generally poor interlaminar shear strength and transverse tensile strength values obtained with aramid reinforced PMCs. Typically, aramid/epoxy interfacial strengths are about half of the interfacial strengths of glass/epoxy or carbon/epoxy composites. A highly oriented chain microstructure and skin/core heterogeneity are responsible for this low, poor interfacial strength. This may not be a disadvantage in aramid/polymer composites used to make impact-resistant items such as helmets or body armor, where ease of delamination may be an advantage from a toughness point of view. However, in high-strength and high-stiffness composites, poor interfacial adhesion can be a disadvantage. Various fiber surface treatments have been tried to alleviate this problem. Among these are the following:

- Bromine water treatment. This also results in reduced fiber strength.

- Silane coupling agents developed for glass fibers.
- Isocyanate-linked polymer.
- Treatment with reactive chemicals such as acetic acid anhydride, methacrylol chloride, sulfuric acid, among others. Such treatments, however, result in a decrease in the tensile strength of aramid fiber and that of aramid/polyester composites attributable to etching of the aramid fiber.
- Acid (HCl, H_2SO_4) or base (NaOH) hydrolysis of aramid fiber yields reactive terminal amino groups to which diepoxide molecules could attach.
- Plasma treatment in vacuum, ammonia, or argon. Plasma treatment in ammonia increases the amine concentration on the fiber surface, which is thought to lead to covalent bonding at the interface. An increase in nitrogen content in the form of amine groups is accompanied by a decrease in oxygen content with increasing exposure time.

5.2.3   Polyethylene Fiber/Polymer Interface

Ultrahigh-molecular-weight polyethylene (UHMWPE) fiber is another chemically very inert fiber, and therefore it does not adhere very well to polymeric matrix materials. High-modulus polyethylene fibers such as Spectra or Dyneema are hard to bond with any polymeric matrix. Some kind of surface treatment must be given to the polyethylene fiber to bond with resins such as epoxy, PMMA. By far the most successful surface treatment involves a cold gas (such as air, ammonia, or argon) plasma (Kaplan et al. 1988). A plasma consists of gas molecules in an excited state, i.e., highly reactive, dissociated molecules. When the polyethylene, or any other fiber, is treated with a plasma, surface modification occurs by removal of any surface contaminants and highly oriented surface layers, addition of polar and functional groups on the surface, and introduction of surface roughness, all these factors contribute to an enhanced fiber/matrix interfacial strength (Biro et al. 1992; Brown et al. 1992; Hild and Schwartz 1992a, b; Kaplan et al. 1988; Li et al. 1992). An exposure of just a few minutes to the plasma is sufficient to do the job.

In a UHMWPE fiber/epoxy composite, a plasma treatment of fiber resulted in an increase in fiber surface roughness and an increased bonding area and interfacial shear strength (Kaplan et al. 1988; Biro et al. 1992). In another work (Brown et al. 1992), it was shown that chemical etching of UHMWPE fibers resulted in more than a sixfold increase in interfacial shear strength of UHMWPE/epoxy composites.

Chemical treatment with chromic acid and plasma etching in the presence of oxygen are two treatments that are commonly used to modify the surface characteristics of polyethylene fiber with a view to improve their adhesion to polymeric matrix materials.

5.3   Structure and Properties of PMCs

Continuous fiber reinforced polymer composites show anisotropic properties. The properties of a composite will depend on the matrix type, fiber type, interface, amount or volume fraction of fiber (or that of the matrix), fabrication process, and, of course, the fiber orientation.

5.3.1   Structural Defects in PMCs

The final stage in any PMC fabrication is called *debulking*, which serves to reduce the number of voids, one of the common defects in PMCs. Nevertheless, there are other common structural defects in PMCs. Following is a list of these:

- Resin-rich (fiber-poor) regions.
- Voids (e.g., at roving crossovers in filament winding and between layers having different fiber orientations, in general). This is a very serious problem; a low void content is necessary for improved interlaminar shear strength. Hence, the importance of the debulking step.
- Microcracks (these may form due to curing stresses or moisture absorption during processing).
- Debonded and delaminated regions.
- Variations in fiber alignment.

5.3.2   Mechanical Properties

Some microstructures of polymer matrices reinforced by continuous and discontinuous fibers are shown in Fig. 5.16. A transverse section of continuous glass fiber in an unsaturated polyester matrix is shown in Fig. 5.16a. The layer structure in the cross section of an injection-molded composite consisting of short glass fibers in a semi-crystalline polyethylene terephthalate (PET) is shown in Fig. 5.16b (Friedrich 1985). Essentially, it is a three-layer structure showing different orientations of the short fibers. More fibers are parallel to the mold fill direction (MFD) in the two surface layers (marked *S*), than in the transverse direction in the central layer (marked *C*). Note the heterogeneity in the microstructure, which results in a characteristically anisotropic behavior.

Laminates of polymer matrix composites made by the stacking of appropriately oriented plies also result in composites with highly anisotropic characteristics. In particular, the properties of continuous fiber reinforced polymers are quite a bit higher in the longitudinal direction than in other directions. It turns out that one generally finds the longitudinal properties of composites being quoted in the literature for comparative purposes. The reader is warned that one must bear in

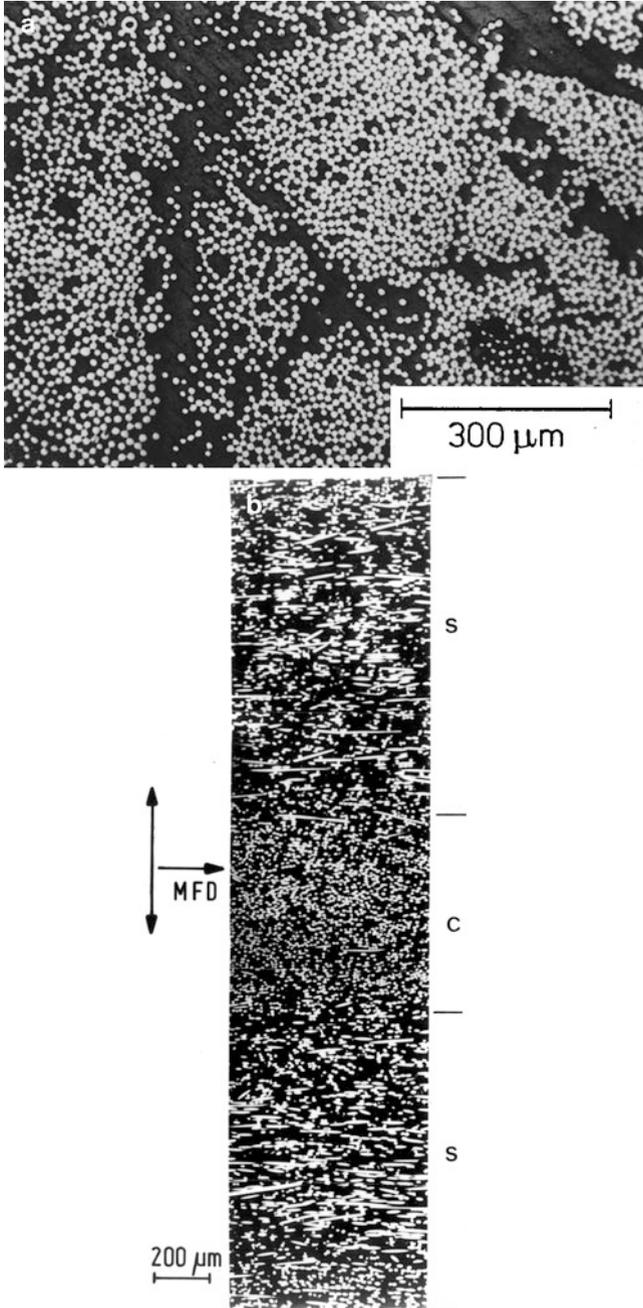**Fig. 5.16** (**a**) Continuous glass fibers in a polyester matrix showing resin-rich regions. (**b**) Discontinuous glass fibers in a semicrystalline polyethylene terephthalate thermoplastic matrix showing anisotropic distribution of fibers. MFD denotes the mold fill direction. S and C denote the surface and central layers, respectively [from Friedrich (1985), used with permission]

mind this discrepancy when comparing such data of highly anisotropic materials with the data of isotropic materials such as common polycrystalline materials. Besides, composites containing aramid and polyethylene fibers will not have such attractive properties in compression in the longitudinal direction. A summary of some important characteristics of PMCs is presented in Tables 5.1 and 5.2.

Most thermoset matrix composites show essentially elastic behavior right up to fracture, i.e., there is no yield point or plasticity. The strain-to-failure values are rather low, typically, less than 0.5 %. Consequently, the work done during fracture is also small. This has some very practical implications for the design engineer, viz., he or she cannot bank on any local yielding in such composites to take care of stress concentrations.

In general, the continuous fiber reinforced composites will be stiff and strong along the fiber axis, but off-angle these properties fall rather sharply. Typically, in a unidirectional PMC, the fiber volume fraction can be 65 %. In composites having fibers aligned bidirectionally, this value can fall to 50 %, while in a composite containing in-plane random distribution of fibers, the volume fraction will rarely be more than 30 %. As a general rule-of-thumb, we can take the Young's modulus of the composite in the longitudinal direction to be given by the following rule-of-mixtures relationship

$$E_{cl} = E_f V_f + E_m V_m,$$

where E and V denote the Young's modulus and the volume fraction of a component and the subscripts c, f, m, and l indicate composite, fiber, matrix, and the longitudinal direction, respectively. From the data provided in Chap. 2 on the mechanical properties of fibers, the reader can easily verify that glass fiber/polymer will only give a modest increase in modulus. However, aramid, polyethylene, and carbon fiber reinforced polymer composites will show a significant increase in modulus. Aramid fiber/polymer composites are likely to show higher creep rate than glass/polymer composites. Aramid fiber has superior impact characteristics, therefore, aramid fiber-based polymer composites will show good ballistic resistance, and impact resistance in general. Similar observations can be made regarding strength characteristics of the other polymer matrix composites. As should be clear to the reader, these properties are highly dependent on the fiber properties.

5.3.2.1   Damping Characteristics

Damping in material has to do with dissipation of vibrations. High damping or the ability to reduce vibrations can be very important in many applications; for example, in mechanical equipment that is subject to variable speeds, resonance problems lead to unacceptable levels of noise. Also, in sporting goods such as tennis rackets, fishing rods, and golf clubs, it is desirable to have high damping. In a composite, damping will depend on relative proportion of fiber and matrix, orientation of

Table 5.1 Representative properties of some PMCs[a]

| Materials | Density (g/cm^3) | Tensile modulus | | Shear modulus (GPa) | Tensile strength | | Compressive strength longitudinal (MPa) | Flexural modulus (GPa) | Flexural strength (MPa) | ILSS[b] (MPa) | Longitudinal coefficient of thermal expansion (10^{-6} K^{-1}) |
		Longitudinal (GPa)	Transverse (GPa)		Longitudinal (MPa)	Transverse (MPa)					
Unidirectional E glass 60 v/o	2	40	10	4.5	780	28	480	35	840	40	4.5
Bidirectional E glass cloth 35 v/o	1.7	16.5	16.5	3	280	280	100	15	220	60	11
Chopped strand mat E glass 20 v/o	1.4	7	7	2.8	100	100	120	7	140	69	30
Boron 60 v/o	2.1	215	24.2	6.9	1,400	63	1,760	–	–	84	4.5
Kevlar 29 60 v/o	1.38	50	5	3	1,350	–	238	51.7	535	44	–
Kevlar 49 60 v/o	1.38	76	5.6	2.8	1,380	30	276	70	621	60	−2.3

[a]The values are only indicative and are based on epoxy matrix at room temperatures
[b]ILSS is interlaminar shear strength
Source: Adapted with permission from Hancox (1983)

Table 5.2 Typical mechanical properties of some carbon fiber/epoxy composites[a]

Property	AS	HMS	Celion 6000	GY 70
Tensile strength (MPa)	1,850	1,150	1,650	780
Tensile modulus (GPa)	145	210	150	290–325
Tensile strain-to-fracture (%)	1.2	0.5	1.1	0.2
Compressive strength (MPa)	1,800	380	1,470	620–700
Compressive modulus (GPa)	140	110	140	310
Compressive strain-to-fracture (%)	–	0.4	1.7	–
Flexural strength (4-point) (MPa)	1,800	950	1,750	790
Flexural modulus (GPa)	120	170	135	255
Interlaminar shear strength (MPa)	125	55	125	60

[a]Values given are indicative only and are for a unidirectional composite (62 % V_f) in the longitudinal direction

Source: Adapted with permission from Riggs et al. (1982)

reinforcement with respect to the axis of loading, viscoelastic characteristics of the matrix and the reinforcement, any slipping at the interface between the matrix and the reinforcement, and last but not least, any source of damage such as cracks or environmental attack. In general, aramid fiber/polymer composites provide good damping characteristics. This, of course, stems from the superior damping of aramid fiber (see Chap. 2).

5.3.2.2 Moisture Effects in Polymer Matrix Composites

Environmental moisture can penetrate organic materials by diffusion. Typically, moisture works as a plasticizer for a polymer, i.e., properties such as stiffness, strength, and glass transition temperature decrease with the ingress of moisture in a polymer. It is now well recognized that the problem of moisture absorption in polymer matrix composites is a very important one. The maximum moisture content under saturated condition, M_m as a function of relative humidity, is given by the following relationship:

$$M_m = A(\% \text{ relative humidity})^B,$$

where A and B are constants. The moisture content in a composite, M, can be written as

$$M = M_i + G(M_m - M_i),$$

where M_i is the initial moisture content (= 0 for a completely dry material) and G is a dimensionless, time-dependent parameter related to the diffusion coefficient. Generally, one assumes that Fickian diffusion prevails, i.e., Fick's law of diffusion is applicable. Under conditions of Fickian diffusion, water diffuses into the

laminate from the two surfaces that are in equilibrium with their surroundings, and the parameter G is given by (Chen and Springer 1976)

$$G \approx 1 - \left(8/\pi^2\right) \exp\left(-\pi^2 Dt/S^2\right),$$

where D is the diffusion coefficient (m^2/s) in the direction normal to the laminate surface; $t =$ time (s); $S = h$ (the laminate thickness), if exposed on both sides, and $S = 2\ h$, if exposed on one side.

A dried specimen, usually in the form of a thin sheet, is placed in a humid environment at a constant temperature, and the mass gained is measured as a function of time. If we plot the mass gained (say, as percentage moisture absorbed) as a function of the square root of time, at a given temperature, we obtain a curve with the following characteristics. After an initial linear portion (i.e., $M \propto \sqrt{t}$), the curve assumes a plateau form in an asymptotic manner as shown in Fig. 5.17. The slope of the linear portion can be used to determine the diffusion coefficient as follows:

$$\text{Slope} = \frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} = \frac{4M_m\sqrt{D}}{h\sqrt{\pi}},$$
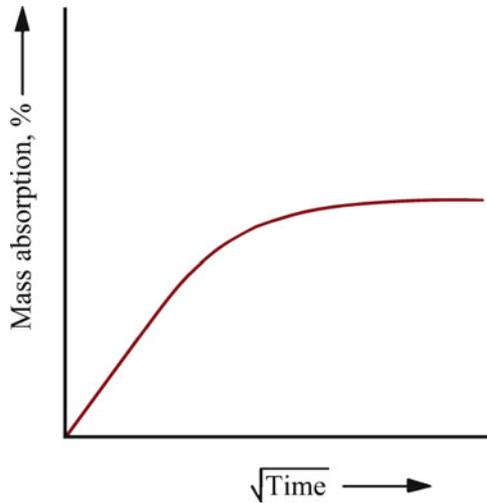

Fig. 5.17 Schematic curve of fractional moisture absorbed as a function of the square root of time, at a given temperature

where M_1 and M_2 are the moisture contents corresponding to times t_1 and t_2, respectively. Rearranging the above expression, we write for D

$$D = \left[\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right]^2 \times \pi \left[\frac{h}{4M_{\mathrm{m}}}\right]^2.$$

The epoxy resins commonly employed as matrices in the composites meant for use in the aerospace industry are fairly impervious to the range of fluids commonly encountered in service, for example, jet fuel, hydraulic fluids, and lubricants (Anderson 1984). There are, however, two fundamental effects that must be taken into account when designing components made of PMCs, namely, temperature and humidity. The combined effect of these two, that is, hygrothermal effects, can result in a considerable degradation in the mechanical characteristics of the PMCs. This is especially so in high performance composites such as carbon fiber/epoxy, which are used in the aerospace industry where dimensional tolerances are rather severe. Because aerospace structures are exposed to a range of environments and temperatures, for example, oils, fuels, moisture, acids, and hot gases, the excellent corrosion-resistance characteristics of carbon/epoxy composites are of great value under such conditions. Commonly encountered damage to polymers by ultraviolet rays is minimized by properly painting the exterior of the composite. Moisture is a major damaging agent. Epoxy matrices can absorb water to as much as 1 % of the composite weight; however, unlike glass fiber, which is attacked by moisture, the carbon fiber itself is unaffected by moisture. Thus, moisture absorbed in carbon fiber PMCs opens up the polymer structure and reduces its glass transition temperature; that is, the moisture acts as a plasticizer for the polymeric matrix. Moisture absorption in polymers occurs according to Fick's law; that is, the weight gain owing to moisture intake varies as the square root of the exposure time. This Fickian moisture absorption in a 16-ply carbon epoxy laminate is shown in Fig. 5.18a (Shirrel and Sandow 1980). An example of moisture-induced degradation in a model composite consisting of a single carbon fiber in an epoxy matrix is shown in Fig. 5.18b–d. A photoelastic technique that shows stress-induced birefringence was used to analyze the stress patterns obtained as a function of immersion time in water. Figure 5.18b shows the initial condition. After an immersion for 10.5 h, a net tensile stress birefringence was obtained (Fig. 5.18c). With continued moisture absorption, more swelling of the epoxy matrix occurred, causing an increase in the axial tensile stress in the fiber and eventually leading to fiber fracture after 151 h, as shown in Fig. 5.18d (Xu and Ashbee 1994). The moisture absorption problem in PMCs is analogous to that of degradation by temperature effects. Collings and Stone (1985) present a theoretical analysis of strains developed in longitudinal and transverse plies of a carbon/epoxy laminate owing to hygrothermal effects. An interesting finding of theirs is that tensile thermal strains that develop in the matrix after curing are reduced by compressive strains generated in the matrix by swelling resulting from water absorption. It is worth pointing out that moisture absorption causes compressive stresses in the resin and tensile stresses in the fibers
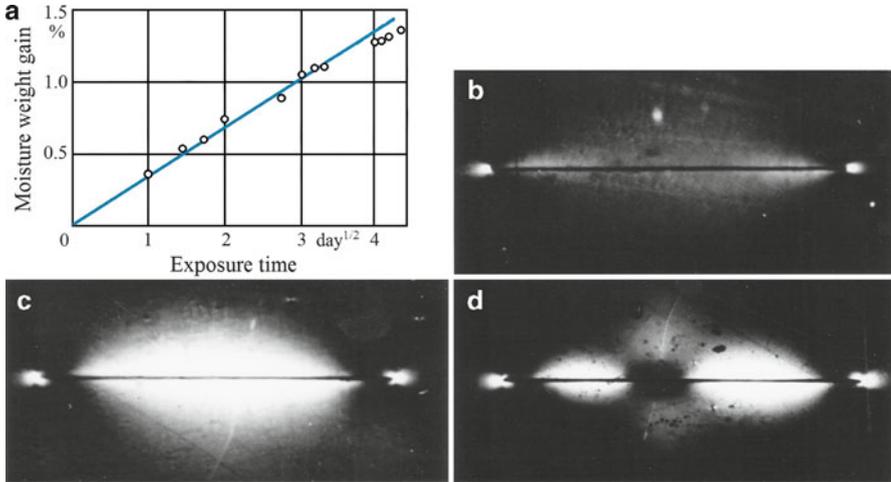
Fig. 5.18 (**a**) Fickian moisture absorption in a 16-ply carbon epoxy laminate (Shirrel and Sandow 1980). Moisture-induced degradation in a model composite consisting of a single carbon fiber in an epoxy matrix as seen by using photoelasticity to show stress-induced birefringence was used to analyze the stress patterns obtained as a function of immersion time in water. (**b**) The initial condition. (**c**) After an immersion for 10.5 h, a net tensile stress birefringence was observed. (**d**) More swelling of the epoxy matrix occurred, causing an increase in the axial tensile stress in the fiber and eventually leading to fiber fracture after 151 h (courtesy of Xu and Ashbee 1994)

(see Fig. 5.18). Also, a temperature increase ΔT generates strains of the same sign as those caused by an increase in the moisture content (Collings and Stone 1985). Thus, it is understandable that moisture absorption should reduce the residual strains after curing.

5.3.2.3 Environmental Issues Related to PMCs

There are certain environmental issues related to the use of polymer matrix composites. Common polymers are derived from petroleum (a nonrenewable resource). They are also difficult to dispose off at the end of life, especially the thermosets. In short, polymers have a reputation of being environmentally unfriendly. Consequently, there is effort to produce polymers and composites from eco-friendly sources. We discuss these biocomposites in Chap. 15.

Degradation of polymers owing to ultraviolet radiation is another important environmental effect. Ultraviolet radiation breaks the covalent bonds in organic polymers, which can degrade the mechanical behavior of PMCs (Goel et al. 2008). This kind of damage, frequently referred to as photo degradation, is actually quite a complex process. It may involve chemicrystallization, i.e., rearrangement of broken polymer chains due to photooxidation, into the crystalline phase; color change, embrittlement, formation of surface cracks, and degradation of mechanical properties. An example of such a loss of mechanical properties is shown in Fig. 5.19. This figure shows the loss of stiffness or modulus as a function of

exposure to ultraviolet radiation for glass fiber reinforced polypropylene composites. Crystallinity of PP increases with rate of oxidation (chemicrystallization). Sometimes a prolonged exposure of epoxy laminates to ultraviolet radiation results in a slight increase in strength, attributed to postcuring of the resin, followed by a gradual loss of strength as a result of laminate surface degradation (Bergmann 1984).
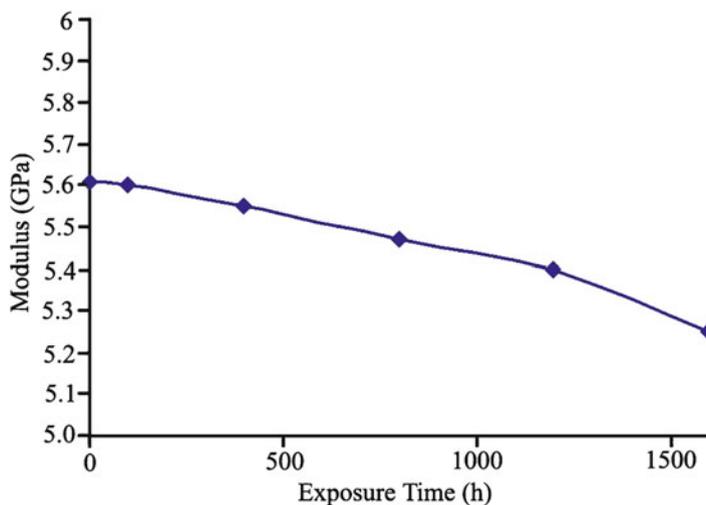

Fig. 5.19 Loss of stiffness or modulus as a function of exposure to ultraviolet radiation for glass fiber reinforced polypropylene composites [from Goel et al. 2008]

Hazardous air pollutants (HAPs) are generated during the curing of thermoset polymers. These include volatile organic compounds (VOCs) and nitrogenous oxides (commonly denoted by NO_x). Certain VOCs are thought to interact photochemically in the atmosphere and form ozone. HAPs may have long-term adverse health effects. Sources of these during processing of PMCs include solvents used to reduce viscosity, gases evolved, and disposal of scrap material. Commonly, styrene is the main culprit. The government regulatory agencies such as the US EPA have set certain regulatory limits on the emission of VOCs and HAPs.

Among the ways to reduce VOC emissions are (Sands et al. 2001): use closed processing, accelerated curing to react or trap VOCs in the curing media, and e-beam curing. Autoclave processing is thought to be a major source of such HAPs, especially NOx. Nonautoclave processing would help in this regard. Substitution of thermosets with thermoplastic is another possibility. E-beam curing of resins is done at room temperature without any solvent; the amount of VOCs is reduced.

5.3.2.4 Mechanical Behavior

Fracture in PMCs, as in other composites, is associated with the characteristics of the three entities: fibers, matrix, and interface. Specifically, fiber/matrix debonding, fiber pullout, fiber fracture, polymer crazing, and fracture of the matrix are the energy-absorbing phenomena that can contribute to the failure process of the composite. Of course, the debonding and pullout processes depend on the type of interface. At low temperatures, the fracture of a PMC involves a brittle failure of the polymeric matrix accompanied by pullout of the fibers transverse to the crack plane. Figure 5.20a shows this kind of fracture at $-80\,^\circ$C in the case of a short glass fiber/ PET composite. Note the brittle fracture in the matrix. At room temperature, the same polymeric matrix (PET) deformed locally in a plastic manner, showing crazing (Friedrich 1985). Generally, stiffness and strength of a PMC increase
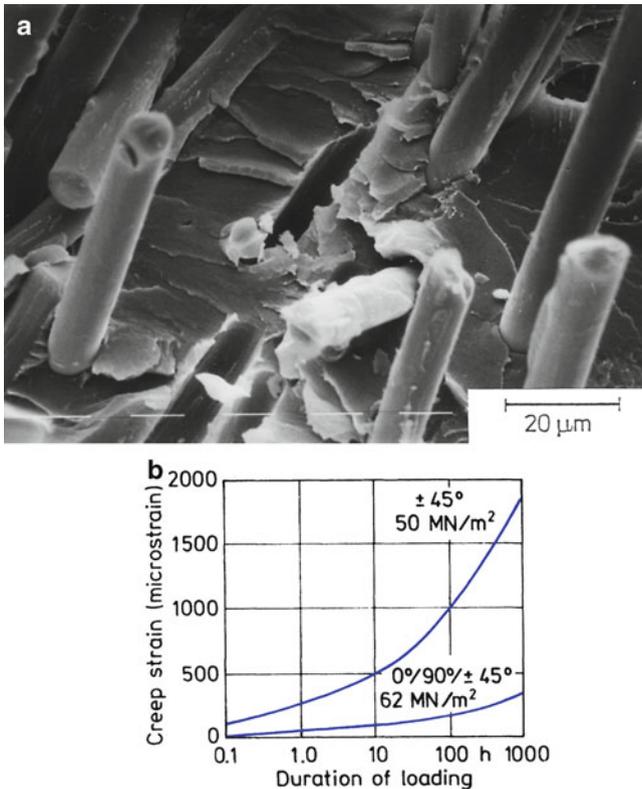

Fig. 5.20 (**a**) Brittle matrix fracture and fiber pullout in a short glass fiber reinforced polyethylene terephthalate (PET) composite fractured at $-80\,^\circ$C [from Friedrich (1985), used with permission] (**b**) Creep strains at ambient temperature for a $\pm 45^\circ$ and for a $0^\circ/90^\circ/\pm 45^\circ$ carbon/epoxy laminate [from Sturgeon (1978), used with permission]

with the amount of stiff and strong fibers introduced in a polymer matrix. The same cannot be said unequivocally for the fracture toughness. The toughness of the matrix and several microstructural factors related to the fibers and the fiber/matrix interface have a strong influence on the fracture toughness of the composite. Friedrich (1985) describes the fracture toughness of short fiber reinforced thermoplastic matrix composite in an empirical manner by a relationship of the form

$$K_{cc} = MK_{cm}$$

where K_{cm} is the fracture toughness of the matrix and M is a microstructural efficiency factor. M can be larger than 1 and depends on fiber amount, fiber orientation, and the fiber orientation distribution over the fracture plane, as well as the deformation behavior of the matrix and the relative effectiveness of all the energy-absorbing mechanisms.

Carbon fiber/epoxy composites exhibit superior properties in creep compared to aramid/epoxy. This is because aramid fibers, similar to other polymeric fibers, creep significantly even at quite low stresses (Eriksen 1976). Additionally, in a laminated composite made by stacking prepregs of different fiber orientations, the ply stacking sequence can affect the composite properties. Figure 5.20b shows tensile creep strain at ambient temperature as a function of time for two different stacking sequences (Sturgeon 1978). The laminate with carbon fibers at $\pm45°$ shows more creep strain than one containing plies at $0°/90°/\pm45°$. The reason for this is that in the $\pm45°$ sequence, the epoxy matrix undergoes creep strain by tension in the loading direction, shear in the $\pm45°$ directions, and rotation of the plies in a scissor-like action. As we shall see in Chap. 11, $0°$ and $90°$ plies do not show this scissor-like rotation, which is a characteristic of the $45°$ plies. Thus, the addition of $0°$ and $90°$ plies reduces the matrix shear deformation. Consequently, the creep resistance of $0°/90°/\pm45°$ sequence is better than that of the $\pm45°$ sequence.

Carbon fiber reinforced PMCs generally show excellent fatigue strength. Depending on the ply stacking arrangement, their fatigue strength (tension–tension) may vary from 60 to 80 % of the ultimate tensile strength for lives over 10^7 cycles (Baker 1983). The higher fatigue strength levels pertain to composites having more than 50 % of the fibers in the longitudinal direction ($0°$), which leads to high longitudinal stiffness and low strains. Pipes and Pagano (1970) showed that certain stacking sequences can result in tensile stresses at the free edges, which can lead to early local delamination effects in fatigue and consequently to lower fatigue lives. Further discussion of these topics can be found in Chaps. 11–14.

A considerable amount of work has been done to toughen the carbon fiber reinforced PMCs. This has involved modifying epoxies and using polymeric matrix materials other than epoxies. Among the latter are modified bismaleimides and some new thermoplastic materials (see also Chap. 3). The latter category includes poly (phenylene sulfide) (PPS), polysulfones (PS), and polyetherether ketone (PEEK), among others. PEEK, a semicrystalline polyether, combines excellent toughness with chemical inertness. Typically, PEEK-based carbon fiber composites

are equivalent to high-performance epoxy-based carbon fiber composites, with the big advantage that the PEEK-based composites have an order-of-magnitude higher toughness than the epoxy-based composites. PEEK matrix composites are more difficult to process and are more expensive than epoxy matrix composites.

PPS is a semicrystalline aromatic sulfide that has excellent properties. A special process has been developed to make continuous fiber prepregs with PPS for use in making composite laminates.

It should be pointed out that incorporation of fibers in a thermoplastic polymer can result in alteration of crystallization kinetics of the thermoplastic matrix (Waddon et al. 1987; Hull 1994). Figure 5.21 shows a schematic representation of two possible spherulitic morphologies resulting from constrained growth in PEEK, a thermoplastic matrix, because of the presence of carbon fibers. The nucleation density of spherulites on the fibers is the same in the two cases but the fiber volume fraction is different, i.e., the interfiber spacing is smaller for the high fiber volume fraction composite. Hence, the constraint on the growth of spherulites is greater in the high fiber volume fraction case. This is really a general issue in all kinds of composites, namely, the microstructure and properties of matrix change during processing of the composite. See Chap. 12 for a further discussion of the importance of such structure-sensitive issues in composites.
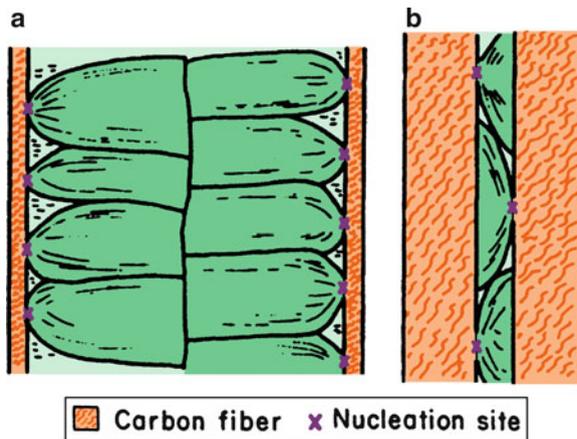

Fig. 5.21 A schematic representation of two possible spherulitic morphologies resulting from constrained growth in PEEK, a thermoplastic matrix, because of the presence of carbon fibers. (**a**) Low fiber volume fraction, (**b**) high fiber volume fraction. The nucleation density of spherulites on the fibers is the same in the two cases but the fiber volume fraction is different, i.e., the interfiber spacing is smaller for the high fiber volume fraction composite. Hence, the constraint on the growth of spherulites is greater in the high fiber volume fraction case [after Waddon et al. (1987)]

5.4   Applications

Glass fiber reinforced polymers are used in a wide variety of industries: from sporting goods to civil construction to aerospace. Tanks and vessels (pressure and nonpressure) in the chemical process industry, as well as process and effluent pipelines, are routinely made of glass fiber reinforced polyester resin. Figure 5.22 shows a wide variety of fiberglass/resin matrix structural shapes made by the pultrusion technique. S-2 glass fibers and aramid fibers are used in the storage bins and floorings of civilian aircraft. Other aircraft applications include doors, fairings, and radomes. Aramid fiber is also used in light load-bearing components in helicopters and small planes. In most applications involving glass fiber reinforced polymers, aramid fibers can be substituted for glass without much difficulty. Racing yachts and private boats are examples of aramid fiber making inroads into the glass fiber fields where performance is more important than cost. Drumsticks made with a pultruded core containing Kevlar aramid fibers and a thermoplastic injection-molded cover are shown in Fig. 5.23. These drumsticks last longer than the wooden ones, are lightweight, do not warp, and are more consistent than wooden sticks. Military applications vary from ordinary helmets to rocket engine cases. One has to guard against using aramid reinforcement in situations involving compressive, shear, or transverse tensile loading paths.

Fig. 5.22 A large variety of fiberglass/resin structural shapes made by pultrusion are available (courtesy of Morrison Molded Fiber Glass Co.)

Fig. 5.23 Drumsticks made with a pultruded Kevlar core and a thermoplastic injection-molded cover (courtesy of Morrison Molded Fiber Glass Co.)

Fig. 5.24 A filament wound pipe (diameter = 2 m) made for irrigation purposes in Ecuador. (courtesy of Odebrecht Co.)

5.4.1 Pressure Vessels

A very important application of PMCs is in the use of natural gas for transportation. Use of natural gas as a fuel results in lower emissions (NO_x, CO_2) vis à vis gasoline fuel. It may also be a cheaper fuel in certain locations. The use of compressed natural gas as a vehicle fuel requires on-board storage of gas at high pressure (~200 kPa). Steel cylinders were used as pressure vessels. These metallic gas cylinders are quite heavy and thus result in a reduced payload. Much lighter, filament-wound PMC cylinders were developed to replace the steel cylinders. Examples of these include steel or aluminum cylinders hoop-wrapped with glass fiber/polyester and hoop- and polar-wound glass or carbon fiber reinforced polymer cylinders with a thermoplastic liner. Other common applications involve pipes for transportation of water or petroleum. Figure 5.24 shows a large diameter (2 m) glass fiber reinforced filament-wound cylinder made for water transport for irrigation purposes in Ecuador.

5.4.1.1 Ballistic Protection

Woven fabrics made of fibers than can deform under impact make an essential constituent of modern ballistic protection systems. Fabrics are commonly used in layers to make what is called concealable body armor, which are used for protection against low- and medium-energy handgun rounds. Ballistic fabrics are made of aramid fiber (Kevlar or Twaron) or polyethylene (Spectra or Dyneema) by many manufacturers in a variety of styles. Typically, concealable body armor is constructed of multiple layers of ballistic fabric, assembled into the "ballistic panel." The ballistic panel is then inserted into the "carrier," which is constructed of conventional garment fabrics such as nylon or cotton. The ballistic panel may be permanently sewn into the carrier or may be removable. Ballistic fabric is available from a number of manufacturers in various styles. Body armor intended for routine use is commonly worn under the normal clothing. Although the overall finished product looks relatively simple in construction, the ballistic panel is very complex.

Kevlar 29, Kevlar 129, and a new line called Kevlar Protera are DuPont aramid fibers meant for this purpose. Spectra fiber of Honeywell is used with resin a product called Spectra Shield composite, which is used to make helmets, hard armor for vehicles, and soft body armor. The helmet manufacture involves a special version of Spectra Shield, a special shell design, and a three-way adjustable liner of shock-absorbing foam padding.

5.4.1.2   Applications of Composites in Aerospace

It can be said without any exaggeration that Boeing 787 aircraft represents a watershed event in the use of composites in the civilian aerospace industry. This aircraft has major structural components such as fuselage, wings, floor beams, etc. made of composite materials. In fact the composites represent 50% by weight. This did not happen overnight though. It should be recognized that Boeing 777 has 9% composites by weight. Most of the larger components in 787 are carbon fiber reinforced epoxy; with smaller parts made of short fibers in a variety matrix materials, including thermoplastic matrix materials. Besides the obvious weight savings resulting from the use of composites, allowing fuel savings and extended range of flying, there are other fundamental design and processing changes made possible by the use of composites.

Modern large airplanes, flying at high altitudes, have pressurized cabins. The limit of pressurization depends on the strength of the fuselage material. In Boeing 787, the fuselage is made of carbon fiber/epoxy composites, which have a higher strength and stiffness than the conventional aluminum. This allows the fuselage to be pressurized to higher stress levels. The use of high strength composites, in turn, allows larger size viewing windows, higher humidity levels in the cabin, etc. than in conventional aircraft. Recall that the cabin of an aircraft undergoes pressurization cycles many thousands of times over its lifetime. A fuselage made of high strength composites can withstand higher pressure (corresponding to 1,800 m altitude) than one made of aluminum (corresponding to 2,400 m). Recall that it is easier to breathe at an altitude of 1,800 m than at 2,400 m. In addition, composites are more resistant to moisture than aluminum which means the level of humidity in the cabin can be increased (more comfortable for the passengers) and bigger windows (better viewing for the passengers) can be used.

Processing and tooling for composites are other areas which saw a tremendous change because of the large size of composite components needed for Boeing 787. An iron-nickel alloy called Invar is used to make tooling for large composites. Boeing uses the tape laying process wherein strips of carbon fiber/epoxy (<30 mm wide) are laid by multiple robotic tape laying heads on a spinning mandrel. The mandrel is made of this special alloy called Invar, which has a constant coefficient of thermal expansion. The mandrel is actually made of six interlocking pieces of Invar. It is etched to provide a mirror image of the plane interior. It has lengthwise grooves which allow composite stringers to be incorporated. Layer upon layer of prepreg strips are laid on the spinning mandrel until desired shape and thickness is obtained. This is followed by curing for about 2 h in an autoclave at around 250 °C. Figure 5.26 shows a specially built huge autoclave for this purpose. The hat shaped longitudinal stringers are cocured with fuselage skin. The strips of composites are laid into etched grooves for structural support. Finally, windows and doors are cut out by abrasive water jets into fuselage after curing.

All of the carbon/epoxy composites for Boeing 787 are supplied be Toray Industries, the world's largest producer of carbon fibers. The demand for ex-PAN

carbon fiber has grown tremendously with the advent of Boeing 787. Boeing 787 represented very large scale application of composites, not seen heretofore. Toray's 3900-Z prepreg, consisting of intermediate modulus T800 carbon fiber and a toughened epoxy matrix (cured at 175 °C) is a major material component. T800 carbon fiber has a tensile strength of 5.49 GPa and tensile modulus of 300 GPa. Toray's T700 carbon fiber (4.9 MPa tensile strength, 235 GPa tensile modulus) and glass fiber are also used.

Nanoparticles are added to polymers for use in the cabin interior to improve flammability. In some areas, Boeing has used resin film infusion (RFI) for horizontal cross-beams that span the fuselage. Tape-laying and fiber-placement machines allowed high speed production of parts. These machines allowed formation of complex geometric shapes using software tools that translate information from CAD and laminate data.

Composite materials enable 787 to have a high aspect ratio than in a conventional aluminum aircraft. In aerodynamics, the aspect ratio of a wing is defined as the square of the wing span divided by the area of the wing:

$$\text{Aspect ratio, } AR = b^2/A,$$

where b is the span of the wing and A it the area of the wing. A high aspect ratio indicates long, narrow wings, whereas a low aspect ratio implies short, stubby wings. Composites allow a high aspect ratio, which together with raked wing tips make it possible for 787 to cruise at 0.85Mach and consume less fuel than a conventional aircraft of a comparable size. The reason for this is that carbon/epoxy composites have high strength and stiffness and low density, which make it feasible to design long, slender (high AR) wings that would not be possible with conventional aluminum. It is worth pointing out that most birds have wings with a high aspect ratio. The V-formation commonly observed in flights of migratory birds has been regarded as akin to a single swept wing with a very high aspect ratio. It is thought that such a formation confers a high efficiency compared to a single bird in flight.

Composites deliver other benefits besides weight reduction. The structural composite can integrate an acoustic damping system, thermal transfer characteristics, and electrical functions. The use of composites also allowed a large reduction in the numbers of fasteners used. Boeing also claims that there is extended lamellar flow where the inlet of the nacelle meets with the structure of nacelle. The enhanced lamellar flow results in large fuel savings.

The main wing boxes are made by Mitsubishi Heavy Industries, Tokyo, Japan. Cured, solid laminate wing skins are cut to shape by abrasive waterjet cutters (Flow International Corp, Kent, WA). These waterjet cutters can cut through thick (25 mm) laminates very quickly and without overheating. Thick sections can be cut at 0.67 m/min. Thinner (6 mm) laminates can be cut at 3 m/min.

PMCs such as carbon/epoxy do not undergo corrosion like metals. They do bring in other problems though, such as photooxidation. This requires painting and use of intermediate barrier coatings. The thermal and electrical characteristics of PMCs

are much inferior from those of aluminum. Electrical shortening is not a problem with aluminum because of its high electrical conductivity. Similarly, metals like aluminum are better against lightening strikes.

5.4.1.3 Use of Composites in Jet Engines: GEnx

Composites have been used in the outer parts of a modern jet engine. These include nacelles, fan exit guide vanes, ducts, etc. Attempts to introduce composite materials inside the engine have been made since mid-twentieth century. Rolls Royce tried compressor fan blades made of PMCs; most noteworthy effort being the blades of the RB-211 engine, made of carbon fiber/epoxy. These blades had severe problems in the area of foreign-object damage (FOD) and reproducible properties. These problems, unfortunately, led to bankruptcy of the company in 1973. Nevertheless, RB-211 did represent important advance of composites into the cold sections of the engines. It had a new, wide-chord design, which allowed a smaller number of blades to be used, which reduced the noise. But the FOD or bird strike problem proved to be fatal one for the company.

General Electric has also been involved in this effort to introduce PMCs into the jet engine. It launched the GE 90-768 engine which had fan blades made of polymer matrix composite. This engine was selected for Boeing B777. These fan blades were wide-chord shape. In particular, we wish to describe the GEnx engine which is used in Boeing 787 and 747. A picture of this engine showing the fanblades made of PMCs is on the cover of the book you are holding in your hands; also in Fig. 5.25. Engine fan cases on GEnx jet engine are made by resin infusion process by GKN Aerospace at its Alabama plant. Among the special features GEnx are the following:

- Advanced dual rotor, axial flow, high by-pass turbofan engine (used in Boeing 787 and 747).
- Represents an advance over GE90 turbofan, especially the use of PMCs to make fan blades and case fan.
- Is designed to produce a thrust between 240 and 330 kN.
- It is a quieter and a more efficient engine compared to the earlier versions.
- Use of composite blades leads to higher by-pass ratio.

  Following are the dimensions of GEnx:

- *Fan diameter*. 2.8 m for 787 and 2.7 m for 747
- *Fanblades*. Carbon fiber/epoxy with titanium leading edges
- *Fan case*. Carbon fiber/epoxy (braided fabric with optimized braid orientations)

The new fan case, made of composites, results in weight savings of about 150 kg/engine. The composite fan case can also survive a blade detachment without requiring an aramid fabric wrapping which is done on conventional aluminum casings. GEnx has only 18 fan blades compared to 36 in CF6. The shape optimization of blades results in this benefit, which leads to a quieter engine.

5.4.1.4 Other Aerospace Applications

The helicopter industry in particular has long been an enthusiastic user of carbon fiber PMCs. It is claimed that composite helicopter rotor blades have lower direct operating costs than aluminum blades (Mayer 1974), and this is without taking into account the intangibles such as longer fatigue life, reduced maintenance, and lower manufacturing costs. Boeing Vertol, Bell Aircraft, and Sikorsky, among others, use composite rotor blades in their helicopters. Cargo bay doors, maneuvering engine pods, arm booms, and booster rocket casings in the US Space Shuttle Orbiter are made of carbon fiber/epoxy composites. Figure 5.26 shows the primary tower structure and several antennas made of carbon fiber/epoxy for use in Intelsat 5. The main attractions for their use are lightness and dimensional stability.

5.4.1.5 Applications in Leisure Industry

The leisure and sporting goods industry is another big market for PMCs. Golf clubs, archery bows, fishing rods, tennis rackets, cricket bats, and skis are commonplace items in which carbon fiber PMCs are used. Figure 5.27a shows a tennis racket, a pair of skis, and a fishing rod while Fig. 5.27b shows a bicycle frame made of carbon fiber/epoxy. Note the sleek lines that have become a hallmark of composite construction. In addition to attractive mechanical characteristics, carbon fiber reinforced thermoplastic composites have excellent electrical properties. This is exploited in situations where a static charge builds up easily, for example, in high-speed computer parts and in musical instruments where rubbing, sliding, or separation of an insulating material results in electrostatic voltages. In parts made of insulating polymeric resins, this charge stays localized until the polymer comes in contact with a body at a different potential and the electrostatic voltage discharges via an arc or spark. Voltages as high as 30–40 kV can build up. This electrostatic charge can be painful to a human being or even fatal in extreme circumstances. Some very sensitive microelectronic parts can be damaged by an electrostatic discharge of a mere 20 V. Thus, it is not surprising that carbon fibers dispersed in thermoplastic resins find applications where dissipation of a static charge is important. Of course, conductive fillers of other than carbon fiber can be used to overcome the problem of static electricity, but carbon fibers also serve to reinforce mechanically in situations requiring high strength and wear resistance. Figure 5.28a, b show a microphone and head shell, the unit that holds the stylus at the end of the turntable arm. Carbon fibers dissipate the static directly, thus eliminating the need for copper conductors. This is coupled with a high stiffness-to-weight ratio of these composites, which allows a weight reduction of the part as well. We should also mention that quite a few companies are making musical instruments such as guitars, violins, and violas as well as bows out of carbon fiber reinforced composites.

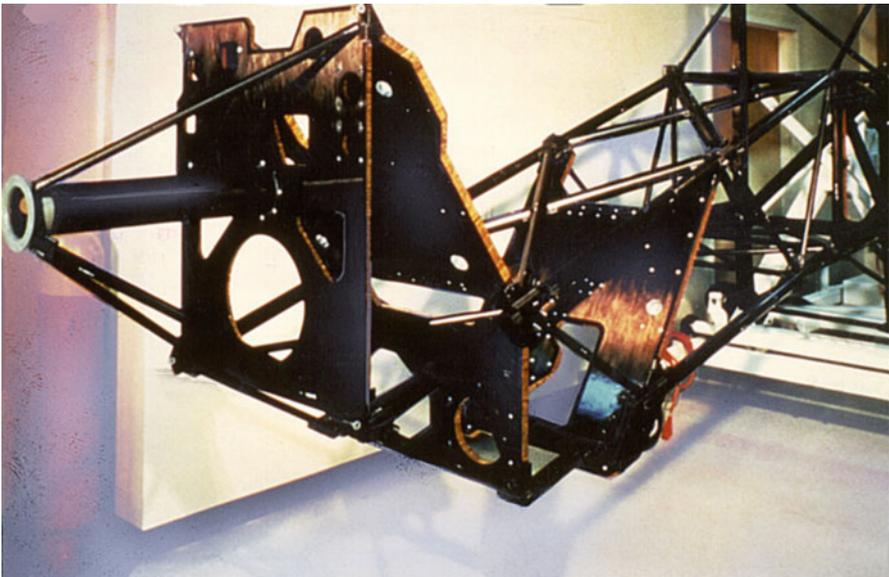**Fig. 5.25** Blades of GEnx engine are made of carbon fiber/epoxy composites (courtesy of General Electric Co.)

Fig. 5.26 Intelsat 5 has a primary structure and several antennas made of carbon fiber PMCs (courtesy of Fiberite Co.)

Fig. 5.27 Examples of sporting goods made of carbon fiber composites where lightness, good mechanical characteristics, and sleek lines make the items very attractive: (**a**) tennis racket, a pair of skis, and a fishing rod (courtesy of Fiberite Co.), (**b**) a bicycle frame made of carbon fiber/epoxy (courtesy of Trek Co.)
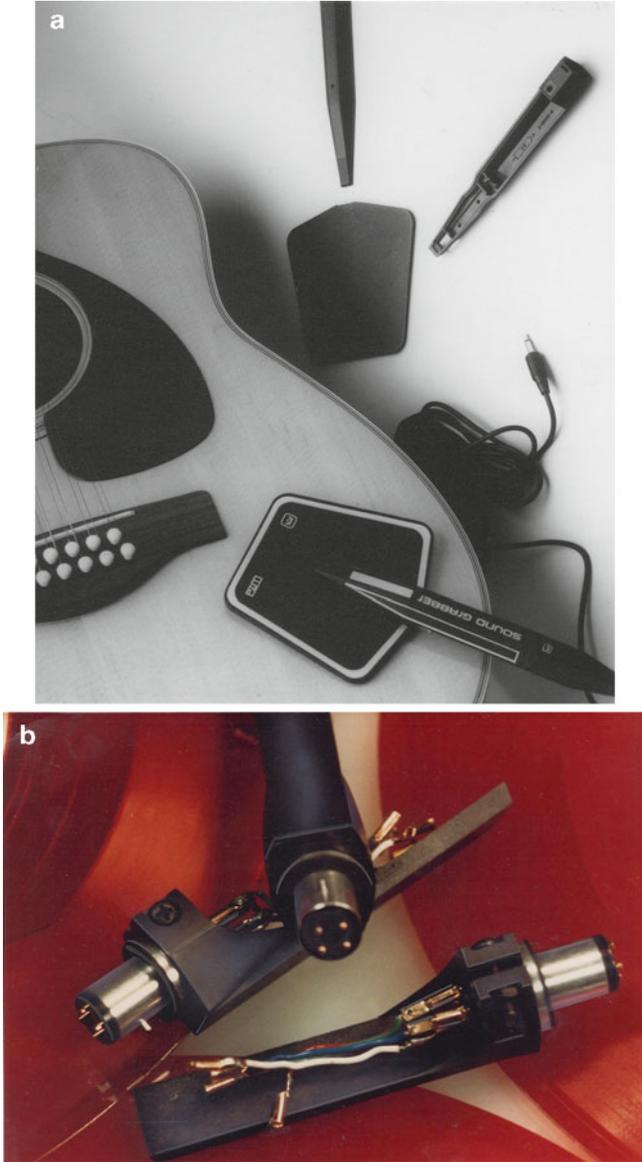
Fig. 5.28 Use of carbon fiber/thermoplastic matrix composites in situations involving static charge: (**a**) microphone, (**b**) a head shell unit of a turntable arm (courtesy of LNP Corporation)

Table 5.3 Correspondence between shielding effectiveness in dB and % signal attenuation

Shielding effectiveness (dB)	Attenuation (%)
20	90
40	99
60	99.9
80	99.99

5.4.1.6 Electromagnetic Shielding

Shielding against electromagnetic interference (EMI) is another area where highly conductive composites based on carbon fibers are finding applications. EMI is nothing but electronic pollution or noise caused by rapidly changing voltages. Examples include avionic housings, computer enclosures, and any other electronic device that needs protection against stray EMI. Nickel-coated carbon fibers are used in shielding against electromagnetic and radio frequency interference. Nickel confers excellent conductivity while retaining the flexibility of carbon fibers. In aircraft, such a composite can provide protection against lightning strikes. Radar-absorbing materials are used to reduce EMI. Navy ships carry a large number of antennas, computers, and telecommunications equipment. A myriad of EMI problems can arise under such circumstances. Nickel is deposited by CVD on carbon fibers. Nickel-coated carbon fibers can be incorporated into a polymeric matrix by any of the methods described earlier. Finely chopped nickel-coated carbon fibers can be incorporated in adhesives, sealants, gaskets, and battery electrodes for use in aerospace and for electronic applications requiring EMI shielding.

It is convenient to measure shielding effectiveness or attenuation in decibels (dB), which is nothing but a logarithmic scale. The decibel scale is preferred when a quantity can vary over several orders of magnitude. Electromagnetic shielding effectiveness (SE) can be defined as follows:

$$\text{Shielding effectiveness (SE)} = 20 \, \log\left(\frac{\text{incident field strength}}{\text{transmitted field strength}}\right).$$

Table 5.3 shows the correspondence between shielding effectiveness in dB and signal attenuation in percentage. A shielding level of 80 dB implies 99.99 % attenuation of the incident electromagnetic radiation. For most business electronic equipment with 30–1,000 MHz frequency, 35–45 dB attenuation is adequate. Requirements of military applications are stringent, and 60–80 dB attenuation is not uncommon.

While there are applications involving the use of the conductive properties of carbon fibers, there are also certain problems associated with this characteristic of carbon fibers. Carbon fibers are extremely fine and light, and if they become accidently airborne, for any reason, and settle on electrical equipment, short circuiting can occur. The conclusion of extensive studies conducted at NASA on this problem was that despite the risk, there was no reason to prohibit the use of carbon fibers in structures; see NASA (1980).

5.4.1.7 Civil Infrastructure Applications

A major development in the 1990s has been the use of fiber reinforced composites in civil infrastructure. Among the major drivers for this are: reduced cost, corrosion resistance, improved life and reduced maintenance, and possible reduction in seismic problems. Major effort has been in the area of bridges, new as well repair and retrofit. As an example, concrete and masonry structures can be strengthened by composites rather than steel plates. One such process involves surface preparation and application of an appropriate primer to the concrete structure, application of a resin coat, followed by a sheet of composite and a second coat of resin. Both glass fiber and carbon fiber reinforced composites are used, although carbon fiber reinforced polymer composites give superior results. As an illustrative example, we show in Fig. 5.29a a concrete column wrapped around with a jacket of carbon fiber/epoxy composite, while Figure 5.29b shows the results after the application of a compressive load. In the part of the concrete column without the composite jacket, the spalling of concrete and buckling of the steel reinforcement bars can be seen.
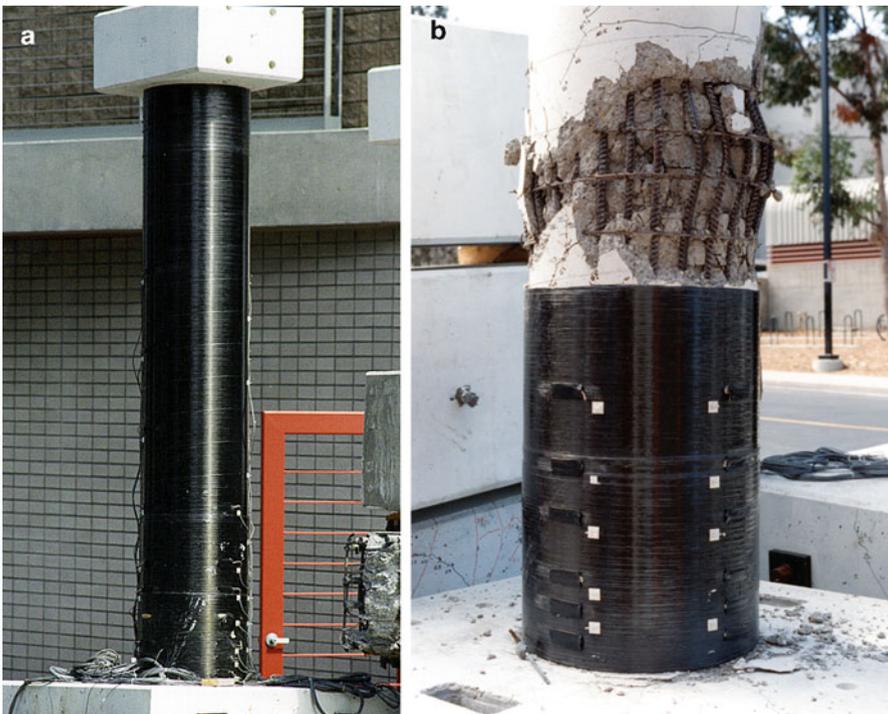

Fig. 5.29 (**a**) A concrete column wrapped around with a jacket of carbon fiber/epoxy composite while (**b**) on application of a compressive load, spalling of concrete and buckling of the steel reinforcement bars can be seen in the part of the concrete column without the composite jacket. In the portion of the column protected with a composite jacket, there is no visible effect (courtesy of B. Kad.)

In the portion of the column protected with a composite jacket, there is no visible effect. Potentially, composite wrapping of structural columns for seismic reinforcement would appear to be a huge market. The reader should not get the impression that everything is perfect in this area of use of composites in the civil infrastructure. There are many problems, such as durability, moisture absorption by the polymer matrix and other environmental effects. In addition, there is a lack of design guidelines and database of material specifications, which makes it difficult for civil engineers to accept the composites.

Carbon fiber is also used to reinforce cement. The resultant brittle composite shows an improved tensile and flexural strength, high impact strength, dimensional stability, and a high resistance to wear. Another application of carbon fiber PMCs in civil infrastructure has to do with the ability of bridges and other structures to withstand earthquakes. Earthquake-proofing of bridge columns is done by wrapping columns with carbon fiber reinforced composites as described above.

Reinforced concrete is a common building construction material. Since reinforced concrete has high compressive strength but low tensile strength, we use reinforcing bars, often referred to as rebar, on the tensile side of concrete structures. Conventional rebar is made of steel; which is quite an effective and cost-efficient reinforcement material for concrete. The main problem with steel rebar is that it is subject to corrosion by chloride ions. Chloride ions are present in coastal areas, locations where salt is used for deicing, and sites where aggressive chemicals and ground conditions provide chloride ions. It turns out that the products of corrosion of rebar have a larger volume (2–5 times) than the original metal that is consumed in the corrosion process. This change in volume leads to tensile loading of the concrete, followed by cracking and spalling. One way out of this problem has been to use epoxy coated steel rebar. Of course, stainless steel would solve the corrosion problem, but it would be highly uneconomical. A glass fiber reinforced polymer composite rebar can be used as non-prestressed reinforcement in concrete These composite rebars are resistant to chloride ion attack, have a tensile strength of 1½ to 2 times that of steel, and weigh only 25 % of the weight of equivalent size steel rebar. The elastic modulus of glass fiber polymer is about 50 GPa, much less than that of steel, about 210 GPa. This lower stiffness causes greater deflection in the structure which can lead to cracking. Other reinforcements such as carbon fiber, aramid fiber or S-glass fiber can be used instead of E-glass fiber, but all these fibers are very expensive, so these options are generally not cost effective compared to steel. Yet another point that needs to be taken into account is the higher ductility of steel compared to that of composite rebar.

5.4.1.8   Composites in Wind Energy

Wind energy is an important renewable energy resource. Here, we briefly describe the basic concept of a wind turbine and how and why polymer matrix composites play a vital role in this field.

Windmills of one sort or another have been around for quite a while. Electrical power is produced by the spinning blades of a wind turbine. The basic principle behind the windmill is very simple. Large, multiple airfoil blades move under the action of wind. When the wind blows, it creates positive pressure on the front side of the blade it and negative pressure behind it, i.e., the blade moves because of differential air pressure on the airfoil, which makes the rotor turn. The blade movement produces mechanical energy which is converted into electrical energy by a generator.

In the past, windmill blades were made of wood. A typical windmill consists of a rotor with aerodynamically shaped blades (commonly, a set of three) placed on a tower. The rotor blade has the shape of an aerofoil like the wing of an airplane. The material for the skins of the aerofoil needs to be strong, stiff, but light. These requirements lead to wood and fiber reinforced polymer composites as the optimum materials. Wood does not measure up to the composites mainly because of a very large variability in properties and likely environmental damage. Since the 1990s, fiber reinforced composites have been increasingly used to make the blades of a windmill. Most common composites used are glass fibers reinforced epoxy composites; carbon fiber/epoxy forms a distant second. Glass fiber composites are cheaper than carbon fiber composites. However, longer blades (60 m) can be made by a judicial mix of glass and carbon fibers to lower the mass of the blade. The longer blades improve the efficiency of turbine (see below).The most common resin matrixes are bisphenol-A epoxy or polyester or vinyl ester. Three blades are commonly used on a windmill turbine. It should be pointed out the skins of the turbine blades fiber are made of fiber reinforced polymers as facings with the core being made of suitable foam.

Figure 5.30 shows an offshore windmill farm. The rotors of such windmills are typically made of glass fiber reinforced epoxy. The rotor blade corresponds to an elastic beam. For such a beam we can define a figure of merit (Brøndsted et al. 2005)

$$M_\mathrm{b} = E^{0.5}/\rho,$$

where E is the young's modulus or tensile stiffness and ρ is the density of the material. One can have a figure of merit based on fracture toughness as well.

The blades spin at 25 rpm under forces that are equivalent to forces encountered by a widebody jet at takeoff. Some blades are comparable in size to the wing of a Boeing 747 aircraft. In a windmill, a turbine converts the kinetic energy of wind into electrical energy with the power, P, given by (Brøndsted et al. 2005)

$$P = \alpha\rho A v^3,$$

where α is a constant based on aerodynamic efficiency, ρ is the density of air, A is the area of the rotor-plane, and v is the wind velocity. We note from the above

expression that the power obtained in a windmill is proportional to the square of the radius, r of the windmill and to the cube of wind velocity, v, i.e.,

$$P \propto r^2 v^3.$$

So, for a given wind velocity, it makes sense to increase the radius of the windmill. In the 1990s, wind turbines commonly had 15 m long blades and could produce 50 kW of power. In 2008, blades of length 60 m were being used, while the largest wind turbines could produce 5 MW of power.

5.4.1.9 Processing of Rotor Blades

Rotor blades can be made manually (e.g., wet layup), but manual processes are restricted to small blades. Manual processes are cheap but quality control is questionable. Variability if the resin content can be a serious problem in wet layup. Use of prepregs helps avoid this problem, but one must apply heat and pressure for consolidation, which adds to the cost. Large blades can be made by filament winding or automatic tape placement. Blade skins made by manual processes are made as two half-shells and cured. The skins are then bonded by adhesives.

Automation of the layup process of fiber in the blade mold can lead to economies of processing large blades. In an automatic process based upon automatic tape laying or automatic fiber placement, the blade geometry is programmed into control system. Commonly the molds themselves are made of composite materials.

5.4.1.10 Loading of Rotor Blades in a Wind Mill

The rotor blades of a wind turbine, made of fiber reinforced polymer composites, experience gravity, centrifugal forces because of the rotation of the rotor, and cyclic fatigue loading. The blades are commonly designed for a lifetime of about 20 years which translates to 10^8 to 10^9 cycles (Brøndsted et al. 2005). Fatigue loading of the turbine blade and the gearbox can be a serious problem. One should point out a major difference between the fatigue loading of the wing of an aircraft and the blade of a wind turbine; the loading conditions in a windmill are more strenuous. An aircraft at its cruising speed at high altitudes is not subjected to the same forces as a wind turbine blade on earth. It is important to realize that if, during high speed spinning of the rotor blades, one of the blades came loose and smashed into the central tower, it could cause the whole structure to collapse. Such incidents have been captured on video.

5.4.1.11   Static Testing

Static loading is carried out in a traction rig attached to the blade by steel wires. The blade is loaded in tension to maximum load. According to the practice used at LMGlasfiber, a large manufacturer of wind mills, the rotor blade must stay under load for at least 10 seconds without breaking. The tensile test is repeated twice flapwise and then the extreme load is tested in all directions: leading edge, trailing edge, suction side and pressure side. It can take about a week to do the static testing, and the test is repeated after the blade has been subjected to the dynamic test (see the description of the dynamic test below). This is done to make sure that the dynamic or fatigue loading of the blade has not introduced a subcritical damage.

5.4.1.12   Dynamic Testing

Dynamic testing of the rotor blades is very important because they must be able to sustain fatigue loads corresponding to 20 years of life. Every materials has a natural frequency of oscillation, *f*, given by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where *k* is the stiffness (N/m) and *m* is the mass. The blade sets into oscillation corresponding to its natural frequency. The larger or more massive the blade, the lower the natural frequency. It is not uncommon to subject the blade to five million oscillations edgewise followed by five million oscillations flapwise. A 60 m long blade could easily be fatigue tested for a year. During fatigue testing, nondestructive techniques are use to detect any damage in the blades, e.g., an infrared camera may be used to detect cracks in the laminate. Concurrently, many strain gages, attached to the surface of the blade, are used to track the deformation and deflections.

5.4.1.13   Protection Against Lightning

As is well known, lightning strikes the highest point in a given area. This makes wind turbines a very likely target, because of their height and elevated location. Lightning strikes involve currents of very large amperage (can be up to 200 kA) and they release very large amount of energy in a very short time period (milliseconds). Besides the obvious electrical and magnetic properties, lightning strikes involve X-rays, thunder which is nothing but an acoustic shock wave, and intense heat. Thus, a lightning strike can easily destroy a blade, if it is not protected. Windmills in offshore locations are particularly vulnerable to lightning strikes. Commonly, lightning protection involves several external copper air termination disks called

receptors, which are fastened to an aluminum cable in the blade interior running its entire length. Conductors are fastened to the blade and to one another with bolts, near the blade root a portion of the conductor is embedded into the fiber composite. From the blade root area the conductor is bonded to the hub and then to the ground. LM Glasfiber uses a system consisting of several receptors placed on both sides of the blade. Each receptor is capable of conducting the energy generated by a lightning strike to the main cable, on its own. Together, the multiple receptors improve the lightning protection along the entire length of the blade.

Fig. 5.30 An offshore wind farm at Middelgrunden near Copenhagen, Denmark. Each rotor blade is 36.8 m long (courtesy of LMGlasfiber, www.lmglasfiber.com)

5.5 Recycling of PMCs

When the useful life of a PMC component, be that aircraft-part or a fishing rod, is finished, we need to be concerned about the recycling or reclamation of the components. Service or use is the main reason that a material or a component loses its restorable value. There are, however, certain additional items that cause restoring the value in case of PMCs difficult. Paint removal of a polymer or composite can frequently be a cause of poor recycling. In thermosetting materials, the cross-linking phenomenon makes recycling very difficult. Continuous fiber reinforced composites pose a great difficulty in recycling; especially the recovery of continuous fibers. Mechanical recycling mainly involves grinding the composite scrap; use the comminuted product as a filler or reinforcement in new composite,

generally meant for less-demanding applications than the virgin material (Pickering 2006). There is the option of using a variety of thermal techniques that breakdown the composite scrap. SMC is a polymer matrix composite containing particles/short fibers. Such a material can easily be ground into a fine powder and reused as filler. Such a technique would not work with continuous fiber reinforced thermoset matrix PMCs. As we know, thermosets are the most common matrix materials in PMCs, and they are not amenable to recycling in a manner similar to metals and thermoplastics. Tertiary recycling, i.e., recovery of the monomer, is one possible way. Tertiary or chemical recycling involving conversion of polymer fractions into a gaseous mixture of low molecular weight hydrocarbons with a low temperature (200 °C) catalytic process has been tried (Manson 1994; Allred et al. 1997). Such chemical recycling breaks polymeric waste into reusable hydrocarbon fractions for use as monomers, chemicals, or fuel. The thermoset polymer matrix is separated into low molecular weight chemicals and the reclaimed fibers and fillers can be reused. It has been claimed that although the reclaimed carbon fibers are not continuous, their structural and mechanical characteristics are not altered by the chemical recycling (Allred et al. 1997). Analysis of the reclaimed carbon fibers by SEM, XPS, and single fiber tensile tests showed them to have surface texture, chemistry and strength close to the virgin fibers. The epoxy was converted to hydrocarbon fractions. It is important to recognize that these recycling procedures result in a material that is suitable for use in applications less demanding than the original application because of a considerably reduced intrinsic value of the material after each step. Figure 5.31 shows schematically the change in value of the constituents with increasing life cycle (Manson 1994).
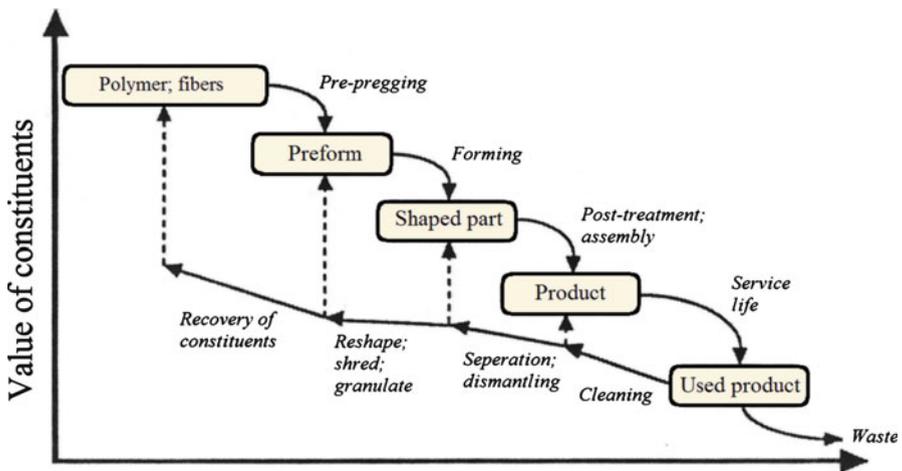

Fig. 5.31 Change in value of the constituents with increasing life cycle [after Manson (1994)]

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Problems

5.1. Why are prepregs so important in polymer matrix composites? What are their advantages? Describe the different types of prepregs.

5.2. Randomly distributed short fibers should result in more or less isotropic properties in an injection molded composite. But this is generally not true. Why? What are the other limitations of injection molding process?

5.3. In a thermally cured PMC, the fiber surface treatments have been well established for certain systems. For example, silanes are used on glass fiber in an epoxy matrix while an oxidizing treatment to carbon fiber for use in an epoxy matrix. What would be the effect of electron beam curing on the interface development in a PMC?

5.4. Describe the major differences in the processing of composites having a thermoset matrix and those having a thermoplastic matrix.

5.5. What are the important factors in regard to fire resistance of PMCs?