

14

Processing of Polymer Matrix Composites and Rubber

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This chapter considers those manufacturing processes by which polymer matrix composites and rubbers are shaped into useful components and products. Many of the processes used for these materials are the same as or similar to those used for plastics (Chapter 13). After all, polymer matrix composites and rubbers are polymeric materials. The difference is that they contain some form of reinforcing ingredient. A **polymer matrix composite** (PMC) is a composite material consisting of a polymer embedded with a reinforcing phase such as fibers or powders. The technological and commercial importance of PMC processes derives from the growing use of this class of material, especially fiber-reinforced polymers (FRPs). In popular usage, PMC generally refers to fiber-reinforced polymers. FRP composites can be designed with very high strength-to-weight and stiffness-to-weight ratios. These features make them attractive in aircraft, cars, trucks, boats, and sports equipment.

The preceding definition of a polymer matrix composite could be applied to nearly all rubber products, except that the polymer is an elastomer whereas the polymer in a PMC is a plastic. Almost all rubber products are reinforced with carbon black, which is what gives pneumatic tires their characteristic black color. Tires are the dominant product in the rubber industry. They are used in large numbers for automobiles, trucks, aircraft, and bicycles.

The coverage in this chapter begins with PMCs that are based on plastics. Sections 14.5 and 14.6 cover composites based on elastomers.

14.1 Overview of PMC Processing

The variety of shaping methods for fiber-reinforced polymers can be bewildering on first reading. A road map will be helpful to the reader entering this new territory. FRP composite shaping processes can be divided into five categories, as organized in Figure 14.1: (1) open mold processes, (2) closed mold processes, (3) filament winding, (4) pultrusion processes, and (5) miscellaneous. Open mold processes include some of the original manual procedures for laying resins and fibers onto forms. Closed mold processes are much the same as those used in plastic molding; the reader will recognize the names—compression molding, transfer molding, and injection molding—although the names are sometimes changed and modifications are sometimes made for PMCs. In **filament winding**, continuous filaments that have been dipped in liquid resin are wrapped around a rotating mandrel; when the resin cures, a rigid, hollow, generally cylindrical shape is created. **Pultrusion** is a shaping process for producing long, straight sections of constant cross section; it is similar to extrusion, but adapted to include continuous fiber reinforcement. The “miscellaneous” category includes several operations that do not fit into the previous categories. To complicate matters, some of the processes in the list are used to shape composites with continuous fibers, whereas others are used for short fiber PMCs. Figure 14.1 identifies the processes in each division.

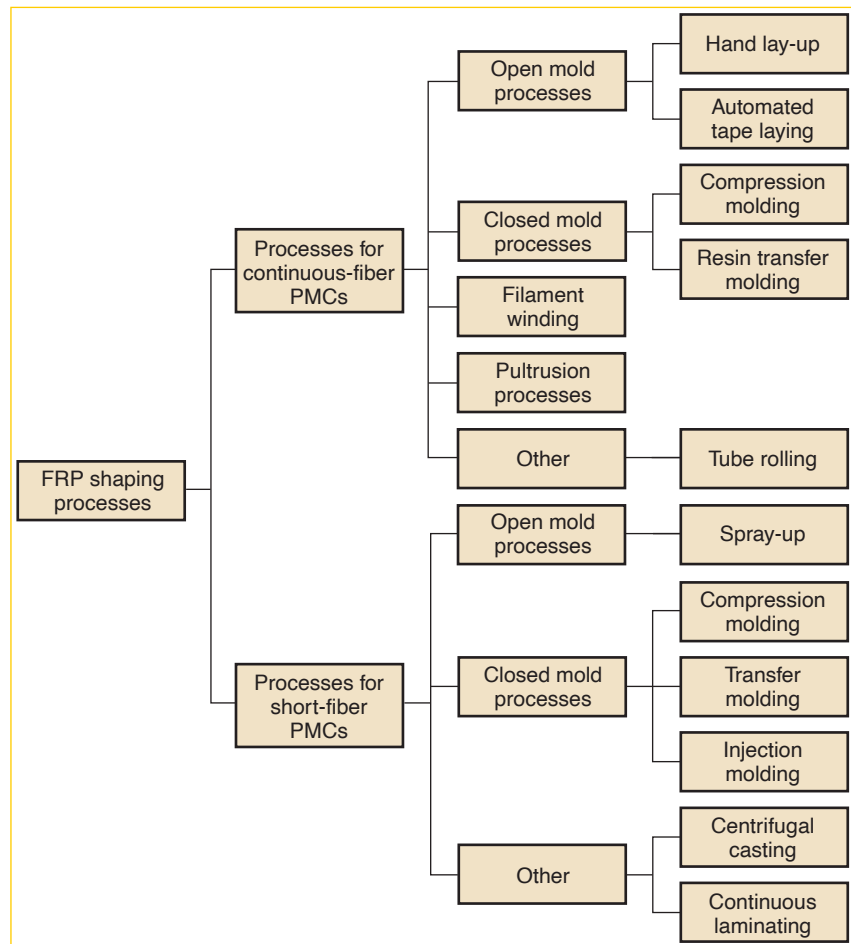


FIGURE 14.1
Classification of
manufacturing
processes for
fiber-reinforced
polymer composites.

Some of the PMC shaping processes are slow and labor intensive. In general, techniques for shaping composites are less efficient than manufacturing processes for other materials. There are two reasons for this: (1) composite materials are more complex than other materials, consisting as they do of two or more phases and the need to orient the reinforcing phase in the case of fiber-reinforced plastics; and (2) processing technologies for composites have not been the object of improvement and refinement over as many years as processes for other materials.

14.1.1 STARTING MATERIALS FOR PMCs

In a PMC, the starting materials are a polymer and a reinforcing phase. They are processed separately before becoming phases in the composite. This section considers how these materials are produced before being combined. Section 14.1.2 describes how they are combined to make the composite part.

Both thermoplastics and thermosets are used as matrices in PMCs. Thermosetting (TS) polymers are the most common matrix materials. The principal TS polymers are phenolics, unsaturated polyesters, and epoxies. Phenolics are associated with the use of particulate reinforcing phases, whereas polyesters and epoxies are more closely associated with FRPs. Thermoplastic (TP) polymers are also used in PMCs, in fact, most TP molding compounds are composite materials because they include fillers and/or reinforcing agents. Many of the polymer shaping processes discussed in Chapter 13 are applicable to polymer matrix composites. However, combining the polymer with the reinforcing agent sometimes complicates the operations.

The reinforcing phase can be any of several geometries and materials. The geometries include fibers, particles, and flakes, and the materials are ceramics, metals, other polymers, or elements such as carbon or boron. The role of the reinforcing phase and some of its technical features are discussed in Section 9.1.2.

Common fiber materials in FRPs are glass, carbon, and the polymer Kevlar. Fibers of these materials are produced by various techniques, some of which have been covered in other chapters. Glass fibers are produced by drawing through small orifices (Section 12.2.3). For carbon, a series of heating treatments is performed to convert a precursor filament containing a carbon compound into a more pure carbon form. The precursor can be any of several substances, including polyacrylonitrile (PAN), pitch (a black carbon resin formed in the distillation of coal tar, wood tar, petroleum, etc.), or rayon (cellulose). Kevlar fibers are produced by extrusion combined with drawing through small orifices in a spinneret (Section 13.4).

Starting as continuous filaments, the fibers are combined with the polymer matrix in any of several forms, depending on the properties desired in the material and the processing method to be used to shape the composite. In some fabrication processes, the filaments are continuous, whereas in others, they are chopped into short lengths. In the continuous form, individual filaments are usually available as rovings. A **roving** is a collection of untwisted (parallel) continuous strands; this is a convenient form for handling and processing. Rovings typically contain from 12 to 120 individual strands. By contrast, a **yarn** is a twisted collection of filaments. Continuous rovings are used in several PMC processes, including filament winding and pultrusion.

The most familiar form of continuous fiber is a **cloth**—a fabric of woven yarns. Very similar to a cloth, but distinguished here, is a **woven roving**, a fabric consisting of untwisted filaments rather than yarns. Woven rovings can be produced with unequal numbers of strands in the two directions so that they possess greater strength in

one direction than the other. Such unidirectional woven rovings are often preferred in laminated FRP composites.

Fibers can also be prepared in the form of a **mat**—a felt consisting of randomly oriented short fibers held loosely together with a binder, sometimes in a carrier fabric. Mats are commercially available as blankets of various weights, thicknesses, and widths. Mats can be cut and shaped for use as **preforms** in some of the closed mold processes. During molding, the resin impregnates the preform and then cures, thus yielding a fiber-reinforced molding.

Particles and flakes are really in the same class. Flakes are particles whose length and width are large relative to thickness. These and other issues on characterization of engineering powders are discussed in Section 15.1. Production methods for metal powders are discussed in Section 15.2, and techniques for producing ceramic powders are discussed in Section 16.1.1.

14.1.2 COMBINING MATRIX AND REINFORCEMENT

Incorporation of the reinforcing agent into the polymer matrix either occurs during the shaping process or beforehand. In the first case, the starting materials arrive at the fabricating operation as separate entities and are combined into the composite during shaping. Examples of this case are filament winding and pultrusion. The starting reinforcement in these processes consists of continuous fibers. In the second case, the two component materials are combined into some preliminary form that is convenient for use in the shaping process. Nearly all of the thermoplastics and thermosets used in plastic shaping processes are really polymers combined with fillers (Section 8.1.5). The fillers are either short fibers or particulate (including flakes).

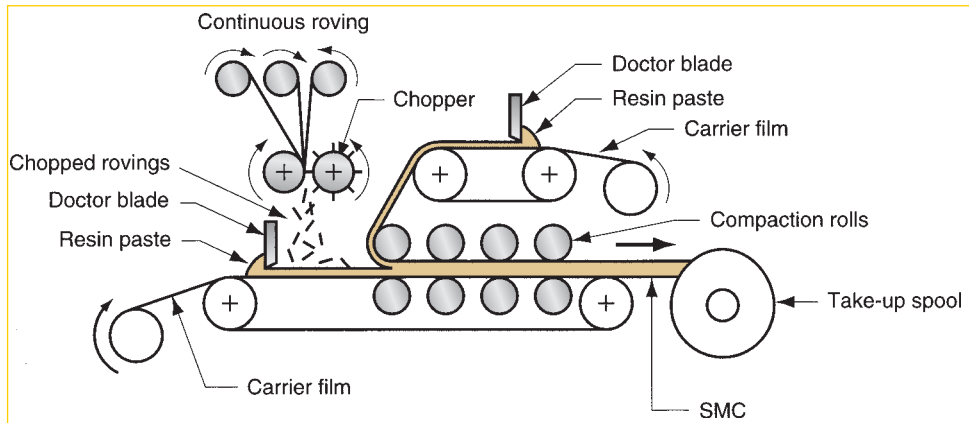
Of greatest interest in this chapter are the starting forms used in processes designed for FRP composites. One might think of the starting forms as prefabricated composites that arrive ready for use at the shaping process. These forms are molding compounds and prepregs.

Molding Compounds Molding compounds are similar to those used in plastic molding. They are designed for use in molding operations, and so they must be capable of flowing. Most molding compounds for composite processing are thermosetting polymers. Accordingly, they have not been cured before shape processing. Curing is done during and/or after final shaping. FRP composite molding compounds consist of the resin matrix with short, randomly dispersed fibers. They come in several forms.

Sheet molding compound (SMC) is a combination of TS polymer resin, fillers and other additives, and chopped glass fibers (randomly oriented) all rolled into a sheet of typical thickness 6.5 mm (0.250 in). The most common resin is unsaturated polyester; fillers are usually mineral powders such as talc, silica, limestone; and the glass fibers are typically 12 to 75 mm (0.5–3.0 in) long and account for about 30% of the SMC by volume. SMCs are very convenient for handling and cutting to proper size as molding charges. Sheet molding compounds are generally produced between thin layers of polyethylene to limit evaporation of volatiles from the thermosetting resin. The protective coating also improves surface finish on subsequent molded parts. The process for fabricating continuous SMC sheets is depicted in Figure 14.2.

Bulk molding compound (BMC) consists of similar ingredients as those in SMC, but the compounded polymer is in billet form rather than sheet. The fibers in BMC are shorter, typically 2 to 12 mm (0.1–0.5 in), because greater fluidity is required in

FIGURE 14.2 Process for producing sheet molding compound (SMC).



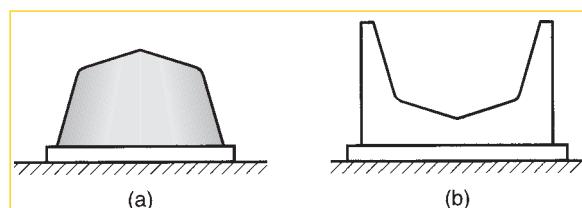
the molding operations for which these materials are designed. Billet diameter is usually 25 to 50 mm (1–2 in). The process for producing BMC is similar to that for SMC, except extrusion is used to obtain the final billet form. BMC is also known as **dough molding compound** (DMC), because of its dough-like consistency. Other FRP molding compounds include **thick molding compound** (TMC), similar to SMC but thicker—up to 50 mm (2 in); and **pelletized molding compounds**—basically conventional plastic molding compounds containing short fibers.

Prepregs Another prefabricated form for FRP shaping operations is **prepreg**, which consists of fibers impregnated with partially cured thermosetting resins to facilitate shape processing. Completion of curing must be accomplished during and/or after shaping. Prepregs are available in the form of tapes or cross-ply sheets or fabrics. The advantage of prepregs is that they are fabricated with continuous filaments rather than chopped random fibers, thus increasing strength and modulus of the final product. Prepreg tapes and sheets are associated with advanced composites (reinforced with boron, carbon/graphite, and Kevlar) as well as fiberglass.

2 Open Mold Processes

The distinguishing feature of this family of FRP shaping processes is its use of a single positive or negative mold surface (Figure 14.3) to produce laminated FRP structures. Other names for open mold processes include **contact lamination** and **contact molding**. The starting materials (resins, fibers, mats, and woven rovings) are applied to the mold in layers, building up to the desired thickness. This is followed by curing and part removal. Common resins are unsaturated polyesters and epoxies, using fiberglass as the reinforcement. The moldings are usually large (e.g., boat hulls). The advantage of using an open mold is that the mold costs much less than if two

FIGURE 14.3 Types of open mold: (a) positive and (b) negative.



matching molds were used. The disadvantage is that only the part surface in contact with the mold surface is finished; the other side is rough. For the best possible part surface on the finished side, the mold itself must be very smooth.

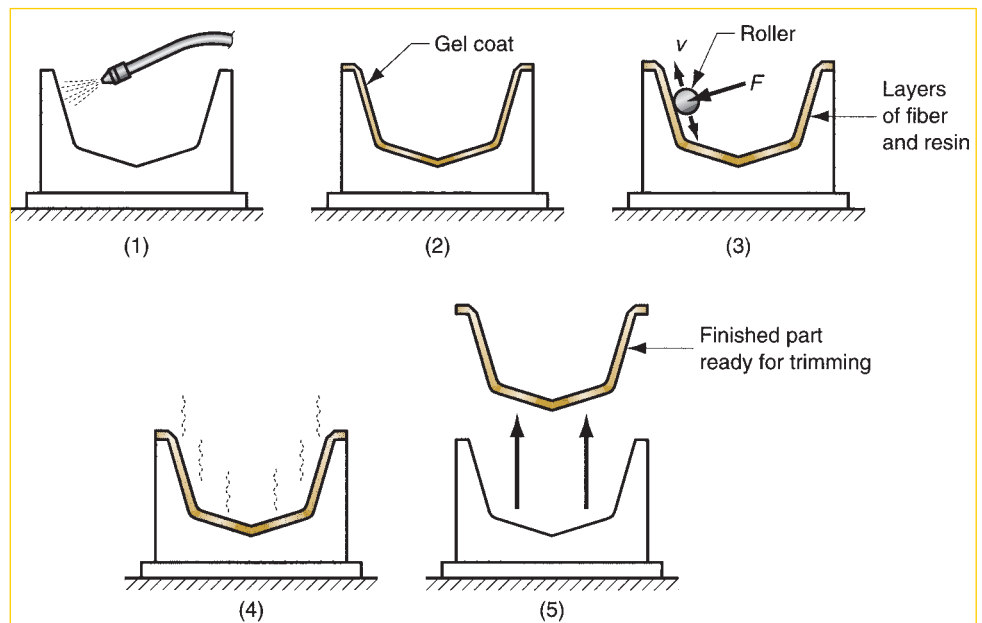
There are several important open mold FRP processes. The differences are in the methods of applying the laminations to the mold, alternative curing techniques, and other variations. In this section, three open mold processes for shaping fiber-reinforced plastics are described: (1) hand lay-up, (2) spray-up, and (3) automated tape-laying machines. Hand lay-up is treated as the base process and the others as modifications and refinements.

14.2.1 HAND LAY-UP

Hand lay-up is the oldest open mold method for FRP laminates, dating to the 1940s when it was first used to fabricate boat hulls. It is also the most labor-intensive method. As the name suggests, hand lay-up is a shaping method in which successive layers of resin and reinforcement are manually applied to an open mold to build the laminated FRP composite structure. The basic procedure consists of five steps, illustrated in Figure 14.4. The finished molding must usually be trimmed with a power saw to size the outside edges. In general, these same five steps are required for all of the open mold processes; the differences between methods occurring in steps 3 and 4.

In step 3 of the hand lay-up process, each layer of fiber reinforcement is dry when placed onto the mold. The liquid (uncured) resin is then applied by pouring, brushing, or spraying. Impregnation of resin into the fiber mat or fabric is accomplished by hand rolling. This approach is referred to as *wet lay-up*. An alternative approach is to use *prepregs*, in which the impregnated layers of fiber reinforcement are first prepared outside the mold and then laid onto the mold surface. Advantages cited for the prepregs include closer control over fiber-resin mixture and more efficient methods of adding the laminations [16].

FIGURE 14.4 Hand lay-up procedure: (1) mold is cleaned and treated with a mold release agent; (2) a thin gel coat (resin, possibly pigmented to color) is applied, which will become the outside surface of the molding; (3) when the gel coat has partially set, successive layers of resin and fiber are applied, the fiber being in the form of mat or cloth; each layer is rolled to fully impregnate the fiber with resin and remove air bubbles; (4) the part is cured; and (5) the fully hardened part is removed from the mold.



Molds for open mold contact laminating can be made of plaster, metal, glass fiber-reinforced plastic, or other materials. Selection of material depends on economics, surface quality, and other technical factors. For prototype fabrication, in which only one part is produced, plaster molds are usually adequate. For medium quantities, the mold can be made of fiberglass-reinforced plastic. High production generally requires metal molds. Aluminum, steel, and nickel are used, sometimes with surface hardening on the mold face to resist wear. An advantage of metal, in addition to durability, is its high thermal conductivity that can be used to implement a heat-curing system, or simply to dissipate heat from the laminate while it cures at room temperature.

Products suited to hand lay-up are generally large in size but low in production quantity. In addition to boat hulls, other applications include swimming pools, large container tanks, stage props, radomes, and other formed sheets. Automotive parts have also been made, but the method is not economical for high production. The largest moldings ever made by this process were ship hulls for the British Royal Navy: 85 m (280 ft) long [3].

14.2.2 SPRAY-UP

This represents an attempt to mechanize the application of resin-fiber layers and to reduce the time for lay-up. It is an alternative for step 3 in the hand lay-up procedure. In the spray-up method, liquid resin and chopped fibers are sprayed onto an open mold to build successive FRP laminations, as in Figure 14.5. The spray gun is equipped with a chopper mechanism that feeds in continuous filament rovings and cuts them into fibers of length 25 to 75 mm (1–3 in) that are added to the resin stream as it exits the nozzle. The mixing action results in random orientation of the fibers in the layer—unlike hand lay-up, in which the filaments can be oriented if desired. Another difference is that the fiber content in spray-up is limited to about 35%, compared with a maximum of around 65% in hand lay-up. This is a shortcoming of the spraying and mixing process.

Spraying can be accomplished manually using a portable spray gun or by an automated machine in which the path of the spray gun is preprogrammed and computer controlled. The automated procedure is advantageous for labor efficiency and environmental protection. Some of the volatile emissions from the liquid resins are hazardous, and the path-controlled machines can operate in sealed-off areas without

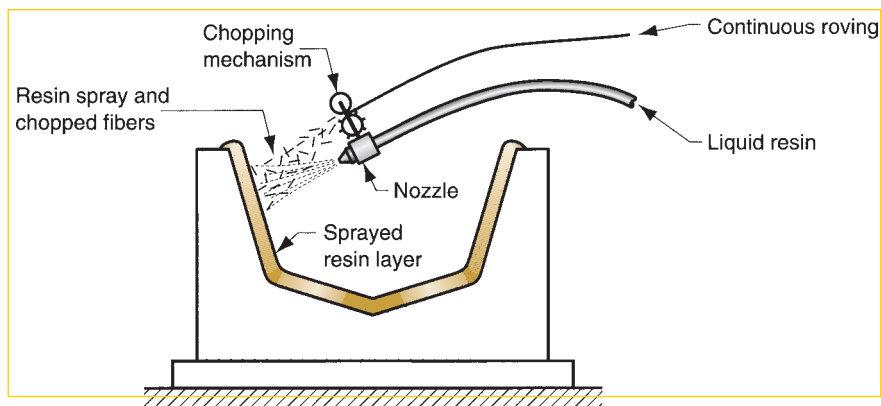


FIGURE 14.5 Spray-up method.

humans present. However, rolling is generally required for each layer, as in hand lay-up.

Products made by the spray-up method include boat hulls, bathtubs, shower stalls, automobile and truck body parts, recreational vehicle components, furniture, large structural panels, and containers. Movie and stage props are sometimes made by this method. Because products made by spray-up have randomly oriented short fibers, they are not as strong as those made by lay-up, in which the fibers are continuous and directed.

14.2.3 AUTOMATED TAPE-LAYING MACHINES

This is another attempt to automate and accelerate step 3 in the lay-up procedure. Automated tape-laying machines operate by dispensing a prepreg tape onto an open mold following a programmed path. The typical machine consists of an overhead gantry, to which is attached the dispensing head, as shown in Figure 14.6. The gantry permits x-y-z travel of the head, for positioning and following a defined continuous path. The head itself has several rotational axes, plus a shearing device to cut the tape at the end of each path. Prepreg tape widths are commonly 75 mm (3 in), although 300 mm (12 in) widths have been reported [15]; thickness is around 0.13 mm (0.005 in). The tape is stored on the machine in rolls, which are unwound and deposited along the defined path. Each lamination is placed by following a series of back-and-forth passes across the mold surface until the parallel rows of tape complete the layer.

Much of the work to develop automated tape-laying machines has been pioneered by the aircraft industry, which is eager to save labor costs and at the same time achieve the highest possible quality and uniformity in its manufactured components. The disadvantage of this and other computer numerically controlled machines is that it must be programmed, and programming takes time.



FIGURE 14.6
Automated tape-laying machine. (Courtesy of Cincinnati Milacron.)

14.2.4 CURING

Curing (step 4) is required of all thermosetting resins used in FRP laminated composites. Curing accomplishes cross-linking of the polymer, transforming it from its liquid or highly plastic condition into a hardened product. There are three principal process parameters in curing: time, temperature, and pressure.

Curing normally occurs at room temperature for the TS resins used in hand lay-up and spray-up procedures. Moldings made by these processes are often large, and heating would be difficult for such parts. In some cases, days are required before room temperature curing is sufficiently complete to remove the part. If feasible, heat is added to speed the curing reaction.

Heating is accomplished by several means. Oven curing provides heat at closely controlled temperatures; some curing ovens are equipped to draw a partial vacuum. Infrared heating can be used in applications in which it is impractical or inconvenient to place the molding in an oven.

Curing in an autoclave provides control over both temperature and pressure. An **autoclave** is an enclosed chamber equipped to apply heat and/or pressure at controlled levels. In FRP composites processing, it is usually a large horizontal cylinder with doors at either end. The term **autoclave molding** is sometimes used to refer to the curing of a prepreg laminate in an autoclave. This procedure is used extensively in the aerospace industry to produce advanced composite components of very high quality.

3 Closed Mold Processes

These molding operations are performed in molds consisting of two sections that open and close during each molding cycle. One might think that a closed mold is about twice the cost of a comparable open mold. However, tooling cost is even greater owing to the more complex equipment required in these processes. Despite their higher cost, advantages of a closed mold are (1) good finish on all part surfaces, (2) higher production rates, (3) closer control over tolerances, and (4) more complex three-dimensional shapes are possible.

The closed mold processes are divided into three classes based on their counterparts in conventional plastic molding, even though the terminology is often different when polymer matrix composites are molded: (1) compression molding, (2) transfer molding, and (3) injection molding.

14.3.1 COMPRESSION MOLDING PMC PROCESSES

In compression molding of conventional molding compounds (Section 13.7.1), a charge is placed in the lower mold section, and the sections are brought together under pressure, causing the charge to take the shape of the cavity. The mold halves are heated to cure the thermosetting polymer. When the molding is sufficiently cured, the mold is opened and the part is removed. There are several shaping processes for PMCs based on compression molding; the differences are mostly in the form of the starting materials. The flow of the resin, fibers, and other ingredients during the process is a critical factor in compression molding of FRP composites.

SMC, TMC, and BMC Molding Several of the FRP molding compounds, namely sheet molding compound (SMC), bulk molding compound (BMC), and thick molding compound (TMC), can be cut to proper size and used as the starting charge in

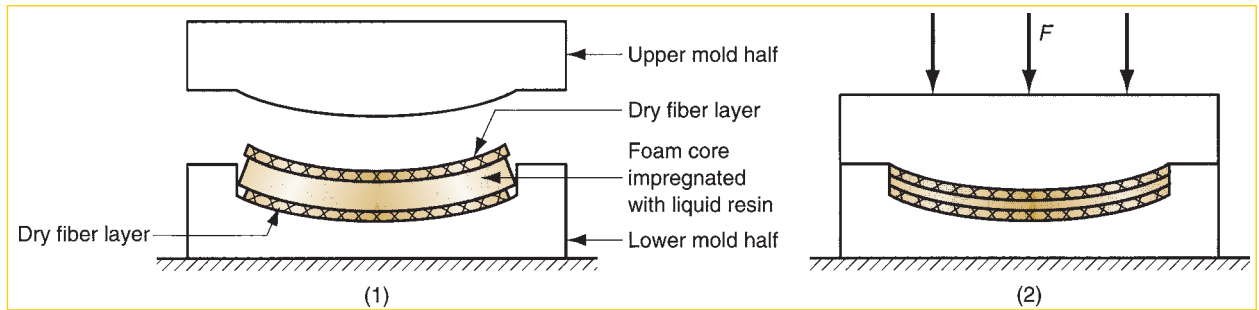


FIGURE 14.7 Elastic reservoir molding: (1) foam is placed into mold between two fiber layers; (2) mold is closed, releasing resin from foam into fiber layers.

compression molding. Refrigeration is often required to store these materials prior to shape processing. The names of the molding processes are based on the starting molding compound (i.e., **SMC molding** is when the starting charge is precut sheet molding compound; **BMC molding** uses bulk molding compound cut to size as the charge; and so on).

Preform Molding Another form of compression molding, called **preform molding** [16], involves placement of a precut mat into the lower mold section along with a polymer resin charge (e.g., pellets or sheet). The materials are then pressed between heated mold halves, causing the resin to flow and impregnate the fiber mat to produce a fiber reinforced molding. Variations of the process use either thermoplastic or thermosetting polymers.

Elastic Reservoir Molding The starting charge in elastic reservoir molding is a sandwich consisting of a center of polymer foam between two dry fiber layers. The foam core is commonly open-cell polyurethane, impregnated with liquid resin such as epoxy or polyester, and the dry fiber layers can be cloth, woven roving, or other starting fibrous form. As depicted in Figure 14.7, the sandwich is placed in the lower mold section and pressed at moderate pressure—around 0.7 MPa (100 lb/in^2). As the core is compressed, it releases the resin to wet the dry surface layers. Curing produces a lightweight part consisting of a low-density core and thin FRP skins.

14.3.2 TRANSFER MOLDING PMC PROCESSES

In conventional transfer molding (Section 13.7.2), a charge of thermosetting resin is placed in a pot or chamber, heated, and squeezed by ram action into one or more mold cavities. The mold is heated to cure the resin. The name of the process derives from the fact that the fluid polymer is transferred from the pot into the mold. It can be used to mold TS resins in which the fillers include short fibers to produce an FRP composite part. Another form of transfer molding for PMCs is called **resin transfer molding** (RTM) [6], [16]; it refers to a closed mold process in which a preform mat is placed in the lower mold section, the mold is closed, and a thermosetting resin (e.g., polyester) is transferred into the cavity under moderate pressure to impregnate the preform. To confuse matters, RTM is sometimes called **resin injection molding** [6],

[18] (the distinction between transfer molding and injection molding is blurry anyway, as the reader may have noted in Chapter 13). RTM has been used to manufacture products such as bathtubs, swimming pool shells, bench and chair seats, and hulls for small boats.

Several enhancements of the basic RTM process have been developed [8]. One enhancement, called **advanced RTM**, uses high-strength polymers such as epoxy resins and continuous fiber reinforcement instead of mats. Applications include aerospace components, missile fins, and snow skis. Two additional processes are thermal expansion resin transfer molding and ultimately reinforced thermoset resin injection. **Thermal expansion resin transfer molding** (TERTM) is a patented process of TERTM, Inc. that consists of the following steps [8]: (1) A rigid polymer foam (e.g., polyurethane) is shaped into a preform. (2) The preform is enclosed in a fabric reinforcement and placed in a closed mold. (3) A thermosetting resin (e.g., epoxy) is injected into the mold to impregnate the fabric and surround the foam. (4) The mold is heated to expand the foam, fill the mold cavity, and cure the resin. **Ultimately reinforced thermoset resin injection** (URTRI) is similar to TERTM except that the starting foam core is cast epoxy embedded with miniature hollow glass spheres.

14.3.3 INJECTION MOLDING PMC PROCESSES

Injection molding is noted for low-cost production of plastic parts in large quantities. Although it is most closely associated with thermoplastics, the process can also be adapted to thermosets (Section 13.6.5).

Conventional Injection Molding In PMC shape processing, injection molding is used for both TP- and TS-type FRPs. In the TP category, virtually all thermoplastic polymers can be reinforced with fibers. Chopped fibers must be used; if continuous fibers were used, they would be reduced anyway by the action of the rotating screw in the barrel. During injection from the chamber into the mold cavity, the fibers tend to become aligned during their journey through the nozzle. Designers can sometimes exploit this feature to optimize directional properties through part design, location of gates, and cavity orientation relative to the gate [13].

Whereas TP molding compounds are heated and then injected into a cold mold, TS polymers are injected into a heated mold for curing. Control of the process with thermosets is trickier because of the risk of premature cross-linking in the injection chamber. Subject to the same risk, injection molding can be applied to fiber-reinforced TS plastics in the form of pelletized molding compound and dough molding compound.

Reinforced Reaction Injection Molding Some thermosets cure by chemical reaction rather than heat; these resins can be molded by reaction injection molding (Section 13.6.5). In RIM, two reactive ingredients are mixed and immediately injected into a mold cavity where curing and solidification of the chemicals occur rapidly. A closely related process includes reinforcing fibers, typically glass, in the mixture. In this case, the process is called reinforced reaction injection molding (RRIM). Its advantages are similar to those in RIM, with the added benefit of fiber reinforcement. RRIM is used extensively in auto body and truck cab applications for bumpers, fenders, and other body parts.

14.4 Other PMC Shaping Processes

This section describes the remaining categories of PMC shaping processes: filament winding, pultrusion processes, and miscellaneous PMC shaping processes.

14.4.1 FILAMENT WINDING

Filament winding is a process in which resin-impregnated continuous fibers are wrapped around a rotating mandrel that has the internal shape of the desired FRP product. The resin is subsequently cured and the mandrel removed. Hollow axisymmetric components (usually circular in cross section) are produced, as well as some irregular shapes. The most common form of the process is depicted in Figure 14.8. A band of fiber rovings is pulled through a resin bath immediately before being wound in a helical pattern onto a cylindrical mandrel. Continuation of the winding pattern finally completes a surface layer of one filament thickness on the mandrel. The operation is repeated to form additional layers, each having a criss-cross pattern with the previous, until the desired part thickness has been obtained.

There are several methods by which the fibers can be impregnated with resin: (1) **wet winding**, in which the filament is pulled through the liquid resin just before winding, as in the figure; (2) **prepreg winding** (also called **dry winding**), in which filaments preimpregnated with partially cured resin are wrapped around a heated mandrel; and (3) **postimpregnation**, in which filaments are wound onto a mandrel and then impregnated with resin by brushing or other technique.

Two basic winding patterns are used in filament winding: (a) helical and (b) polar (Figure 14.9). In **helical winding**, the filament band is applied in a spiral pattern around the mandrel, at a helix angle θ . If the band is wrapped with a helix angle approaching 90° , so that the winding advance is one bandwidth per revolution and the filaments form nearly circular rings around the mandrel, this is referred to as a **hoop winding**; it is a special case of helical winding. In **polar winding**, the filament is wrapped around the long axis of the mandrel, as in Figure 14.9(b); after each longitudinal revolution, the mandrel is indexed (partially rotated) by one bandwidth, so that a hollow enclosed shape is gradually created. Hoop and polar patterns can

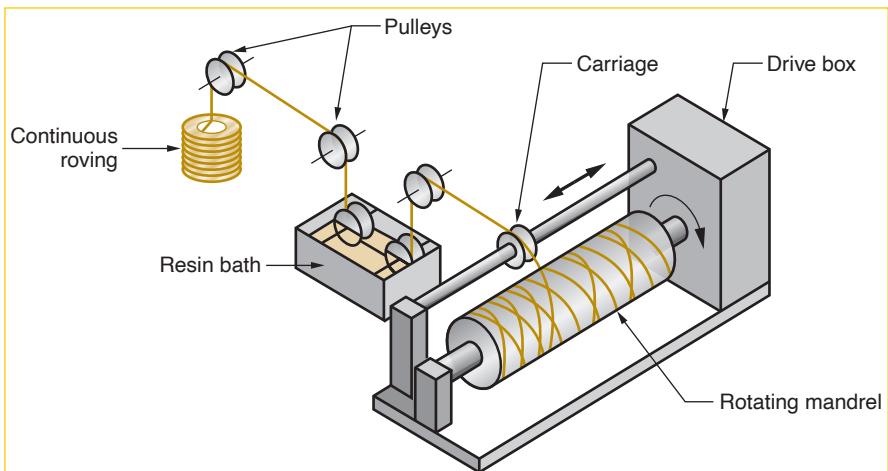
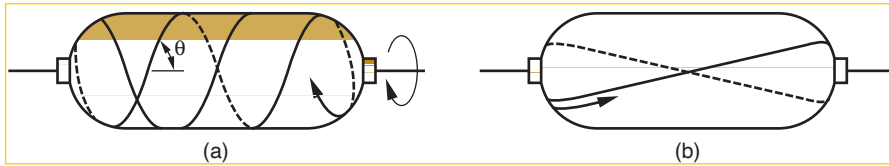


FIGURE 14.8 Filament winding.

FIGURE 14.9 Two basic winding patterns in filament winding: (a) helical and (b) polar.



be combined in successive windings of the mandrel to produce adjacent layers with filament directions that are approximately perpendicular; this is called a **bi-axial winding** [3].

Filament winding machines have motion capabilities similar to those of an engine lathe (Section 21.2.3). The typical machine has a drive motor to rotate the mandrel and a powered feed mechanism to move the carriage. Relative motion between mandrel and carriage must be controlled to accomplish a given winding pattern. In helical winding, the relationship between helix angle and the machine parameters can be expressed as follows:

$$\tan \theta = \frac{v_c}{\pi D N} \quad (14.1)$$

where θ = helix angle of the windings on the mandrel, as in Figure 14.9(a); v_c = speed at which the carriage traverses in the axial direction, m/s (in/sec); D = diameter of the mandrel, m (in); and N = rotational speed, 1/s (rev/sec).

Various types of control are available in filament winding machines. Modern equipment uses **computer numerical control** (CNC, Section 37.3), in which mandrel rotation and carriage speed are independently controlled to permit greater adjustment and flexibility in the relative motions. CNC is especially useful in helical winding of contoured shapes, as in Figure 14.10. As indicated in Equation (14.1), the ratio v_c/DN must remain fixed to maintain a constant helix angle θ . Thus, either v_c and/or N must be adjusted on-line to compensate for changes in D .

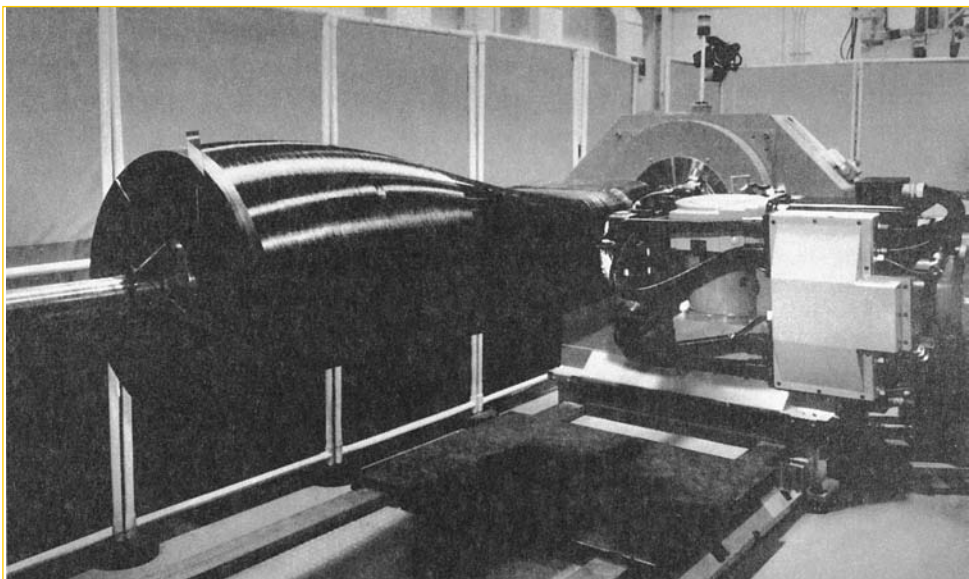


FIGURE 14.10 Filament winding machine. (Courtesy of Cincinnati Milacron.)

The **mandrel** is the special tooling that determines the geometry of the filament-wound part. For part removal, mandrels must be capable of collapsing after winding and curing. Various designs are possible, including inflatable/deflatable mandrels, collapsible metal mandrels, and mandrels made of soluble salts or plasters.

Applications of filament winding are often classified as aerospace or commercial [15], the engineering requirements being more demanding in the first category. Aerospace applications include rocket-motor cases, missile bodies, radomes, helicopter blades, and airplane tail sections and stabilizers. These components are made of advanced composites and hybrid composites (Section 9.4.1), with epoxy resins being most common and reinforced with fibers of carbon, boron, Kevlar, and glass. Commercial applications include storage tanks, reinforced pipes and tubing, drive shafts, wind-turbine blades, and lightning rods; these are made of conventional FRPs. Polymers include polyester, epoxy, and phenolic resins; glass is the common reinforcing fiber.

14.4.2 PULTRUSION PROCESSES

The basic pultrusion process was developed around 1950 for making fishing rods of glass fiber-reinforced polymer (GFRP). The process is similar to extrusion (hence the similarity in name), but it involves pulling of the workpiece (so the prefix “pul-” is used in place of “ex-”). Like extrusion, pultrusion produces continuous, straight sections of constant cross section. A related process, called pulforming, can be used to make parts that are curved and may have variations in cross section throughout their lengths.

Pultrusion Pultrusion is a process in which continuous fiber rovings are dipped into a resin bath and pulled through a shaping die where the impregnated resin cures. The setup is sketched in Figure 14.11, which shows the cured product being cut into long, straight sections. The sections are reinforced throughout their length by continuous fibers. Like extrusion, the pieces have a constant cross section, whose profile is determined by the shape of the die opening.

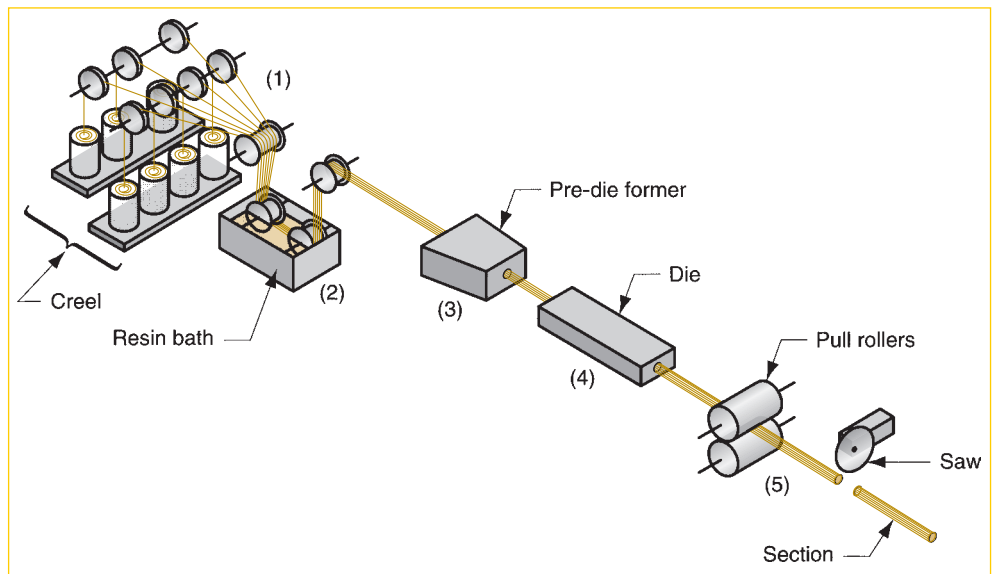


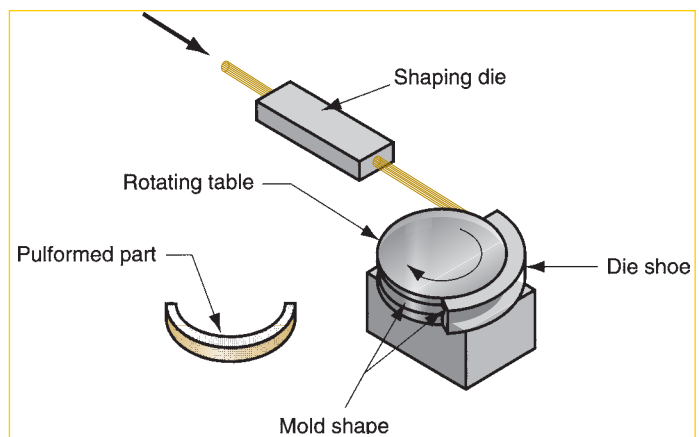
FIGURE 14.11
Pultrusion process (see
text for interpretation of
sequence numbers).

The process consists of five steps (identified in the sketch) performed in a continuous sequence [3]: (1) **filament feeding**, in which the fibers are unreeled from a creel (shelves with skewers that hold filament bobbins); (2) **resin impregnation**, in which the fibers are dipped in the uncured liquid resin; (3) **pre-die forming**—the collection of filaments is gradually shaped into the approximate cross section desired; (4) **shaping and curing**, in which the impregnated fibers are pulled through the heated die whose length is 1–1.5 m (3–5 ft) and whose inside surfaces are highly polished; and (5) **pulling and cutting**—pullers are used to draw the cured length through the die, after which it is cut by a cut-off wheel with SiC or diamond grits.

Common resins used in pultrusion are unsaturated polyesters, epoxies, and silicones, all thermosetting polymers. There are difficulties in processing with epoxy polymers because of sticking on the die surface. Thermoplastics have also been studied for possible applications [3]. E-glass is by far the most widely used reinforcing material; proportions range from 30% to 70%. Modulus of elasticity and tensile strength increase with reinforcement content. Products made by pultrusion include solid rods, tubing, long and flat sheets, structural sections (such as channels, angled and flanged beams), tool handles for high-voltage work, and third-rail covers for subways.

Pulforming The pultrusion process is limited to straight sections of constant cross section. There is also a need for long parts with continuous fiber reinforcement that are curved rather than straight and whose cross sections may vary throughout the length. The pulforming process is suited to these less-regular shapes. Pulforming can be defined as pultrusion with additional steps to form the length into a semicircular contour and alter the cross section at one or more locations along the length. A sketch of the equipment is illustrated in Figure 14.12. After exiting the shaping die, the continuous workpiece is fed into a rotating table with negative molds positioned around its periphery. The work is forced into the mold cavities by a die shoe, which squeezes the cross section at various locations and forms the curvature in the length. The diameter of the table determines the radius of the part. As the work leaves the die table, it is cut to length to provide discrete parts. Resins and fibers used in pulforming are similar to those for pultrusion. An important application of the process is production of automobile leaf springs.

FIGURE 14.12
Pulforming process
(not shown in the
sketch is the cut-off
of the pulformed part).



14.4.3 MISCELLANEOUS PMC SHAPING PROCESSES

Additional PMC shaping processes worth noting include centrifugal casting, tube rolling, continuous laminating, and cutting. In addition, many of the traditional thermoplastic shaping processes are applicable to (short-fiber) FRPs based on TP polymers; these include blow molding, thermoforming, and extrusion.

Centrifugal Casting This process is ideal for cylindrical products such as pipes and tanks. The process is the same as its counterpart in metal casting (Section 11.3.5). Chopped fibers combined with liquid resin are poured into a fast-rotating cylindrical mold that is heated. Centrifugal force presses the ingredients against the mold wall, where curing takes place. The resulting inner surfaces of the part are quite smooth. Part shrinkage or use of split molds permits part removal.

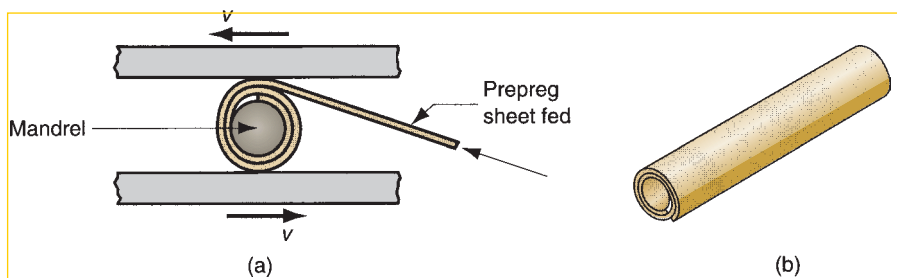
Tube Rolling FRP tubes can be fabricated from prepreg sheets by a rolling technique [11], shown in Figure 14.13. Such tubes are used in bicycle frames and space trusses. In the process, a precut prepreg sheet is wrapped around a cylindrical mandrel several times to obtain a tube wall of multiple sheet thicknesses. The rolled sheets are then encased in a heat-shrinking sleeve and oven cured. As the sleeve contracts, entrapped gases are squeezed out the ends of the tube. When curing is complete, the mandrel is removed to yield a rolled FRP tube. The operation is simple, and tooling cost is low. There are variations in the process, such as using different wrapping methods or using a steel mold to enclose the rolled prepreg tube for better dimensional control.

Continuous Laminating Fiber-reinforced plastic panels, sometimes translucent and/or corrugated, are used in construction. The process to produce them consists of (1) impregnating layers of glass fiber mat or woven fabric by dipping in liquid resin or by passing beneath a doctor blade; (2) gathering between cover films (cellophane, polyester, or other polymer); and (3) compacting between squeeze rolls and curing. Corrugation (4) is added by formed rollers or mold shoes.

Cutting Methods FRP laminated composites must be cut in both uncured and cured states. Uncured materials (prepregs, preforms, SMCs, and other starting forms) must be cut to size for lay-up, molding, and so on. Typical cutting tools include knives, scissors, power shears, and steel-rule blanking dies. Also used are nontraditional cutting methods, such as laser beam cutting and water jet cutting (Chapter 25).

Cured FRPs are hard, tough, abrasive, and difficult to cut; but cutting is necessary in many FRP shaping processes to trim excess material, cut holes and outlines, and so forth. For fiberglass-reinforced plastics, cemented carbide cutting tools and

FIGURE 14.13 Tube rolling, showing (a) one possible means of wrapping FRP prepregs around a mandrel, and (b) the completed tube after curing and removal of mandrel.



high-speed steel saw blades must be used. For some advanced composites (e.g., boron-epoxy), diamond cutting tools obtain best results. Water jet cutting is also used with good success on cured FRPs; this process reduces the dust and noise problems associated with conventional sawing methods.

14.5 Rubber Processing and Shaping

Although pneumatic tires date from the late 1880s, rubber technology can be traced to the discovery of vulcanization in 1839 (Historical Note 8.2), the process by which raw natural rubber is transformed into a usable material through cross-linking of the polymer molecules. During its first century, the rubber industry was concerned only with the processing of natural rubber. Around World War II, synthetic rubbers were developed (Historical Note 8.3), and today they account for the majority of rubber production.

Production of rubber goods can be divided into two basic steps: (1) production of the rubber itself, and (2) processing of the rubber into finished goods. Production of rubber differs, depending on whether it is natural or synthetic. The difference is in the raw materials. Natural rubber (NR) is produced as an agricultural crop, whereas most synthetic rubbers are made from petroleum.

Production of rubber is followed by processing into final products; this consists of (1) compounding, (2) mixing, (3) shaping, and (4) vulcanizing. Processing techniques for natural and synthetic rubbers are virtually the same, differences being in the chemicals used to effect vulcanization (cross-linking). This sequence does not apply to thermoplastic elastomers, whose shaping techniques are the same as for other thermoplastic polymers.

There are several distinct industries involved in the production and processing of rubber. Production of raw natural rubber might be classified as farming because latex, the starting ingredient for natural rubber, is grown on large plantations located in tropical climates. By contrast, synthetic rubbers are produced by the petrochemical industry. Finally, the processing of these materials into tires, shoe soles, and other rubber products occurs at processor (fabricator) plants. The processors are commonly known as the rubber industry. Some of the great names in this industry include Goodyear, B. F. Goodrich, and Michelin. The importance of the tire is reflected in these names.

14.5.1 PRODUCTION OF RUBBER

This section surveys the production of rubber before it goes to the processor, distinguishing between natural rubber and synthetic rubber.

Natural Rubber Natural rubber is tapped from rubber trees (*Hevea brasiliensis*) as latex. The trees are grown on plantations in Southeast Asia and other parts of the world. Latex is a colloidal dispersion of solid particles of the polymer polyisoprene (Section 8.4.2) in water. Polyisoprene is the chemical substance that comprises rubber, and its content in the emulsion is about 30%. The latex is collected in large tanks, thus blending the yield of many trees together.

The preferred method of recovering rubber from the latex involves coagulation. The latex is first diluted with water to about half its natural concentration. An acid such as formic acid (HCOOH) or acetic acid (CH_3COOH) is added to cause the

latex to coagulate after about 12 hours. The coagulum, now in the form of soft solid slabs, is then squeezed through a series of rolls that drive out most of the water and reduce the thickness to about 3 mm (1/8 in). The final rolls have grooves that impart a criss-cross pattern to the resulting sheets. The sheets are then draped over wooden frames and dried in smokehouses. The hot smoke contains creosote, which prevents mildew and oxidation of the rubber. Several days are normally required to complete the drying process. The resulting rubber, now in a form called **ribbed smoked sheet** is folded into large bales for shipment to the processor. This raw rubber has a characteristic dark brown color. In some cases, the sheets are dried in hot air rather than smokehouses, and the term **air-dried sheet** is applied; this is considered to be a better grade of rubber. A still better grade, called **pale crepe** rubber, involves two coagulation steps; the first removes undesirable components of the latex, then the resulting coagulum is subjected to a more involved washing and mechanical working procedure, followed by warm air drying. The color of pale crepe rubber approaches a light tan.

Synthetic Rubber The various types of synthetic rubber were identified in Section 8.4.3. Most synthetics are produced from petroleum by the same polymerization techniques used to synthesize other polymers (Section 8.1.1). However, unlike thermoplastic and thermosetting polymers, which are normally supplied to the fabricator as pellets or liquid resins, synthetic rubbers are supplied to rubber processors in the form of large bales. The industry has developed a long tradition of handling natural rubber in these unit loads.

14.5.2 COMPOUNDING AND MIXING

Rubber is always compounded with additives. It is through compounding that the specific rubber is designed to satisfy the requirements of a given application in terms of properties, cost, and processability. Compounding adds chemicals for vulcanization. Sulfur has traditionally been used for this purpose. The vulcanization process and the chemicals used to accomplish it are discussed in Section 14.5.4.

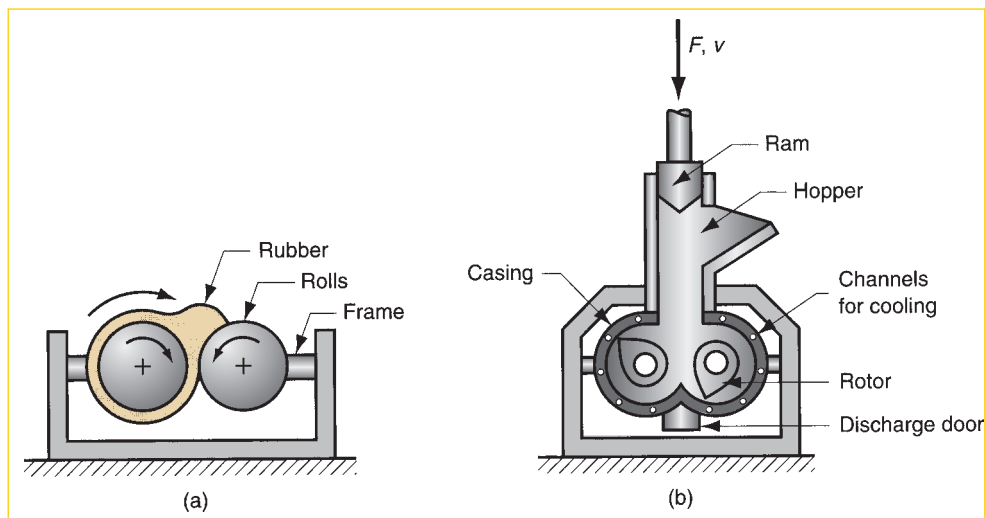
Additives include fillers that act either to enhance the rubber's mechanical properties (reinforcing fillers) or to extend the rubber to reduce cost (nonreinforcing fillers). The single most important reinforcing filler in rubber is **carbon black**, a colloidal form of carbon, black in color, obtained from the thermal decomposition of hydrocarbons (soot). Its effect is to increase tensile strength and resistance to abrasion and tearing of the final rubber product. Carbon black also provides protection from ultraviolet radiation. These enhancements are especially important in tires. Most rubber parts are black in color because of their carbon black content.

Although carbon black is the most important filler, others are also used. They include china clays—hydrous aluminum silicates ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$)—which provide less reinforcing than carbon black but are used when the black color is not acceptable; calcium carbonate (CaCO_3), which is a nonreinforcing filler; silica (SiO_2), which can serve reinforcing or nonreinforcing functions depending on particle size; and other polymers, such as styrene, PVC, and phenolics. Reclaimed (recycled) rubber is also added as a filler in some rubber products, but usually not in proportions exceeding 10%.

Other additives compounded with the rubber include antioxidants, to retard aging by oxidation; fatigue- and ozone-protective chemicals; coloring pigments;

FIGURE 14.14

Mixers used in rubber processing: (a) two-roll mill and (b) Banbury-type internal mixer. These machines can also be used for mastication of natural rubber.



plasticizers and softening oils; blowing agents in the production of foamed rubber; and mold-release compounds.

Many products require filament reinforcement to reduce extensibility but retain the other desirable properties of rubber. Tires and conveyor belts are notable examples. Filaments used for this purpose include cellulose, nylon, and polyester. Fiberglass and steel are also used as reinforcements (e.g., steel-belted radial tires). These continuous fiber materials must be added during the shaping process; they are not mixed with the other additives.

The additives must be thoroughly mixed with the base rubber to achieve uniform dispersion of the ingredients. Uncured rubbers possess high viscosity. Mechanical working experienced by the rubber can increase its temperature up to 150°C (300°F). If vulcanizing agents were present from the start of mixing, premature vulcanization would result—the rubber processor’s nightmare [14]. Accordingly, a two-stage mixing process is usually employed. In the first stage, carbon black and other nonvulcanizing additives are combined with the raw rubber. The term **masterbatch** is used for this first-stage mixture. After thorough mixing has been accomplished, and time for cooling has been allowed, the second stage is carried out in which the vulcanizing agents are added.

Equipment for mixing includes the two-roll mill and internal mixers such as the Banbury mixer, Figure 14.14. The **two-roll mill** consists of two parallel rolls, supported in a frame so they can be brought together to obtain a desired “nip” (gap size), and driven to rotate at the same or slightly different speeds. An **internal mixer** has two rotors enclosed in a casing, as in Figure 14.14(b) for the Banbury-type internal mixer. The rotors have blades and rotate in opposite directions at different speeds, causing a complex flow pattern in the contained mixture.

14.5.3 SHAPING AND RELATED PROCESSES

Shaping processes for rubber products can be divided into four basic categories: (1) extrusion, (2) calendering, (3) coating, and (4) molding and casting. Most of these processes are discussed in the previous chapter. Here the special issues that arise when they are applied to rubber are examined. Some products require several basic processes plus assembly work in their manufacture, tires for example.

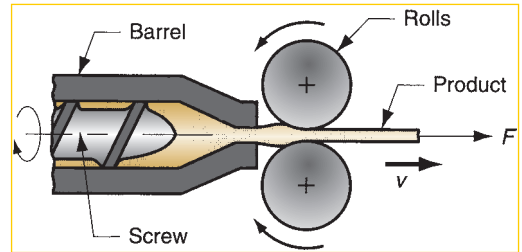


FIGURE 14.15 Roller die process: extrusion of rubber followed by rolling.

Extrusion Extrusion of polymers was discussed in the preceding chapter. Screw extruders are generally used for extrusion of rubber. As with extrusion of thermosetting plastics, the L/D ratio of the extruder barrels is less than for thermoplastics, typically in range 10 to 15, to reduce the risk of premature cross-linking. Die swell occurs in rubber extrudates, because the polymer is in a highly plastic condition and exhibits the memory property. It has not yet been vulcanized.

Calendering This process involves passing rubber stock through a series of gaps of decreasing size made by a stand of rotating rolls (Section 13.3). The rubber process must be operated at lower temperatures than for thermoplastic polymers to avoid premature vulcanization. Also, equipment used in the rubber industry is of heavier construction than that used for thermoplastics, because rubber is more viscous and harder to form. The output of the process is a rubber sheet of thickness determined by the final roll gap; again, swelling occurs in the sheet, causing its thickness to be slightly greater than the gap size. Calendering can also be used to coat or impregnate textile fabrics to produce rubberized fabrics.

There are problems in producing thick sheet by either extrusion or calendering. Thickness control is difficult in the former process, and air entrapment occurs in the latter. These problems are largely solved when extrusion and calendering are combined in the **roller die** process (Figure 14.15). The extruder die is a slit that feeds the calender rolls.

Coating Coating or impregnating fabrics with rubber is an important process in the rubber industry. These composite materials are used in automobile tires, conveyor belts, inflatable rafts, and waterproof cloth for tarpaulins, tents, and rain coats. The **coating** of rubber onto substrate fabrics includes a variety of processes. Calendering is one of the coating methods. Figure 14.16 illustrates one possible way in which the fabric is fed into the calendering rolls to obtain a reinforced rubber sheet.

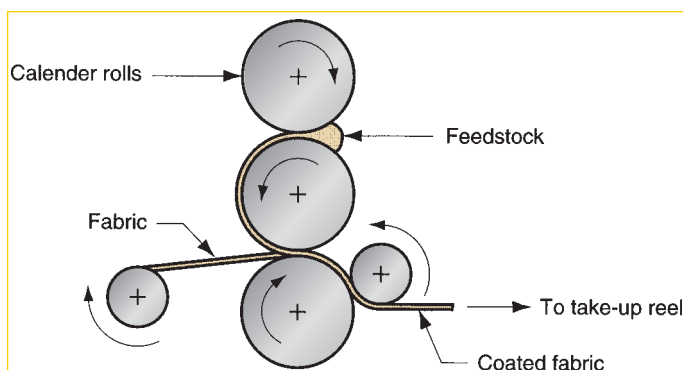


FIGURE 14.16 Coating of fabric with rubber using a calendering process.

Alternatives to calendaring include skimming, dipping, and spraying. In the **skimming** process, a thick solution of rubber compound in an organic solvent is applied to the fabric as it is unreeled from a supply spool. The coated fabric passes under a doctor blade that skims the solvent to the proper thickness, and then moves into a steam chamber where the solvent is driven off by heat. As its name suggests, **dipping** involves temporary immersion of the fabric into a highly fluid solution of rubber, followed by drying. In **spraying**, a spray gun is used to apply the rubber solution.

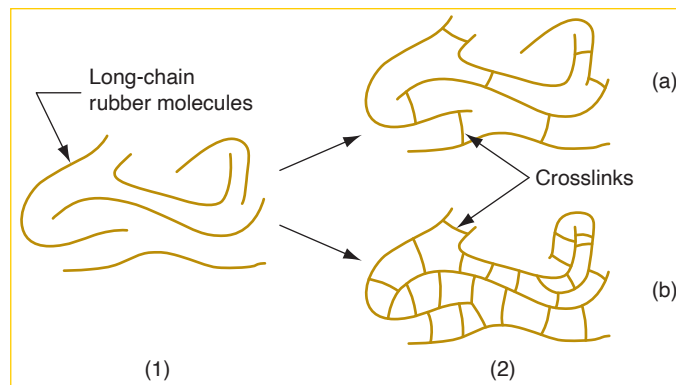
Molding and Casting Molded articles include shoe soles and heels, gaskets and seals, suction cups, and bottle stops. Many foamed rubber parts are produced by molding. In addition, molding is an important process in tire production. Principal molding processes for rubber are (1) compression molding, (2) transfer molding, and (3) injection molding. Compression molding is the most important technique because of its use in tire manufacture. Curing (vulcanizing) is accomplished in the mold in all three processes, this representing a departure from the shaping methods already discussed, which require a separate vulcanizing step. With injection molding of rubber, there are risks of premature curing similar to those faced in the same process when applied to thermosetting plastics. Advantages of injection molding over traditional methods for producing rubber parts include better dimensional control, less scrap, and shorter cycle times. In addition to its use in the molding of conventional rubbers, injection molding is also applied for thermoplastic elastomers. Because of high mold costs, large production quantities are required to justify injection molding.

A form of casting, called **dip casting**, is used for producing rubber gloves and overshoes. It involves submersion of a positive mold in a liquid polymer (or a heated form into plastisol) for a certain duration (the process may involve repeated dip-pings) to form the desired thickness. The coating is then stripped from the form and cured to cross-link the rubber.

14.5.4 VULCANIZATION

Vulcanization is the treatment that accomplishes cross-linking of elastomer molecules, so that the rubber becomes stiffer and stronger but retains extensibility. It is a critical step in the rubber processing sequence. On a submicroscopic scale, the process can be pictured as in Figure 14.17, in which the long-chain molecules of

FIGURE 14.17 Effect of vulcanization on the rubber molecules: (1) raw rubber; (2) vulcanized (cross-linked) rubber. Variations of (2) include (a) soft rubber, low degree of cross-linking; and (b) hard rubber, high degree of cross-linking.



the rubber become joined at certain tie points, the effect of which is to reduce the ability of the elastomer to flow. A typical soft rubber has one or two cross-links per thousand units (mers). As the number of cross-links increases, the polymer becomes stiffer and behaves more like a thermosetting plastic (hard rubber).

Vulcanization, as it was first invented by Charles Goodyear in 1839, involved the use of sulfur (about 8 parts by weight of S mixed with 100 parts of natural rubber) at a temperature of 140°C (280°F) for about 5 hours. No other chemicals were included in the process. Vulcanization with sulfur alone is no longer used as a commercial treatment today, because of the long curing times. Various other chemicals, including zinc oxide (ZnO) and stearic acid ($\text{C}_{18}\text{H}_{36}\text{O}_2$), are combined with smaller doses of sulfur to accelerate and strengthen the treatment. The resulting cure time is 15 to 20 minutes for a typical passenger car tire. In addition, various nonsulfur vulcanizing treatments have been developed.

In rubber-molding processes, vulcanization is accomplished in the mold by maintaining the mold temperature at the proper level for curing. In the other forming processes, vulcanization is performed after the part has been shaped. The treatments generally divide between batch processes and continuous processes. Batch methods include the use of an *autoclave*, a steam-heated pressure vessel; and *gas curing*, in which a heated inert gas such as nitrogen cures the rubber. Many of the basic shaping processes make a continuous product, and if the output is not cut into discrete pieces, continuous vulcanization is appropriate. Continuous methods include *high-pressure steam*, suited to the curing of rubber coated wire and cable; *hot-air tunnel*, for cellular extrusions and carpet underlays [5]; and *continuous drum cure*, in which continuous rubber sheets (e.g., belts and flooring materials) pass through one or more heated rolls to effect vulcanization.

14.5.5 PROCESSING OF THERMOPLASTIC ELASTOMERS

A thermoplastic elastomer (TPE) is a thermoplastic polymer that possesses the properties of a rubber (Section 8.4.3); the term *thermoplastic rubber* is also used. TPEs can be processed like thermoplastics, but their applications are those of an elastomer. The most common shaping processes are injection molding and extrusion, which are generally more economical and faster than the traditional processes used for rubbers that must be vulcanized. Molded products include shoe soles, athletic footwear, and automotive components such as fender extensions and corner panels (but not tires—TPEs have been found to be unsatisfactory for that application). Extruded items include insulation coating for electrical wire, tubing for medical applications, conveyor belts, and sheet and film stock. Other shaping techniques for TPEs include blow molding and thermoforming (Sections 13.8 and 13.9); these processes cannot be used for vulcanized rubbers.

14.6 Manufacture of Tires and Other Rubber Products

Tires are the principal product of the rubber industry, accounting for about three-fourths of total tonnage. Other important products include footwear, hose, conveyor belts, seals, shock-absorbing components, foamed rubber products, and sports equipment.

14.6.1 TIRES

Pneumatic tires are critical components of the vehicles on which they are mounted. They are used on automobiles, trucks, buses, farm tractors, earth-moving equipment, military vehicles, bicycles, motorcycles, and aircraft. Tires support the weight of the vehicle and the passengers and cargo on board; they transmit the motor torque to propel the vehicle (except on aircraft); and they absorb vibrations and shock to provide a comfortable ride.

Tire Construction and Production Sequence A tire is an assembly of many parts, whose manufacture is unexpectedly complex. A passenger car tire consists of about 50 individual pieces; a large earthmover tire may have as many as 175. To begin with, there are three basic tire constructions: (a) diagonal ply, (b) belted bias, and (c) radial ply, pictured in Figure 14.18. In all three cases, the internal structure of the tire, known as the **carcass**, consists of multiple layers of rubber-coated cords, called **plies**. The cords are strands of various materials such as nylon, polyester, fiberglass, and steel, which provide inextensibility to reinforce the rubber in the carcass. The **diagonal ply tire** has the cords running diagonally, but in perpendicular directions in adjacent layers. A typical diagonal ply tire may have four plies. The **belted bias tire** is constructed of diagonal plies with opposite bias but adds several more layers around the outside periphery of the carcass. These **belts** increase the stiffness of the tire in the tread area and limit its diametric expansion during inflation. The cords in the belt also run diagonally, as indicated in the sketch.

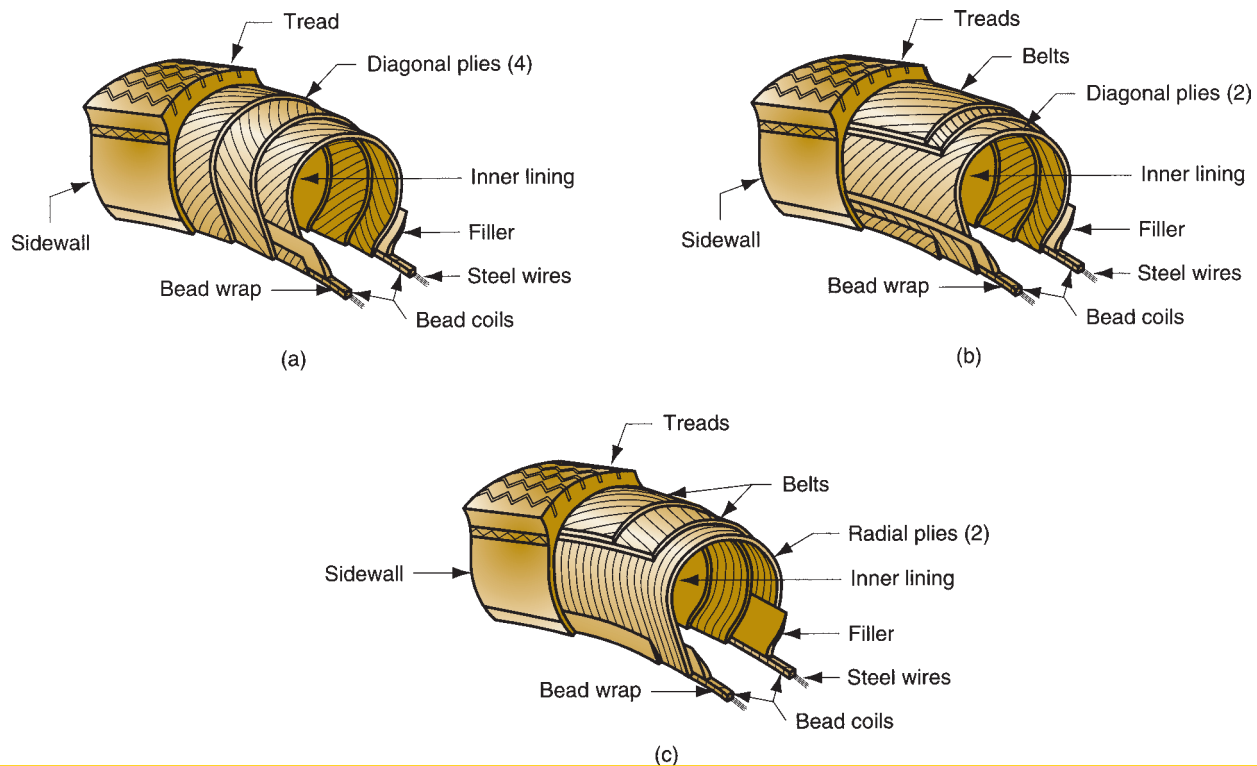


FIGURE 14.18 Three principal tire constructions: (a) diagonal ply, (b) belted bias, and (c) radial ply.

A **radial tire** has plies running radially rather than diagonally; it also uses belts around the periphery for support. A **steel-belted radial** is a tire in which the circumferential belts have cords made of steel. The radial construction provides a more flexible sidewall which tends to reduce stress on the belts and treads as they continually deform on contact with the flat road surface during rotation. This effect is accompanied by greater tread life, improved cornering and driving stability, and a better ride at high speeds.

In each construction, the carcass is covered by solid rubber that reaches a maximum thickness in the tread area. The carcass is also lined on the inside with a rubber coating. For tires with inner tubes, the inner liner is a thin coating applied to the innermost ply during its fabrication. For tubeless tires, the inner liner must have low permeability because it holds the air pressure; it is generally a laminated rubber.

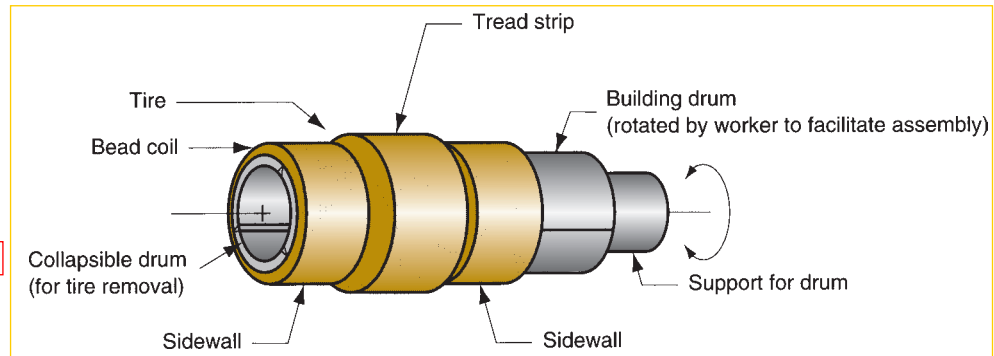
Tire production can be summarized in three steps: (1) preforming of components, (2) building the carcass and adding rubber strips to form the sidewalls and treads, and (3) molding and curing the components into one integral piece. The descriptions of these steps that follow are typical; there are variations in processing depending on construction, tire size, and type of vehicle on which the tire will be used.

Preforming of Components As Figure 14.18 shows, the carcass consists of a number of separate components, most of which are rubber or reinforced rubber. These, as well as the sidewall and tread rubber, are produced by continuous processes and then pre-cut to size and shape for subsequent assembly. The components, labeled in Figure 14.18, and the preforming processes to fabricate them are:

- **Bead coil.** Continuous steel wire is rubber-coated, cut, coiled, and the ends joined.
- **Plies.** Continuous fabric (textile, nylon, fiber glass, steel) is rubber coated in a calendering process and pre-cut to size and shape.
- **Inner lining.** For tube tires, the inner liner is calendered onto the innermost ply. For tubeless tires, the liner is calendered as a two-layer laminate.
- **Belts.** Continuous fabric is rubber coated (similar to plies), and cut at different angles for better reinforcement; then made into a multi-ply belt.
- **Tread.** Extruded as continuous strip; then cut and preassembled to belts.
- **Sidewall.** Extruded as continuous strip; then cut to size and shape.

Building the Carcass The carcass is traditionally assembled using a machine known as a **building drum**, whose main element is a cylindrical arbor that rotates. Pre-cut strips that form the carcass are built up around this arbor in a step-by-step procedure. The layered plies that form the cross section of the tire are anchored on opposite sides of the rim by two bead coils. The bead coils consist of multiple strands of high-strength steel wire. Their function is to provide a rigid support when the finished tire is mounted on the wheel rim. Other components are combined with the plies and bead coils. These include various wrappings and filler pieces to give the tire the proper strength, heat resistance, air retention, and fitting to the wheel rim. After these parts are placed around the arbor and the proper number of plies have been added, the belts are applied. This is followed by the outside rubber that will become

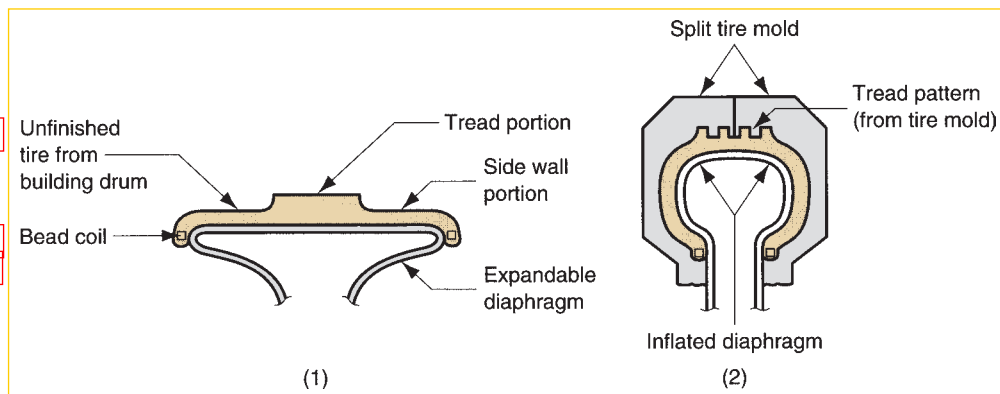
FIGURE 14.19 Tire just before removal from building drum, prior to molding and curing.



the sidewall and tread.¹ At this point in the process, the treads are rubber strips of uniform cross section—the tread design is added later in molding. The building drum is collapsible, so that the unfinished tire can be removed when finished. The form of the tire at this stage is roughly tubular, as portrayed in Figure 14.19.

Molding and Curing Tire molds are usually two-piece construction (split molds) and contain the tread pattern to be impressed on the tire. The mold is bolted into a press, one half attached to the upper platen (the lid) and the bottom half fastened to the lower platen (the base). The uncured tire is placed over an expandable diaphragm and inserted between the mold halves, as in Figure 14.20. The press is then closed and the diaphragm expanded, so that the soft rubber is pressed against the cavity of the mold. This causes the tread pattern to be imparted to the rubber. At the same time, the rubber is heated, both from the outside by the mold and from the inside by the diaphragm. Circulating hot water or steam under pressure are used to heat the diaphragm. The duration of this curing step depends on the thickness of the tire wall. A typical passenger tire can be cured in about 15 minutes. Bicycle tires cure in about 4 minutes, whereas tires for large earth moving equipment take several hours to cure. After curing is completed, the tire is cooled and removed from the press.

FIGURE 14.20 Tire molding (tire is shown in cross-sectional view): (1) the uncured tire is placed over expandable diaphragm; (2) the mold is closed and the diaphragm is expanded to force uncured rubber against mold cavity, impressing tread pattern into rubber; mold and diaphragm are heated to cure rubber.



¹Technically, the tread and sidewall are not usually considered to be components of the carcass.

14.6.2 OTHER RUBBER PRODUCTS

Most other rubber products are made by less complex processes. Rubber belts are widely used in conveyors and mechanical power transmission systems. As with tires, rubber is an ideal material for these products, but the belt must have flexibility but little or no extensibility. Accordingly, it is reinforced with fibers, commonly polyester or nylon. Fabrics of these polymers are usually coated in calendering operations, assembled together to obtain the required number of plies and thickness, and subsequently vulcanized by continuous or batch heating processes.

Rubber hose can be either plain or reinforced. Plain hose is extruded tubing. Reinforced tube consists of an inner tube, a reinforcing layer (sometimes called the carcass), and a cover. The internal tubing is extruded of a rubber that has been compounded for the particular substance that will flow through it. The reinforcement layer is applied to the tube in the form of a fabric, or by spiraling, knitting, braiding, or other application method. The outer layer is compounded to resist environmental conditions. It is applied by extrusion, using rollers, or other techniques.

Footwear components include soles, heels, rubber overshoes, and certain upper parts. Various rubbers are used to make footwear components (Section 8.4). Molded parts are produced by injection molding, compression molding, and certain special molding techniques developed by the shoe industry; the rubbers include both solid and foamed varieties. In some cases, for low volume production, manual methods are used to cut rubber from flat stock.

Rubber is widely used in sports equipment and supplies, including ping pong paddle surfaces, golf club grips, football bladders, and sports balls of various kinds. Tennis balls, for example, are made in significant numbers. Production of these sports products relies on the various shaping processes discussed in Section 14.5.3, as well as special techniques that have been developed for particular items.

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