POLYMER–MATRIX COMPOSITES

Polymer-matrix composites (PMCs) consist of a polymer resin as the matrix, filled with various types of materials. This type of composite is used in the greatest diversity of composite applications, as well as in the largest quantities, low density, good thermal and electrical insulator, ease of fabrication, and cost.

The drawbacks are

1. Can not be used at relatively high temperatures.
2. Has low shear strength.
3. Has a relatively low tensile strength.

Polymers are divided into two types

1-Thermoset Resins

Thermoset materials once cured cannot be remelted or reformed. During curing, they form three-dimensional molecular chains, called cross-linking, as shown in Figure below. Due to these cross-linkings, the molecules are not flexible and cannot be remelted and reshaped. The higher the number of cross-linkings, the more rigid and thermally stable the material will be. Thermosets may soften to some extent at elevated temperatures. Thermosets are brittle in nature and are generally used with some form of filler and reinforcement. Thermoset resins provide easy processability and better fiber impregnation because the liquid resin is used at room temperature for various processes. Thermosets offer greater dimensional stability, better rigidity, and higher electrical, chemical, and solvent resistance. The most common resin materials used in thermoset composites are epoxy, polyester, vinylester, phenolics, and polyimides.
2-Thermoplastic Resins

Thermoplastic materials are, in general, ductile and tougher than thermoset materials. Thermoplastics can be melted by heating and solidified by cooling, which render them capable of repeated reshaping and reforming. Thermoplastic molecules do not cross-link and therefore they are flexible and reformable. Thermoplastics can be either amorphous or semicrystalline, as shown in Figure 2. Their lower stiffness and strength values require the use of fillers and reinforcements for structural applications. Thermoplastics generally exhibit poor creep resistance, especially at elevated temperatures, as compared to thermosets.

Fig. (2), Molecular arrangements in (a) amorphous and (b) semicrystalline.
Thermoplastic composites typically require higher forming temperatures and pressures than comparable thermoset systems. The most common materials used in thermoplastic composites are Nylon, polyetheretherketone PEEK, polyphenylene sulfide PPS, Polyester, Polycarbonate, Acetal, Polyethylene, and Teflon.

**Composites Manufacturing Processes**

Composite production techniques utilize various types of composite raw materials, including resins, fibers, mats, fabrics, prepregs (prepreg is a resin-impregnated fiber, fabric, or mat in flat form, which is stored for later use in hand lay-up or molding operations), and molding compounds, for the fabrication of composite parts. Each manufacturing technique requires different types of material systems, different processing conditions, and different tools for part fabrication.

Composites manufacturing processes can be subdivided into two main manufacturing categories: manufacturing processes for thermoset composites and manufacturing processes for thermoplastic composites. In terms of commercial applications, thermoset composite parts dominate the composite market.

**1-Manufacturing Processes for Thermoset Composites**

In terms of commercial applications, more than 75% of all composites are made of thermoset composites. Their uses predominate in the aerospace, automotive, marine, boat, sporting goods, and consumer markets.

**1-Wet Lay-Up Process**

The wet lay-up process was the dominant fabrication method for the making of composite parts; it is called the hand lay-up process. It is still widely used in the marine industry as well as for making prototype parts. This process is
widely used for making boats, windmill blades, storage tanks, and swimming pools.

The major processing steps in the wet lay-up process include:

1. A release agent is applied to the mold.
2. The reinforcement layer is placed on the mold surface and then it is impregnated with resin. Sometimes, the wetted fabric is placed directly on the mold surface.
3. A roller is used to squeeze out excess resin and create uniform distribution of the resin throughout the surface. By the squeezing action of the roller, homogeneous fiber wetting is obtained.
4. Subsequent reinforcing layers are placed until a suitable thickness is built up. The part is allowed to cure at room temperature, or at elevated temperature.

Fig. (1), Schematic of the wet lay-up process.
Fig. (2), 41-ft cruiser boat made using hand lay-up process.

2- Spray-Up Process

The spray-up process is similar to the wet lay-up process, with the difference being in the method of applying fiber and resin materials onto the mold. In the spray-up process, a spray gun is used to deposit chopped fiber glass and resin / catalyst onto the mold. The spray-up process is much faster than the wet lay-up process and is less expensive choice. Bathtubs, swimming pools, boat hulls, storage tanks, and furniture components such as seating are some of the commercial uses of this process.

Fig. (3), Schematic of the spray-up process.
Fig. (4), robotic spray-up process for making a bathtub. The robot is applying chopped fiberglass with gel.

3- Filament Winding Process

Filament winding is a process in which long fibers are wound over a rotating mandrel at the desired angle. A typical filament winding process is shown in Figure 5, in which a carriage unit moves back and forth and the mandrel rotates at a specified speed. By controlling the motion of the carriage unit and the mandrel, the desired fiber angle is generated. The process is very suitable for making tubular parts. The process can be automated for making high-volume parts in a cost-effective manner.

Fig. (5), Schematic of the filament winding process.
Before winding begins, the mandrel is coated with release agent. Sometimes, a gel coat is applied on the top of the release agent to get high surface finish quality on the interior surface of the composite.

The winding process may be done in two ways:
In wet winding, fibers are passed through the resin bath located in the carriage unit and then to the mandrel. While in dry winding the fibers are wounded around a mandrel and then the polymer is applied until the fibers are saturated. The object is cured and the mandrel is removed from the fiber reinforced composite. Certain applications, the mandrel is not removed and it becomes an integral part of the composite structure.

4- Pultrusion Process

The pultrusion process is a low-cost, simple, continuous length, automatic and high-volume manufacturing process. Pultrusion creates parts of constant cross-section. Figure 9 illustrates a typical pultrusion process in which resin-impregnated fibers are pulled through a heated die at constant speed. As the material passes through the heated die, it becomes partially or completely cured. Pultrusion yields smooth finished parts that usually do not require post-processing.

Fig. (8), Illustration of a pultrusion process.
5- Compression Molding Process

Compression molding is very popular in the automotive industry because of its high volume capabilities. Sheet molding compounds (SMCs) and bulk molding compounds (BMCs) are the more common raw materials for compression molding. The SMC is obtained by mixing liquid resin, fillers, and fibers into a sheet product. SMC is stored in rolled form or in square pieces; the part should be usually manufactured within 2 weeks of manufacturing the molding compound. The SMC is cut into rectangular sizes and placed on the bottom half of the preheated mold as shown in Figure 10. These rectangular plies are called charge. The mold is closed by bringing the upper half of the mold to a certain velocity. Compression molding is used for making Class A surfaces. For Class A surfaces, the overall percentage of fiber content is limited to 30% to optimize smoothness of the surface.
Fig. (10), Schematic of the compression molding process.

Electrical applications of compression molding processes are fuses, outdoor lamps, lamp housings, switches, and home applications such as showers/tubs. An SMC molded automotive part is shown in Figure 11.

Fig.11, SMC molded automotive component.
6- Injection Molding of Thermoset Composites

Injection molding is a high-volume manufacturing process and is suitable for automotive. The typical parts produced are sewing machine parts, small power tools, and electrical plug fuses. In injection molding, a fixed amount of material is injected into the heated mold cavities. After the completion of cross-linking, the mold opens and the part is dropped into a receiving bin. Typically, the complete process takes about 30 to 60 s. The production rate can be further increased by having a multiple-cavity mold.

![Schematic of the injection molding process.](image1)

**Fig. 12, Schematic of the injection molding process.**

![Injection molded components.](image2)

**Fig. 13, Injection molded components.**
7- Vacuum Bagging Process

This process is very common in the aerospace industry. Wing structures, yacht parts, and sporting goods are made using this process. It is also called the autoclave or prepreg lay-up process. Complicated shapes with very high fiber volume fractions can be manufactured using this process to drive out the air bubbles. It is an open molding process, a release agent is applied to the mold for easy removal of the part, prepregs are cut, laid down in the desired fiber orientation on a tool and then vacuum bagged. After vacuum bagging, the composite with the mold is put inside an oven or autoclave and then heat and pressure are applied for curing and consolidation of the part.

Fig. (14), Vacuum bagging process.

Fig. 15, Vacuum bagged aerospace part ready to go inside an autoclave.
8- Resin Transfer Molding Process

The resin transfer molding (RTM) process is also known as a liquid transfer molding process. Continuous fibers are usually used in the RTM process. The RTM process is a closed mold operation in which a dry fiber is placed into the mold cavity. A matching mold half is mated to the first half and the two are clamped together. Then, a pressurized mixture of thermoset resin, a catalyst, color, filler, etc., is pumped or injected through an inlet port until the mold is filled with resin. The resin is then cured and the part is removed from the mold with good surface finish on both sides. The RTM process is suitable for making small- to large-sized structures in small- to medium-volume quantities. RTM is used in automotive, aerospace, and sporting goods.

Fig. (16), Schematics of the RTM process.

Fig. (17), Match molds.
2-Manufacturing Processes for Thermoplastic Composites

The use of thermoplastic composites is becoming popular in the aerospace and automotive industries because of their higher toughness, higher production rate, and minimal environmental concerns.

1- Thermoplastic Tape Winding

Thermoplastic tape winding is also called thermoplastic filament winding. In this process, a thermoplastic prepreg tape is wound over the mandrel as shown in Figure 18. In thermoplastic tape winding, heat and pressure are applied at the contact point of the roller and the mandrel for melting and consolidation of thermoplastics. In this process, lay down, melting, and consolidation are obtained in a single step.

![Fig. 18, Schematic of thermoplastic tape winding.](image)

2- Compression Molding of GMT

Compression molding of GMT (glass mat thermoplastic) is very similar to compression molding of SMC, with the only major difference being the type of raw material used in the process. The process is primarily used in the
automotive industry. The process is two to three times faster than compression molding of SMC.

Fig. 19, Compression molded automotive parts.

3- Hot Press Technique

This process is also called compression molding of thermoplastic prepregs, or the matched die technique. In this process, thermoplastic prepregs are stacked together and then placed between heated molds. Unlike GMT, the prepregs in this case are made with unidirectional continuous fibers. The fiber volume fraction is greater than 60%. This process is primarily used for making simple shapes such as flat laminates with constant thickness.

Fig. 20, Schematic of the hot press technique.
4- Autoclave Processing

Autoclave processing of thermoplastic composites is similar to autoclave processing of thermoset composites. In this process, thermoplastic prepregs are laid down on a tool in the desired sequence, the entire assembly is then vacuum bagged and placed inside an autoclave.

5- Diaphragm Forming Process

Thermoplastic forming techniques have gained a lot of interest because of their potential for forming complex parts in a high production volume environment.

![Diagram of diaphragm forming process](image)

**Fig. 21, Schematic of the diaphragm forming process.**

In diaphragm forming, prepreg layer in the form of a composite sheet is heated close to the melt temperature. The composite sheet is placed between two highly flexible diaphragms and then formed under heat and pressure against a female mold. Vacuum is used to evacuate the air between the diaphragms. The prepreg layers float freely between the two constrained diaphragms. There are several ways heat and pressure are applied during the diaphragm-forming process.
6- Injection Molding

Injection molding of thermoplastics is the process of choice for a tremendous variety of parts, ranging from 5 g to 85 kg. Injection molding is used for making complex parts at a very high rate. It is a much automated process and usually has a process cycle time of 20 to 60 s. The segment of the molding cycle that frequently requires the most time is the cooling time for the parts. Single-cavity or multiple-cavity molds are used to make the part. The process is suitable for large-volume applications such as automotive and consumer goods.