

Module 3 - Processing methods

Introduction

A key ingredient in the successful production application of a material or a component is a cost-effective and reliable manufacturing method. Cost effectiveness depends largely on the rate of production, and reliability requires a uniform quality from part to part (1). Every material possesses unique physical, mechanical, and processing characteristics and therefore a suitable manufacturing technique must be utilized to transform the material to the final shape. One transforming method may be best suited for one material and may not be an effective choice for another material (2). With the introduction of automation, fast-curing resins, new fiber forms, high-resolution quality control tools, and so on, the manufacturing technology for fiber-reinforced polymer composites has advanced at a remarkably rapid pace. Transformation of uncured or partially cured fiber-reinforced thermoset polymers into composite parts or structures involves curing the material at elevated temperatures and pressures for a predetermined length of time. High cure temperatures are required to initiate and sustain the chemical reaction that transforms the uncured or partially cured material into a fully cured solid. High pressures are used to provide the force needed for the flow of the highly viscous resin or fiber-resin mixture in the mold, as well as for the consolidation of individual unbonded plies into a bonded laminate. The magnitude of these two important process parameters, as well as their duration, significantly affects the quality and performance of the molded product. The length of time required to properly cure a part is called the cure cycle. Since the cure cycle determines the production rate for a part, it is desirable to achieve the proper cure in the shortest amount of time. It should be noted that the cure cycle depends on a number of factors, including resin chemistry, catalyst reactivity, cure temperature, and the presence of inhibitors or accelerators (1). Composite production techniques utilize various types of composite raw materials, including fibers, resins, mats, fabrics, prepregs, 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. Each technique has its own advantages and disadvantages in terms of processing, part size, part shapes, part cost, etc. Part production success relies on the correct selection of a manufacturing technique as well as judicious selection of processing parameters.

Manufacturing Process Selection Criteria

The selection of right process for composite part manufacturing is highly challenging job since there are so many choices in terms of raw materials and processing techniques to fabricate the part. Selection of a process depends on the application need. The criteria for

selecting a process depend on the production rate, cost, strength, and size and shape requirements of the part.

Manufacturing Process Selection Criteria

Process	Production Speed	Cost	Strength	Size	Shape	Raw Material
Filament winding	Slow to fast	Low to high	High	Small to large	Cylindrical and axisymmetric	Continuous fibers with epoxy and polyester resins
Pultrusion	Fast	Low to medium	High (along longitudinal direction)	No restriction on length; small to medium size cross-section	Constant cross-section	Continuous fibers, usually with polyester and vinylester resins
Hand lay-up	Slow	High	High	Small to large	Simple to complex	Prepreg and fabric with epoxy resin
Wet lay-up	Slow	Medium	Medium to high	Medium to large	Simple to complex	Fabric/mat with polyester and epoxy resins
Spray-up	Medium to fast	Low	Low	Small to medium	Simple to complex	Short fiber with catalyzed resin
RTM	Medium	Low to medium	Medium	Small to medium	Simple to complex	Preform and fabric with vinylester and epoxy
SRIM	Fast	Low	Medium	Small to medium	Simple to complex	Fabric or preform with polyisocyanurate resin
Compression molding	Fast	Medium	Medium	Small to medium	Simple to complex	Molded compound (e.g., SMC, BMC)
Stamping	Fast	Low	Medium	Medium	Simple to contoured	Fabric impregnated with thermoplastic (tape)
Injection molding	Fast	Low to medium	Low to medium	Small	Complex	Pallets (short fiber with thermoplastic)
Roll wrapping	Medium to fast	Low to medium	High	Small to medium	Tubular	Prepregs

Production Rate/Speed

Depending on the application and market needs, the rate of production is different. For example, the automobile market requires a high rate of production, for example, 10,000 units per year to 5,000,000 per year. In the aerospace market, production requirements are usually in the range of 10 to 100 per year. Similarly, there are composites manufacturing techniques that are suitable for low-volume and high-volume production environments. For example, hand lay-up and wet lay-up processes cannot be used for high-volume production, whereas compression molding (SMC) and injection molding are used to meet high-volume production needs.

Cost

Most consumer and automobile markets are cost sensitive and cannot afford higher production costs. Factors influencing cost are tooling, labor, raw materials, process cycle time, and assembly time. There are some composite processing techniques that are good at producing low-cost parts, while others are cost prohibitive. The cost of a product is significantly affected by production volume needs as well. For example, compression molding (SMC) is selected over stamping of steel for the fabrication of automotive body panels when the production volume is less than 150,000 per year. For higher volume rates, steel stamping is preferred.

Performance

Each composite process utilizes different starting materials and therefore the final properties of the part are different. The strength of the composite part strongly depends on fiber type, fiber length, fiber orientation, and fiber content (60 to 70% is strongest, as a rule). For

example, continuous fiber composites provide much higher stiffness and strength than shorter fiber composites. Depending on the application need, a suitable raw material and thus a suitable composite manufacturing technique are selected.

Size

The size of the structure is also a deciding factor in screening manufacturing processes. The automobile market typically requires smaller-sized components compared to the aerospace and marine industries. For small- to medium-sized components, closed moldings are preferred; whereas for large structures such as a boat hull, an open molding process is used. Above table reveals the suitability of composites manufacturing techniques in terms of product size.

Shape

The shape of a product also plays a deciding role in the selection of a production technique. For example, filament winding is most suitable for the manufacture of pressure vessels and cylindrical shapes. Pultrusion is very economical in producing long parts with uniform cross-section, such as circular and rectangular. The process selection criteria in shown in the above table are useful in prescreening of the fabrication choices. For the final selection of a process, a detailed study in terms of the above variables (e.g., cost, speed, and size) is performed.

Basic Steps in a Composites Manufacturing Process

There are four basic steps involved in composites part fabrication:

1. wetting/ impregnation
2. lay-up,
3. consolidation and
4. solidification

All composites manufacturing processes involve the same four steps, although they are accomplished in different ways.

Impregnation

In this step, fibers and resins are mixed together to form a lamina. For example, in a filament winding process, fibers are passed through the resin bath for impregnation. In a hand lay-up process, prepregs that are already impregnated by the material supplier in a controlled environment are used. In a wet lay-up process, each fabric layer is wetted with resin using a squeezing roller for proper impregnation. The purpose of this step is to make sure that the resin flows entirely around all fibers. Viscosity, surface tension, and capillary action are the main parameters affecting the impregnation process. Thermosets, which have viscosities in

the range of 10^1 to 10^4 cp are easier to wet-out. Viscosities of thermoplastics fall in the range of 10^4 to 10^8 cp and require a greater amount of pressure for good impregnation.

Lay-up

In this step, composite laminates are formed by placing fiber resin mixtures or prepregs at desired angles and at places where they are needed. The desired composite thickness is built up by placing various layers of the fiber and resin mixture. In filament winding, the desired fiber distribution is obtained by the relative motions of the mandrel and carriage unit. In a prepreg lay-up process, prepregs are laid at a specific fiber orientation, either manually or by machine. Performance of a composite structure relies heavily on fiber orientation and lay-up sequence.

Consolidation

This step involves creating intimate contact between each layer of prepreg or lamina. This step ensures that all the entrapped air is removed between layers during processing. Consolidation is a very important step in obtaining a good quality part. Poorly consolidated parts will have voids and dry spots. Consolidation of continuous fiber composites involves two important processes: resin flow through porous media and elastic fiber deformation. During the consolidation process, applied pressure is shared by both resin and fiber structure. Initially, however, the applied pressure is carried solely by the resin (zero fiber elastic deformation). Fibers go through elastic deformation when the compressive pressure increases and resins flow out toward the boundary. There are various consolidation models that ignore the fiber deformation and consider only resin flow.

Solidification

The final step is solidification, which may take less than a minute for thermoplastics or may take up to 120 min for thermosets. Vacuum or pressure is maintained during this period. The lower the solidification time, the higher the production rate achievable by the process. In thermoset composites, the rate of solidification depends on the resin formulation and cure kinetics. Heat is supplied during processing to expedite the cure rate of the resin. In thermoset resins, usually the higher the cure temperature, the faster the cross-linking process. In thermoplastics, there is no chemical change during solidification and therefore solidification requires the least amount of time. In thermoplastics processing, the rate of solidification depends on the cooling rate of the process. In thermoset composites, the temperature is raised to obtain faster solidification; whereas in thermoplastics processing, the temperature is lowered to obtain a rigid part. The above four steps are common in thermoset as well as thermoplastic composites processing. The methods of applying heat and pressure, as well as creating a desired fiber distribution, are different for different manufacturing methods (2).

Degree of cure

Cure study can be performed in DSC. DSC measures the heat evolved in a curing reaction and related it to the degree of cure achieved at any time during the curing process. The instrumentation in DSC monitors the rate of heat generation as a function of time and records it. The below figure schematically illustrates the rate of heat generation curves for isothermal and dynamic heating. (1)

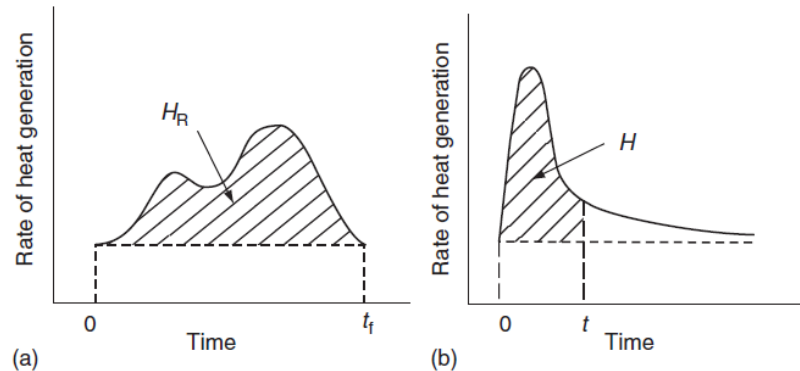


FIGURE 5.1 Schematic representation of the rate of heat generation in (a) dynamic and (b) isothermal heating of a thermoset polymer in a differential scanning calorimeter (DSC).

The total heat generation to complete a curing reaction (i.e., 100% degree of cure) is equal to the area under the rate of heat generation–time curve obtained in a dynamic heating experiment. It is expressed as

$$H_R = \int_0^{t_f} \left(\frac{dQ}{dt} \right)_d dt,$$

where

H_R = heat of reaction

$(dQ/dt)_d$ = rate of heat generation in a dynamic experiment

t_f = time required to complete the reaction

The amount of heat released in time t at a constant curing temperature T is determined from isothermal experiments. The area under the rate of heat generation–time curve obtained in an isothermal experiment is expressed as

$$H = \int_0^t \left(\frac{dQ}{dt} \right)_i dt,$$

where H is the amount of heat released in time t and $(dQ/dt)_i$ is the rate of heat generation in an isothermal experiment conducted at a constant temperature T . The degree of cure a_c at any time t is defined as

$$\alpha_c = \frac{H}{H_R}$$

Figure 5.2 shows a number of curves relating the degree of cure α_c to cure time for a vinyl ester resin at various cure temperatures. From this figure, it can be seen that α_c increases with both time and temperature; however, the rate of cure, $d\alpha_c/dt$, is decreased as the degree of cure attains asymptotically a maximum value. If the cure temperature is too low, the degree of cure may not reach a 100% level for any reasonable length of time. The rate of cure $d\alpha_c/dt$ obtained from the slope of α_c vs. t curve and plotted in Figure 5.3, exhibits a maximum value at 10%–40 % of the total cure achieved. Higher cure temperatures increase the rate of cure and produce the maximum degree of cure in shorter periods of time. On the other hand, the addition of a low-profile agent, such as a thermoplastic polymer, to a polyester or a vinyl ester resin decreases the cure rate.

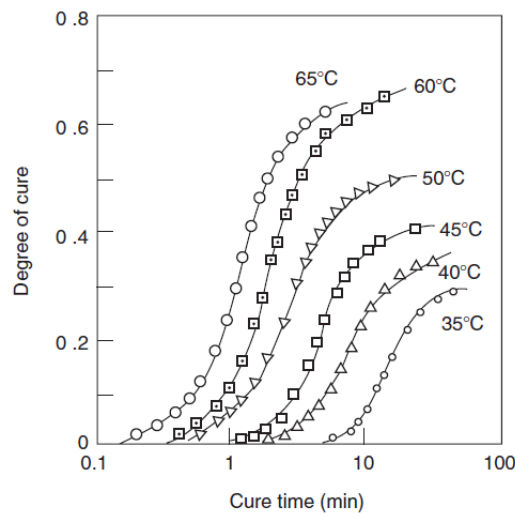


FIGURE 5.2 Degree of cure for a vinyl ester resin at various cure temperatures.

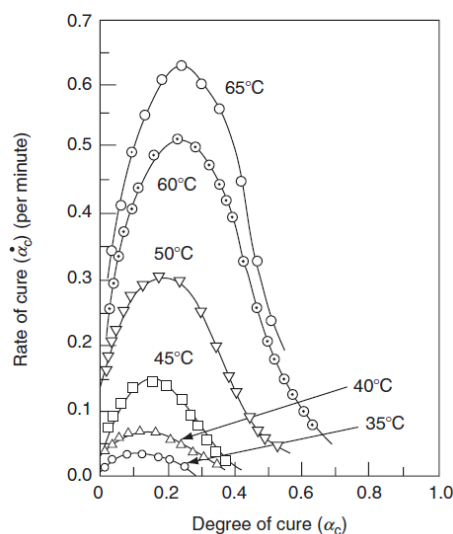


FIGURE 5.3 Rate of cure for a vinyl ester resin at various cure temperatures

Types of Composite Manufacturing: (3)

Composites are manufactured through different techniques. The techniques are chosen based on type of fiber, resin and the size of the product. Some of the commonly used manufacturing techniques are given below.

1. Lay-up
 - Hand lay-up
 - Spray lay-up
 - Prepreg Lay-Up
 - Automatic tape lay-up
2. Prepregs
3. Compression molding
 - Resin injection molding
 - Incremental molding
 - Stamp molding
 - High-pressure compression molding
 - Injection molding
4. Bag molding
 - Pressure bag molding
 - Vacuum bag molding
5. Autoclave molding
6. Filament winding
 - Helical winding
 - Hoop winding
7. Resin transfer molding (RTM)
 - Flexible RTM (FRTM)
 - Continuous RTM (CRTM)
 - Vacuum assisted RTM (VARTM)
 - High-speed RTM (HSRTM)
8. Pultrusion
9. Molding compounds
 - SMC (sheet molding compound)
 - BMC (bulk molding compound)
10. Centrifugal Casting
11. Extrusion method

Prepreg Lay-Up Process (1)

The hand lay-up process is mainly divided into two major methods:

1. wet layup and
2. prepreg lay-up.

Prepreg lay-up process is very common in the aerospace industry. It is also called the autoclave processing or vacuum bagging process. Complicated shapes with very high fiber volume fractions can be manufactured using this process. It is an open molding process with low-volume capability.

Working principle

In this process, preregs 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.

Preparation of preregs (3)

a. Method:

Preregs can be made by basically two methods:

1. Wetting the glass fiber cloth with the resin and heating it to a B-stage of curing (partial curing) so that the material becomes tack free. After sometime, if the heat is withdrawn and the material is stored at -18°C the cross linking operation can be stopped. At the correct B-stage the cloth will be tack free and very flexible. The preregs are slightly heated before processing to get soften and bond with the successive layers. After shaping (winding, press moulding), the material is heated to take it to the full cure.
2. If the matrix is in powder form it cannot go through the B-staging. In such cases, the resin is dissolved in a suitable solvent and brought to required viscosity.

b. Equipment:

The Machine used for manufacture of prepreg is called Tower. Fibers tensioned by tensioning device are passed through resin bath. It is then passed through a set of scrap bars to squeeze out the excess resin. The wetted fibers are then passed through drying oven, where temperature gradually increases. Volatiles are removed and resin reaches a tack free stage called B-stage. The prepreg fibers are covered by polythene sheet and completely rolled in aluminum foil.

c. Storage Condition: The preregs are stored in refrigerated chambers. The temperature of the storage area is important in improving the shelf life of the material. Moisture should be completely avoided. Shelf life is 6-8 months when stored at -18°C .

Evaluation of Prepregs:

Parameters to be evaluated in cured state are:

1. Weight per unit area
2. Tackiness and durability
3. Resin content
4. Fiber content
5. Volatile content
6. Resin flow

Characteristics of good prepreg

1. The fiber to resin ratio should be high and should not vary from place to place.
2. Volatile contents and solvents should be minimum.
3. The prepreg should be flexible and tack free.
4. The material should have long storage life.
5. During moulding, the resin should be soften and flow filling the mold cavity should be without voids and defects.

Basic Raw Materials for prepreg layup technique (1)

Graphite/epoxy prepregs are the most commonly used materials for the prepreg lay-up process. Glass/epoxy and Kevlar/epoxy are also used but their use is much less than carbon/epoxy prepregs. The main reason is that carbon/epoxy is much lighter and stronger than other prepreg materials and provides greater mass savings in the component. Because this process is widely used in the aerospace industry, where weight is a critical design factor, carbon fiber prepreg is the material of choice. Other than epoxy, high-temperature resins such as polyimides, polycyanate and BMI are also used in prepreg systems.

Tooling Requirements

The tooling for the prepreg lay-up process is an open mold on which prepregs are laid in the desired fiber orientation and sequence. For prototype building purposes, tools are made by machining metals, woods, and plastics.

Basic Processing Steps

The basic steps in making composite components by prepreg lay-up process are summarized as follows.

1. The prepreg is removed from the refrigerator and is kept at room temperature for thawing.
2. The prepreg is laid on the cutting table and cut to the desired size and orientation.
3. The mold is cleaned and then release agent is applied to the mold surface.
4. Backing paper from the prepreg is removed and the prepreg is laid on the mold surface in the sequence mentioned in the manufacturing chart.

5. Entrapped air between prepreg sheets is removed using a squeezing roller after applying each prepreg sheet.
6. After applying all the prepreg sheets, vacuum bagging arrangements are made by applying release film, bleeder, barrier film, breather, and bagging materials.
7. The entire assembly is then placed into the autoclave using a trolley if the structure is large.
8. Connections to thermocouples and vacuum hoses are made and the autoclave door is closed.
9. The cure cycle data are entered into a computer-controlled machine and followed.
10. After cooling, the vacuum bag is removed and the part is taken out.

Typical Manufacturing Challenges

1. Maintaining accurate fiber orientations in the part is difficult because prepregs are laid down by hand. Automated tape placement equipment can be used for precise fiber orientation control.
2. Obtaining void-free parts is a challenge during this process. Voids are caused by entrapped air between layers.
3. Achieving warpage or distortion-free parts during the prepreg layup process is challenging. Warpage is caused by built-in residual stresses during processing.

Advantages of the prepreg layup process

1. It allows production of high fiber volume fraction (more than 60%) composite parts because of the use of prepregs. Prepregs usually have more than 60% fiber volume fraction.
2. Simple to complex parts can be easily manufactured using this process.
3. This process is very suitable for making prototype parts. It has the advantage of low tooling cost but the process requires high capital investment for the autoclave.
4. Very strong and stiff parts can be fabricated using this process.

Limitations of the Prepreg Lay-Up Process

1. It is very labor intensive and is not suitable for high-volume production applications.
2. The parts produced by the prepreg lay-up process are expensive.

LIQUID COMPOSITE MOLDING PROCESSES (1)

In liquid composite molding (LCM) processes, a premixed liquid thermoset resin is injected into a dry fiber preform in a closed mold. As the liquid spreads through the preform, it coats the fibers, fills the space between the fibers, expels air, and finally as it cures, it transforms into the matrix. Ex. RTM, structural reaction injection molding (SRIM), VARTM, etc.

Resin Transfer Molding Process (3)

Principle

It is a low pressure closed molding process for moderate volume production quantities. Dry continuous strand mats and woven reinforcements are laid up in the bottom half mold. The mold is closed and clamped, and a low viscosity, catalyzed resin is pumped in, displacing the air through strategically located vents. The injection pressure of resin is in the range of 70-700 kPa.

Basic Raw Materials (2)

For the RTM process, fiber preforms or fabrics are used as reinforcements. There are several types of preforms (e.g., thermoformable mat, conformal mats, and braided preforms) used in the RTM process.

A wide range of resin systems can be used, including polyester, vinylester, epoxy, phenolic, and methacrylate, combined with pigments and fillers including alumina trihydrate and calcium carbonates. The most common resins used for the RTM process is unsaturated polyester and epoxies. Epoxy with carbon fiber is very common in the aerospace industry. The use of epoxies and other high-viscosity resins requires changes in equipment to meter and condition the resin prior to injection.

Filler may be added to the resin during the RTM process. The main purpose of adding filler is to lower the cost of the part. When mixing filler material such as ground calcium carbonate with the resin, precautions are taken to ensure that filler size does not exceed 10 μm . A larger filler size creates a filtering problem with preforms. A filler size of 5 to 8 μm is recommended so that the filler can move with the resin without any problem inside the fiber architecture. Mixing the filler with the resin increases the viscosity of the resin and slows the production rate. It also significantly increases the weight of the part. The weight increase may be 30%, but the volume increase may be only 12% by adding the filler.

Tooling

The RTM process provides the advantage of utilizing a low-cost tooling system as compared to other molding processes such as injection and compression molding, the reason being that the pressure used during the RTM process is low compared to the pressure requirements of compression and injection molding processes. Because of this, tooling need not be strong and heavy. At the same time, low-cost tooling provides benefits of low initial investment for prototype building and for production run. Another benefit of RTM process is that the closed nature of the process provides a better work environment (low styrene emissions). The mold for the RTM process is typically made of aluminum and steel but for prototype purposes plastic and wood are also used. The mold is generally in two halves containing

single or multiple inlet ports for resin injection and single or multiple vents for air and resin outlet. The wall thickness of the mold should be sufficiently rigid to take all the pressure exerted during processing. The mold design should also take into account handling and thermal considerations. Thermal properties of the mold and composite materials affect the dimensional tolerances of the finished part and therefore the coefficients of thermal expansion for the mold and part need to be considered while designing the mold. The tool should be designed to ensure that it can be clamped and sealed properly (2). Guide pins are provided in the mould for guiding the two halves of the mould to a perfect closure without lateral displacement. Sealing gasket is provided along the parting line while crossing the mould for preventing the flow of resin through the parting line. Neoprene and silicone can be used as the gaskets.

PROCESS EQUIPMENT AND TOOLS

Types of RTM machines

The machines used for RTM include a mixing head attached to a nozzle, a pumping unit, and a solvent flushing unit. The pumping unit generates the pressure to inject the resin through the layers of reinforcement. The solvent flushing unit pumps solvent such as acetone to clean the mixing and injection chamber free of resin. There are three types of RTM injection equipments based on position of mixing of catalyst with resin.

Two pot system

This system has two equal volume containers or pots. In one of these pots the resin is mixed with accelerator. In the other pot the resin is mixed with the catalyst. Two pumps are used to pump these mixtures (as shown in fig.2.6a) to the injection points where they are mixed well in the mixing head.

b. Catalyst injection system

In this system the catalyst is not mixed with the resin until it reaches the entry pot attached to the mould (Fig.2.6b). The resin mixed with accelerator is pumped into the injection chamber. The catalyst is taken separately into the chamber by means of controlling valve. The advantage of this system is that the gel and cure time can be controlled by varying the amount of catalyst added.

Pre-mixing system

This is a simple process by mixing the resin, accelerator, and catalyst in a vessel directly and injecting the mixture into the mould. A thick walled airtight metallic cylinder provided with inlet and outlet holes is taken. The injection is carried out through the outlet by means of compressed air. The cylinder has to be washed periodically with acetone to prevent clogging by cured resin (3).

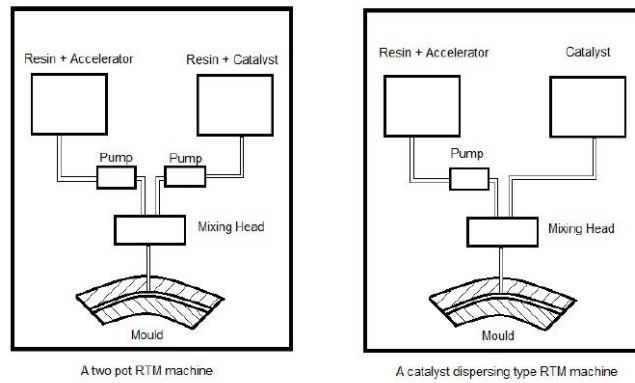


Figure 2.6a Two pot RTM machine Figure 2.6b catalyst dispersed RTM machine

Basic Processing Steps

The steps during the RTM process are summarized below:

1. A thermoset resin and catalyst are placed in tanks A and B of the dispensing equipment.
2. A release agent is applied to the mold for easy removal of the part.
3. Sometimes, a gel coat is applied for good surface finish.
4. The preform is placed inside the mold and the mold is clamped.
5. The mold is heated to a specified temperature.
6. Mixed resin is injected through inlet ports at selected temperature and pressure. Sometimes, a vacuum is created inside the mold to assist in resin flow as well as to remove air bubbles.
7. Resin is injected until the mold is completely filled. The vacuum is turned off and the outlet port is closed.
8. The pressure inside the mold is increased to ensure that the remaining porosity is collapsed.
9. After curing (depending on resin chemistry), the composite part is removed from the mold.

Advantages of the Resin Transfer Molding Process

1. Initial investment cost is low because of reduced tooling costs and operating expenses as compared to compression molding and injection molding.
2. Moldings can be manufactured close to dimensional tolerances.
3. Can make complex parts at intermediate volume rates. This feature allows limited production runs in a cost-effective manner
4. RTM provides for the manufacture of parts that have a good surface finish on both sides. Sides can have similar or dissimilar surface finishes.

5. RTM allows for production of structural parts with selective reinforcement and accurate fiber management.
6. Higher fiber volume fractions, up to 65%, can be achieved.
7. Inserts can be easily incorporated into moldings and thus allows good joining and assembly features.
8. A wide variety of reinforcement materials can be used.
9. RTM offers low volatile emission during processing because of the closed molding process.
10. RTM offers production of near-net-shape parts, hence low material wastage and reduced machining cost.
11. The process can be automated, resulting in higher production rates with less scrap.

Limitations of the Resin Transfer Molding Process

1. The manufacture of complex parts requires a good amount of trial and- error experimentation or flow simulation modeling to make sure that porosity- and dry fiber-free parts are manufactured.
2. The tooling design is complex.

Major Applications (2)

The RTM process is suitable for making small- to large-sized structures in small- to medium-volume quantities. RTM is used in automotive, aerospace, sporting goods, and consumer product applications.

The structures typically made are helmets, doors, hockey sticks, bicycle frames, windmill blades, sports car bodies, automotive panels, and aircraft parts.

Some aircraft structures made by the RTM process include spars, bulkheads, control surface ribs and stiffeners, fairings, and spacer blocks.

MOULD TIME CYCLE (3)

Total moulding time is given by the relation:

$$T_T = T_{mf} = T_{gel} = T_c = T_u = T_{cl} + T_p + T_{fp}$$

T_{mf} = mould fill up time

T_{gel} = gel time

T_c = cure time

T_u = un mould time

T_{cl} = cleaning time

T_p = preparation time

T_{fp} = fiber packing time

Vacuum Bag Molding (3)

Vacuum impregnation is a process in which the resin to fiber wetting is assisted by a vacuum. The main purpose of vacuum process is it removes the air which is trapped inside the laminate thus reducing the defect and improving the strength of the laminate.

Advantages of vacuum impregnation method

- Improves the strength of the laminates by reducing the defects.
- Low cost when compared with compression mould laminates.
- Density of laminate is considerably lower than that of compression mould laminates.

Materials

Reinforcements

All types of fiber reinforcements can be impregnated with resin using vacuum method.

Effects of vacuum method on reinforcements

- Good formability
- High strength
- Good surface quality
- Wear resistance
- High complex forms

Resins

The curing procedure of the resin, initial viscosity, the gelation time, and wettability, are the important properties to be considered for processing. For vacuum impregnation purpose the volatile content should be as low as possible. Both polyester and epoxy resins are used.

Factors to be considered for resins in vacuum method

- Long pot life
- Less viscosity (11 Pa.s or 100 CP or less)
- Short gel time (less than 1 hour)

Mold Releasing Agents

Releasing agents used include backed on Teflon (PTFE) or PVA coatings on the mould parts. For vacuum bag systems PTFE films which are porous are used along with conventional materials. The lay-up is placed in the mould with separator on top of it usually made of Teflon coated glass. The bleeder is placed to absorb the excess resin from the lay-up, thus controlling the amount content during the curing process. Pressure plates are introduced to supply additional compression to the lay-up. Barrier film is used to control the resin flow in the bleeder. Fig.2.9b Breather film is given beneath the vacuum bag to allow the uniform application of vacuum all over the area of the laminate and removal of excess air or volatiles

developed during the cure. Vacuum bag is used to contain the vacuum generated by the pump and applied to the lay-up. The application of vacuum bag is very critical. Bag porosity or punctures can result in a porous product. Complex tools may require the bag to be folded in places and thus require excess bag material. If the folds are not properly made or placed, wrinkles may be developed in the parts. The vacuum may be maintained till the resin gels.

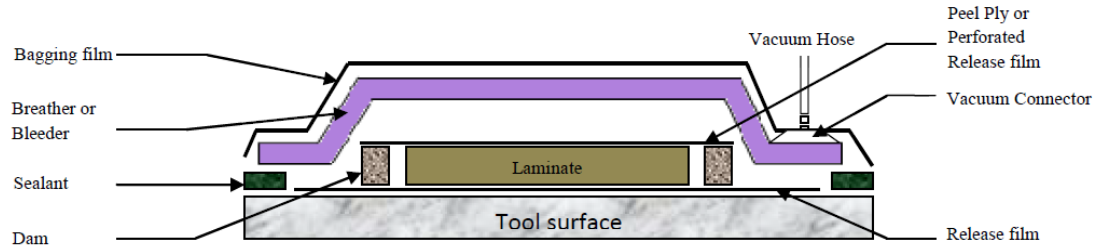


Figure 2.9b Vacuum Bag method

Molding Compound

There are several types of molding compounds available to meet various needs. Molding compounds are made of short or long fibers impregnated with resins. In general, they are used for compression molding and injection molding processes.

Sheet Molding Compound

SMC (sheet molding compound) is a sheet of ready-to-mold composites containing uncured thermosetting resins and uniformly distributed short fibers and fillers. It primarily consists of polyester or vinyl ester resin, chopped glass fibers, inorganic fillers, additives, and other materials. Normally, SMC contains 30% by weight short glass fibers. The typical composition of various ingredients in SMC is shown in [Table 2.5](#).

TABLE 2.5
Composition of a Typical SMC

Ingredients	Purpose	Weight %
Chopped glass fibers	Reinforcement	30.00
Unsaturated polyester resin	Base resin	10.50
Calcium carbonate	Filler	40.70
Styrene monomer	Co-monomer	13.40
Polyvinyl acetate	Low shrink additive	3.45
Magnesium oxide	Thickener	0.70
Zinc stearate	Mold release (lubricant)	1.00
<i>t</i> -Butyl perbenzoate	Catalyst (initiator)	0.25
Hydroquinone	Inhibitor	Trace amount, <0.005 g
		Total = 100%

The purpose of adding filler is to reduce the overall cost, increase dimensional stability, and reduce shrinkage during molding. Thickener is used to increase resin viscosity. Styrene is added for the curing or cross-linking process. An inhibitor prevents premature curing of the resin mix. A release agent (mold release) is added to the compound for easy release of compression molded parts from the mold. SMC containing 50 to 60 weight fraction glass fibers is called HMC. SMC is a low-cost technology and used for high-volume production of composite components requiring moderate strength. Currently, SMC dominates the

automotive market because of its low-cost, high-volume production capabilities. SMC comes in various thicknesses, up to a maximum thickness of 6 mm. SMC is cut into a rectangular strip and then kept in the mold cavity for compression molding. During molding, suitable temperature and pressure are applied to spread the charge into the cavity and then to cure it. The process cycle time for compression molding is in the range of 1 to 4 min. The manufacture of sheet molding compound is shown in Figure 2.19. In this process, a resin paste (resin, inhibitor, thickener, filler, etc., except fiber) as described in Table 2.5 is placed on a polyethylene moving film through a metering device. Before placing, all the ingredients of the resin paste are thoroughly mixed. Continuous strands of glass fibers are chopped through a chopping machine and evenly dispersed over the moving resin paste. Another layer of resin paste is placed over dispersed fibers for good fiber impregnation. Another moving polyethylene film is placed on top of the above compound. These top and bottom polyethylene films remain until it is placed in a compression mold. These carrier films help in packaging and handling. The thickness of the sheet is controlled by a mechanical adjuster. Instead of chopped glass fibers alone, continuous glass fiber or any other fiber (e.g., carbon fiber) can be added. The complete sheet then passes through a heated compaction roller and is then rolled up or cut into rectangular shapes for shipping. A polyester-based SMC requires 1 to 7 days of exposure at around 30°C prior to use in compression molding. This period is called the maturation period, wherein resin viscosity increases to a level satisfactory for its use for the molding operation.

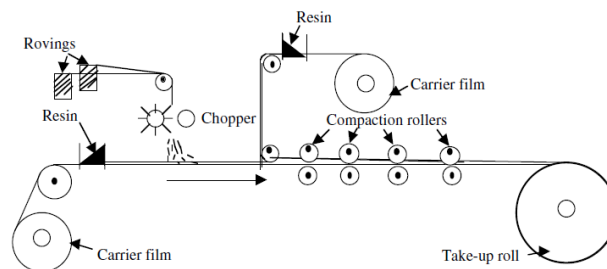
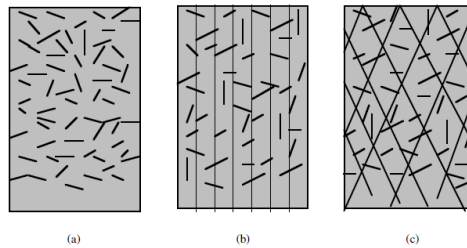


FIGURE 2.19
Schematic of SMC manufacturing.

There are three types of SMC commonly available, depending on the fiber form used: SMC-R, for randomly oriented short fibers. The weight percent of the fiber is written after R. For example, SMC-R25 has 25 wt% short fibers (Figure 2.20a). SMC-CR contains continuous (C) unidirectional fibers in addition to random (R) short fibers, as shown in Figure 2.8. The percentage amounts of C and R are denoted after the letters C and R as SMCC30R20 (Figure 2.20b). XMC represents a mixture of random short fibers with continuous fibers in an X pattern. The angle between cross fibers is in the range of 5 to 7° (Figure 2.20c).



Common types of SMC: (a) SMC-R; (b) SMC-CR; and (c) XMC.

Thick Molding Compound (TMC)

Thick molding compound (TMC) is a thicker form of SMC. The thickness of TMC goes up to 50 mm whereas the maximum thickness of SMC is 6 mm. TMC is used for making thicker molded parts. TMC eliminates having to use several SMC plies. Due to its greater thickness, TMC provides reduced pliability. In TMC, fibers are randomly distributed in three dimensions, whereas in SMC fibers are in two dimensions.

Compression Molding Process (2)

Compression molding is a high volume production process mainly used in automotive industry. This process is used for molding large automotive panels. Sheet molding compounds (SMCs) and bulk molding compounds (BMCs) are the more common raw materials for compression molding. Compression molding is also used for making structural panels using prepregs and core materials;

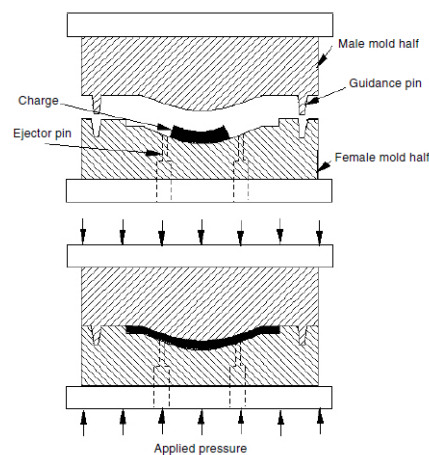
Basic Raw Materials

SMC, BMC, and TMC are used as raw materials for compression molding operations.

Basic Processing Steps

In compression molding operation, the mold is preheated to about 140°C, or as required by the resin formulation. Then the SMC is cut into rectangular sizes and placed on the bottom half of the preheated mold. These rectangular plies are called charge. The charge usually covers 30 to 90% of the total area, and the remaining area is filled by forced flow of the charge. The amount of charge is determined by calculating the final volume or weight of the part. The mold is closed by bringing the upper half of the mold to a certain velocity. Typically, the working speed of the mold is 40 mm/s with SMC and 80 mm/s. Press closing speed depends primarily on mold temperature and resin gel time, higher molding temp and faster curing formulations require faster press closure for rapid pressure build in mold. If closing too slow, material will pre-gel in mold if closing too fast, fiber wash will result. With the movement of mold, the charge starts flowing inside the mold and fills the cavity. The flow of the molding compound causes removal of entrapped air from the mold as well as from the charge. After a reasonable amount of cure under heat and pressure, the mold is opened and the part is removed from the mold. Ejector pins are used to facilitate easy

removal of the part. Total cycle time depends on the resin cure time and mold closing time. Actually molding of part often occupies only about 10% of total press cycle time, remaining 90% is cure time. The parts made by compression molding are usually thin as compared to RTM, injection molding, and other manufacturing processes. For thin sections, the temperature across the thickness remains uniform and is on par with mold temperature. Uniform temperature across the thickness allows uniform curing in the part and thus avoids residual stress in the part caused by curing. For thick cross sections, the temperature distribution is not uniform across the thickness. In thick sections, the layer adjacent to the mold reaches the mold temperature quickly and remains uniform. It takes some time for the centerline layer to reach the mold temperature because of the low thermal conductivity of the charge material. However, because of the exothermic curing reaction of resin material, the temperature of the centerline layer goes above the mold temperature. As curing completes, the centerline temperature flattens to mold temperature. Compression molding of SMC has the potential for several defects. The defects could be on the outer surface (such as an unacceptable surface finish or fiber read-throughs) or internal defects (such as porosities, blisters, weld lines, and warpage). Porosities are caused by air entrapment, whereas blisters are interlaminar cracks formed at the end of molding due to excessive gas pressure inside the molded part. This internal gas pressure may result from unreacted styrene monomer in undercured parts or from large pockets of entrapped air between the stacked layers. Weld lines are formed when two flow fronts meet inside the mold. Weld lines have poor mechanical properties normal to the weld line because the fibers tend to align themselves along the weld line. Warpage in the composite results from residual stress. Typically, parts with nonuniform cross-section have variations in cooling rate between sections of different thickness. This differential cooling rate is a potential source of residual stress and thus warpage in the component.



Schematic of the compression molding process.

Advantages of the Compression Molding Process

Compression molding of SMC provides the following advantages.

1. It offers high-volume production and thus is very suitable for automotive applications. The mold cycle time is only 60 to 240 s (1 to 4 min).
2. It offers production of low-cost components at high volume because it utilizes SMC, which is fairly inexpensive.
3. The process offers high surface quality and good styling possibilities.
4. Multiple parts can be consolidated into one single molded part and thus is very advantageous compared to the metal stamping process.

Limitations of the Compression Molding Process

Despite the many advantages of compression molding, this process has the following limitations.

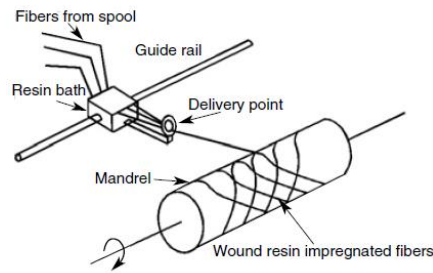
1. The initial investment for the process is high because of high equipment and mold costs.
2. The process is not suitable for making a small number of parts or for prototyping applications.
3. Compression molding of SMC provides nonstructural parts; but by utilizing ribs and stiffeners, structural parts can be manufactured.

Major Applications

Compression molding of SMC is used for making one- and two-piece panels for automotive applications. One-piece panels are used where the panel is fixed and can be supported around the majority of its periphery. Roof panels, quarter panels, fenders, and add-ons such as spoilers, ground-effects packages, and limited-access panels are examples of this category. Two-piece panels are used for closure panels such as doors, hoods, and deck lids. These panels are usually supported by hinges with body structures and therefore should have enough rigidity of their own.

Filament Winding Process

Filament winding is a process in which resin-impregnated fibers are wound over a rotating mandrel at the desired angle. In a typical filament winding process 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. Filament winding is the only manufacturing technique suitable for making certain specialized structures, such as pressure vessels.



Schematic of the filament winding process

Basic Raw Materials

The starting materials for filament winding are continuous fibers (yarns) and liquid thermoset resins. Yarns are kept in spool form at the back rack and passed through a resin bath located in the carriage unit. Fibers get wet as they pass through the resin bath. Glass, carbon, and Kevlar fibers are used for the filament winding process but glass fibers are more common because of its low cost. Epoxy, polyester, and vinyl ester are used as resin materials. Glass fibers with polyester resins are widely used for low-cost applications. Glass with epoxy is used in spoolable filament-wound tubes for offshore applications. Sometimes, prepreg tows are used as starting materials. The use of prepreg tows provides uniform fiber distribution and resin content throughout the thickness of the part. The filament winding process is also used for making preforms for the RTM process.

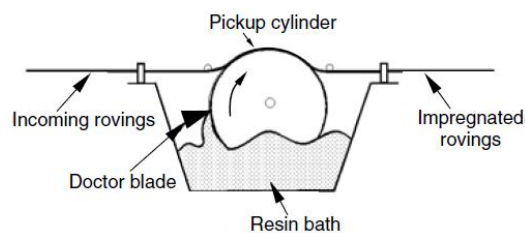
Tooling

The most common tooling material for the filament winding process is a steel mandrel. Steel mandrels are chrome plated in certain applications to get a high-gloss finish on the inside surface of the composite structure as well as to aid in easy removal of the mandrel. Aluminum is also used for making mandrels. For some applications, such as pressure vessels, the mandrel is not removed and becomes an integral part of the composite structure. The non-removal mandrel provides an impermeable layer/barrier surface on the composite inner surface and thus avoids leakage of compressed gas or liquid inside the pressure vessel. Typically, metals and thermoplastic materials are used as barrier materials. Plaster of Paris and sand are also used to make destructible/collapsible mandrels. For prototyping purposes, wood, plastics, and cardboard can be used.

Making of the Part

To make filament wound structures, a mandrel is placed on the filament winding machine as shown in the above figure. A filament winding machine is similar to a lathe machine where the head and tail stocks are used to hold the mandrel and the cutting tool is replaced by a payout eye on the carriage unit. The mandrel rotates and the carriage unit moves relative to the mandrel to lay down the resin-impregnated fibers at a specific angle. Various

types of computer-operated filament winding machines are used, ranging from two-axes to six-axes filament winding machines. The carriage unit can move along the x , y , and z axes as well as rotate about these axes. In two-axes filament winding machines, the mandrel rotates and the carriage unit moves back and forth only in one direction. 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. Once the mandrel is prepared, it is placed between the head and tail stocks of the machine. During wet winding, fiber yarns, which are placed in spool form at the creels, are passed through the resin bath located in the carriage unit and then to the mandrel through the payout eye. To achieve good fiber wet-out, air held inside the fiber bundle must be removed and replaced with the resin. The impregnation system must facilitate the break-up of any film formers on the bundle for resin ingress. To achieve good impregnation, several things are done: rovings are kept at constant tension, rovings are passed through guided pins, a doctor blade at resin bath is used.



Doctor blade arrangement in the filament winding operation

If the tension on the rovings is too small, the laminate is not fully compacted and creates an excess resin region on the laminate. If the tension is too high, it can cause fiber breakage or resin starved areas near inside layers. The use of a doctor blade arrangement scrapes off excess resin and creates a uniform resin layer. Laminate is formed after a series of relative motions between the mandrel and the carriage unit. To get the desired winding, the machine operator inputs various parameters such as pipe diameters, mandrel speed, pressure rating, band width, fiber angle, etc., depending on the software requirements. After creating the desired fiber angle distribution, the mandrel with the composite laminate is removed to a curing area where the laminate is cured at room temperature or at elevated temperature. For thick laminates, it may be necessary to wind in stages and allow the laminate to cure between winding operations. Once the part is cured, the mandrel is extracted using an extracting device. Sometimes, a small taper angle is provided in the mandrel for easy removal of the composite part.

Methods of Applying Heat and Pressure

The pressure during filament winding is applied by creating fiber tension. In general, 1 lbf to 6 lbf fiber tension is created using some tensioning device or by passing the fibers through

the carriage unit in such a way that it creates tension. Composites thus fabricated are cured at room temperature, or in an oven at a higher temperature. For large-volume production, the process of part fabrication is automated. In an automated line, the filament wound part with the mandrel is moved to a heated chamber using a robot. The part slowly moves in the heated chamber and comes out after partial or full cure of the composite part. The part is then sent to the mandrel extracting station where the mandrel is extracted and sent back to the filament winding machine for winding purposes. All of this can be done automatically. Ultraviolet (UV) curing as well as electron beam curing are also performed during the filament winding process to cure the resin. Radiation energy is used for curing the resin in both UV and electron beam curing. To facilitate UV curing, photo initiator additive is added to the resin formulation. The photoinitiator is sensitive to radiation energy. A light source such as an electrode-based mercury/ vapor bulb is used to deliver the correct UV wavelength energy to initiate the curing action. Once exposed to the UV rays, the chemical structure of the photoinitiator breaks down into energized free radicals that actively seek new chemical bond sites within the resin mix. When the free radicals bond with other free radicals, the size of the polymer chain increases, causing the resin mix to polymerize into the solid state. The outer surface finish quality of filament wound parts is usually not good and requires extra machining and sanding of the outer surface. To create a good outer finish, the part is sometimes shrink taped after winding is complete or a teflon-coated air breather is applied on the outer surface to absorb excess resin.

Advantages of the Filament Winding Process

Filament winding has gained significant commercial importance due to its capability in laying down the fibers at a precise angle on the mandrel surface. Filament winding offers the following advantages.

1. For certain applications such as pressure vessels and fuel tanks, filament winding is the only method that can be used to make cost effective and high-performance composite parts.
2. Filament winding utilizes low-cost raw material systems and low cost tooling to make cost-effective composite parts.
3. Filament winding can be automated for the production of high volume composite parts.

Limitations of the Filament Winding Process

Filament winding is highly suitable for making simple hollow shapes. However, the process has the following limitations.

1. It is limited to producing closed and convex structures. It is not suitable for making open structures such as bathtubs. In some applications, filament winding is used to make

open structures such as leaf springs, where the filament wound laminate is cut into two halves and then compression molded.

2. Not all fiber angles are easily produced during the filament winding process. In general, a geodesic path is preferred for fiber stability. Low fiber angles (0 to 15°) are not easily produced.
3. The maximum fiber volume fraction attainable during this process is only 60%.
4. During the filament winding process, it is difficult to obtain uniform fiber distribution and resin content throughout the thickness of the laminate.

Major Applications

The most common products produced by the filament winding process are tubular structures, pressure vessels, pipes, rocket motor casings, chemical storage tanks, and rocket launch tubes. The introduction of sophisticated filament winding machines and dedicated CAD systems has enabled more complex geometries to be produced and many of the original geometric limitations have now been overcome. Bent shapes, connecting rods, bottles, fishing rods, golf shafts, pressure rollers, bushings, bearings, driveshafts (industrial and automotive), oil field tubing, cryogenics, telescopic poles, tool handles, fuse tubes, hot sticks (non-conducting poles), conduits, fuse lugs, bicycle frames and handle bars, baseball/softball bats, hockey sticks, fishing rods, ski poles, oars, tubes, etc. are currently produced using filament winding techniques.

Pultrusion Process

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

Basic Raw Materials

E-glass, S-glass, carbon, and aramid fibers are used as reinforcements, the most common type being E-glass rovings. Fabrics and mats are also used to add bidirectional and multidirectional strength properties. Unsaturated polyester is the most common resin material for the pultrusion process. Vinylesters and epoxies can be used for improved properties but the processing of these resins becomes difficult. Moreover, the pulling speeds with these resins are lower because of lower resin reactivity.

Tooling

For the pultrusion process, steel dies are used to transform resin-impregnated fibers to the desired shape. Dies have a constant cross-section along their length, except for some

tapering at the raw material entrance. The dies are heated to a specific temperature for partial or complete cure of the resin. Dies are segmented for easy assembly, disassembly, machining, and chrome plating. At the joining of these segments, surface marks (parting lines) are created on the pultruded part.

Basic Processing Steps

The major steps performed during the pultrusion process are described here. These steps are common in most pultrusion processes:

1. Spools of fiber yarns are kept on creels.
1. Several fiber yarns from the spool are taken and passed through the resin bath.
2. Hardener and resin systems are mixed in a container and then poured in the resin bath.
3. The die is heated to a specified temperature for the cure of resin.
4. Resin-impregnated fibers are then pulled at constant speed from the die, where resin gets compacted and solidified.
5. The pultruded part is then cut to the desired length.
6. The surface is prepared for painting. Surface preparation is an important element to perform finishing operations because the pultrusion process utilizes internal mold releases. These mold releases are a form of wax that form a film on the outer surface of the part. This film can be removed by solvent wiping, sanding, or sandblasting. Solvent wiping is the simplest method of surface preparation. Several solvents (e.g., toluene, xylene, methylene chloride, or acetone) can be used for this purpose.

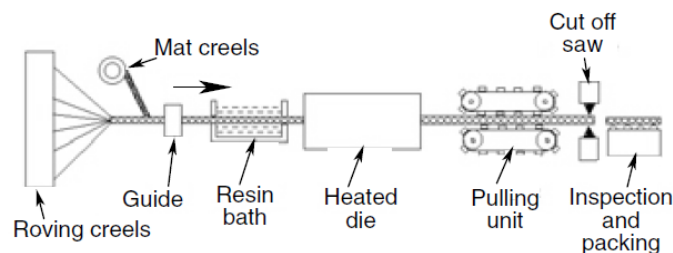


Illustration of a pultrusion process

Methods of Applying Heat and Pressure

During pultrusion, there is no external source to apply pressure for consolidation. Therefore, this process is known as a low-pressure process. The resin impregnated rovings or mat, when passed through a restricted passage of the die, gets compacted and consolidated. The die is heated to a temperature and applies heat to incoming material for desired cure. The heat in the die cures the resin. The part coming out of the die is hot and is allowed to cool before it is gripped by the puller.

Following are some of the considerations while manufacturing and designing pultruded parts.

Wall Thickness: Wherever possible, select uniform thickness in the cross-section because it provides uniform cooling and curing, and thus avoids the potential of residual stress and distortions in the part. Moreover, uniform thickness will provide uniform shrinkage in the part and thus will limit the warpage in the product. Typically, 2 to 3% shrinkage occurs in the pultruded part. Also, maintain symmetry in the cross section for minimal distortion. For high-volume production, the thickness of the part is critical because the curing time and therefore the rate of pull depend on the thickness of the part. Therefore, if a design requires high rigidity in the part, then it can be achieved by creating deeper sections with thinner wall or by including ribs in the cross-section.

Corner Design: In a pultruded part, avoid sharp corners and provide generous radii at those corners. Generous radii offer better material flow at corners as well as improve the strength by distributing stress uniformly around the corner. A minimum of 0.0625-in. radius is recommended at corners. Another important consideration in the design of corners is to maintain uniform thickness around the corner. This will avoid the build-up of resin rich areas, which can crack or flake off during use. Moreover, uniform thickness will provide uniformity in fiber volume fraction and thus will help in obtaining consistent part properties.

Tolerances, Flatness, and Straightness: Pultrusion is a low-pressure process and therefore does not offer tight tolerances in the part. Shrinkage is another contributing factor that affects tolerances, flatness, and straightness. The cost of a product is significantly affected by tolerance requirements. Tight tolerance implies higher product cost. Therefore, whenever possible, provide generous tolerances on the part as long as the functionality of the product is not affected.

Surface Texture: Pultrusion is a low-pressure process and typically provides a fiber-rich surface. This can cause pattern-through of reinforcing materials or fibers getting easily exposed under wear or weathering conditions. Surfacing veils or finer fiber mats are used as an outer layer to minimize this problem. To create good UV and outdoor exposure resistance, a 0.001- to 0.0015-in. thick layer of polyurethane coating is applied as a secondary operation.

Advantages of the Pultrusion Process

Pultrusion is an automated process with the following advantages:

1. It is a continuous process and can be completely automated to get the finished part. It is suitable for making high-volume composite parts. Typical production speeds are 2 to 10 ft/min.
2. It utilizes low-cost fiber and resin systems and thus provides production of low-cost commercial products.

Limitations of the Pultrusion Process

Pultruded components are used on a large scale in infrastructure, building, and consumer products because of lower product cost. However, pultrusion has the following limitations.

1. It is suitable for parts that have constant cross-sections along their length. Tapered and complex shapes cannot be produced.
2. Very high-tolerance parts on the inside and outside dimensions cannot be produced using the pultrusion process.
3. Thin wall parts cannot be produced.
4. Fiber angles on pultruded parts are limited to 0°. Fabrics are used to get bidirectional properties.
5. Structures requiring complex loading cannot be produced using this process because the properties are mostly limited to the axial direction.

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. In the commercial sector, the predominant thermoplastic manufacturing techniques include injection molding, compression molding, and, to some degree, the autoclave/prepreg lay-up process. However, most of the manufacturing processes (e.g., filament winding and pultrusion) available for thermoset composites are also used for the production of thermoplastic composite parts. There is a major difference in the processing of thermoplastic composites as compared to thermoset composites. In the case of thermoplastics, processing can take place in matter of seconds. The processing of thermoplastics is entirely a physical operation because there is no chemical reaction as there is in thermoset composites.

Autoclave Molding(3)

Autoclave molding is a modification of pressure-bag and vacuum-bag molding. This advanced composite process produces denser, void free moldings because higher heat and pressure are used for curing. and resin, a nonadhering film of polyvinyl alcohol or nylon is placed over the lay-up and sealed at the mold flange. Autoclaves are essentially heated pressure vessels usually equipped with vacuum systems into which the bagged lay-up on the mold is taken for the cure cycle. Curing pressures are generally in the range of 350 to 700 kPa and cure cycles normally involve many hours. The method accommodates higher temperature matrix resins such as epoxies, having higher properties than conventional resins. Autoclave size limits part size. It is widely used in the aerospace industry to fabricate high strength/weight ratio parts from preimpregnated high strength fibers for aircraft, spacecraft and missiles. Many large primary structural components for aircraft, such as fins,

wing spars and skins, fuselages and flying control surfaces, are manufactured by this method. The starting material for autoclave moulding process is prepreg (Fig.2.11). A prepreg contains 42% weight of resin. If this prepreg is allowed to cure without any resin loss the cures laminate would contains 50% volume of fibers. Since, nearly 10% weight of resin flows out during the moulding process, the actual volume of fiber in the cured laminate is 60%. After layup, a porous release cloth and a few layers of bleeder papers are placed on top of the prepreg stack. The bleeder paper is used to absorb the excess resin in the moulding process. The complete layup is covered with another Teflon sheet and then a thin heat resistant vacuum bag. The entire assembly is kept inside a preheated autoclave where a combination of pressure and temperature is applied and the plies are converted into a solid laminate.

Cure cycle of an epoxy prepreg consists of two stages:

The first stage consists of increasing the temperature up to 130°C and dwelling at this temperature for 60 min. When the minimum viscosity reaches external pressure is applied to flow out the excess resin into the bleeder papers. This will remove the air entrapment and volatile from the prepreg. At the end of temperature dwell, the autoclave temperature resets to the actual curing temperature of the resin. The cure temperature and the pressure is maintained for 2 hours or complete cure takes place. At the end of the cure cycle, the temperature is slowly reduced while the laminate is still under pressure. Finally, the laminate is removed from the bag and post cured if needed.

Equipment

The following data have to be specified for autoclave:

1. Maximum operating temperature
2. Rate of temperature rise
3. Rate of temperature decrease
4. Temperature control stability
5. Stabilized temperature uniformity
6. Maximum pressure
7. Pressurizing medium
8. Pressurization
9. Depressurization
10. Number of vacuum stations
11. Maximum exterior surface temperature
12. Workspace size
13. Heating

14. Cooling

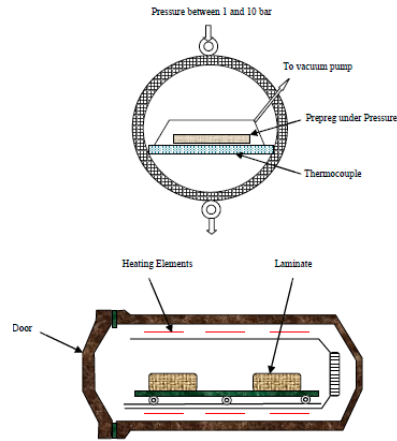


Figure 2.11 Autoclave molding

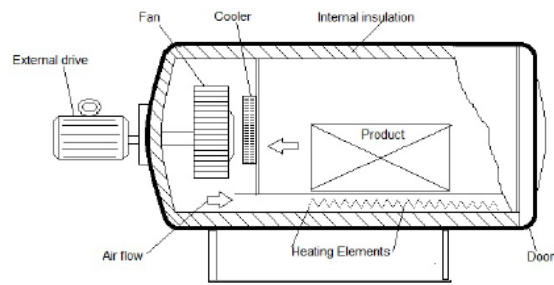


Figure 2.11a Autoclave Setup

References:

1. P.K. Mallick, "Fiber reinforced composites, Materials, Manufacturing and Design", CRC Press, 2008.
2. Sanjay K. Mazumdar "Composites Manufacturing, Materials, Product and Process Engineering", CRC press, 2002.
3. Prof. R. Velmurugan, "Composite Materials", Dept. of Aerospace Engg., Indian Institute of Technology, Madras