5
Component Form and Manufacture

5.1 Introduction

Because fiber reinforcement is essentially a one-dimensional strengthening process, a major function of the component-forming process is to orientate the fibers in the matrix in the appropriate directions and proportions to obtain the desired two-dimensional or 3-dimensional mechanical properties. The forming process must also produce the shape of the component and develop the required properties of the matrix and the fiber/matrix bond. The forming process must not damage the fibers and must ensure that they are reasonably evenly distributed in a matrix, free from significant voiding or from large areas devoid of fibers.

The simplest method that satisfies these requirements is to infiltrate an appropriately aligned fiber bed with a liquid, which is then converted by chemical reaction (in the case of thermosets) or simply by cooling (in the case of thermoplastics) to form a continuous solid matrix with the desired properties. Techniques based on liquid resin are known as liquid molding, with several subcategories according to various modifications of the process.

Alternatively, sheets of aligned fibers may be pre-coated with matrix precursor and the continuous matrix formed by flowing the coatings together (and curing, if a thermoset matrix) under heat and pressure. In this widely used form, the material is known as pre-preg (pre-impregnated).

There are several methods that can be used to arrange the fibers when forming the composite structure. The main method for the manufacture of aircraft components is laminating woven cloth, or aligned fiber sheets, with the fibers orientated in appropriate directions in each layer.

There are also several methods based on continuous fiber tow or yarn; these include:

(1) filament winding onto a rotating mandrel; (2) braiding onto a rotating mandrel (the process of braiding is covered in detail in Chapter 14); (3) tow placement; and (4) pultrusion.

The main differences between the use of thermosets and thermoplastic matrices are the need for extended times to cure (cross-link) the thermosets and the relatively high viscosities of the thermoplastics melts and the consequential requirement for high processing temperatures and pressures. Table 5.1 lists generic aircraft components made using these manufacturing procedures.

Table 5.1 Typical Aircraft Fiber Composite Forms Made by the Different Techniques, as Listed

Type of Structure	Typical Application
Laminates	
Sheets, thick monolithic	Wing skins
Sheets, integrally stiffened	Tail skins
Sandwich panels	Control surfaces, floor sections
Shells	Fuselage sections
Beams	Spars/ribs
Complex forms	Aerofoils
Filament Wound	
Closed shells	Pressure vessels
Open shells	Radomes
	Rocket motors
Tubes	Drive shafts
Secondary formed tubes	Helicopter blades
Braided	
Tubes	Drive shafts
Complex tubes	Curved pipes
	Truss joints
	Ducts
Closed shells	Pressure vessels
Secondary formed	Fuselage frames
	Aircraft propellers
	Helicopter blades
Tow Placed	
See laminates	See laminates
Complex wraps	Grips
	Shafts
	Ducts
Pultrusion	
Beams	Floor beams
	Stringers
	Spars
	Ribs
	Longerons

Considerable structural and cost efficiency can be obtained by using the composite in the most highly stressed regions, for example, in the upper and lower surfaces of components subject to bending or buckling. This is achieved by using a sandwich construction, as also listed in Table 5.1, with the composite laminate forming the outer skins, which are bonded to a metallic or polymeric composite honeycomb or polymeric foam core. The metallic honeycomb is generally an aluminum alloy such as 5052, often with a coating or anodized layer to resist corrosion. The composite honeycomb would generally be glass-reinforced epoxy or phenolic; however, the most usual honeycomb material is Nomex, which is the trade name for a composite based on random meta-aramid fibers in a phenolic matrix. The foam core used for aerospace applications is generally made of PVC, but this material is not generally used in applications exposed to high temperatures. Polyetherimide (PEI) and polymethacrylimide (PMI) polyimide foams are alternative cores for higher-temperature applications.

This chapter deals primarily with pre-preg laminating procedures in some detail because this is the prime method for manufacturing aircraft composite components. Methods based on liquid resin are then considered, followed by details of the various processes, resin transfer and infusion, and filament winding and pultrusion. Finally, the particular processes for manufacturing with thermoplastic resins are covered.

5.2 Outline of General Laminating Procedures

Most reinforced-plastic components based on long fibers are manufactured by some form of laminating procedure.[1] In this process, sheets of reinforcement, pre-coated with resin (pre-preg) or with resin freshly applied, are forced against the surface of a mold under the required conditions of pressure, temperature, and time. Chapter 3 provides details of some of the cloth materials available, and details of the pre-pregging process are provided later in this chapter.

5.2.1 Open Die Molding

Open die molding involves the use of only one mold surface, over which the layers of fiber are placed or "laid-up." If dry cloth is used, the resin may be applied by brushing or spraying. With care and suitable materials, this method (which is still widely used outside the aircraft industry) can produce good-quality parts. However, handling wet resins can be messy and can raise occupational health and safety (OH&S) concerns. In addition, a particular concern with the use of wet lay-up in aircraft-part production is the lack of repeatability of the process, especially the control of resin content and therefore the weight, thickness, and mechanical properties. Some smaller companies, notably in the German Glider Industry, have adopted wet pre-preg dispensing machines, which saturate reinforcement fabric on demand with a controlled amount of liquid resin, normally epoxy, and hardener. This solution is cheap and flexible, and it does not require cold storage.

Various methods are engaged to apply pressure to consolidate the lay-up. In contact molding, which is generally used only for fairly low-stress applications of glass/polyester composites, the pressure is developed by hand-rolling over a sheet of plastic film placed over the surface of the lay-up.

The bag procedure involves the use of a flexible plastic membrane that is formed over the surface of the lay-up to form a vacuum-tight bag. In vacuum bagging, the bag is evacuated and atmospheric pressure used to consolidate the lay-up against the surface of the mold. The vacuum initially removes most of the air and volatile materials. Vacuum bagging is an inexpensive and versatile procedure; however, it can provide only limited consolidation pressure and may produce voided laminates due to the enlargement of the bubbles (formed by any residual gases or volatile material) trapped in the resin in regions where the bag is unable to apply pressure, for example, because of local bridging. To minimize this problem, autoclave procedures, described later, are used to manufacture most of the high-quality laminates used in the aircraft industry.

Alternatively, pressure may be applied to the surface of an open mold by means of a flexible plunger mounted in a press, by gas-bags, or by thermal expansion of an entrapped rubber or metallic insert.

Temperature, generally required to cure the resin, can be applied to the open mold in various ways, including external methods such as hot-air blowers and ovens or internally by electric elements or steam or oil pipes buried in the mold. Temperatures up to 180 °C may be required in aerospace-grade epoxy resin systems.

5.2.2 Compression Molding

Compression or matched-die molding involves the use of matching male and female dies that close to form a cavity of the shape of the component (Fig. 5.1). The dies, generally made of tool steel, can be internally heated, if required, by electric elements or steam, or hot oil pipes. The fiber layers are placed over the lower mold section, and the two halves of the mold are brought together in a press. Lands built into the mold usually control the thickness of the part. Advantages of matched-die molding include excellent dimensional control; high-quality surface finish, produced on both surfaces; high production rates; and good consolidation and high fiber content.

However, the cost of the matching dies (with hardened faces) is very high, and the size of the available hydraulic presses used to apply the closing pressure limits the size of parts that can be produced.

Wet laminating procedures may be used, in which case the dry fiber is laid in the mold and the resin added. High-quality fiber composite components are generally based on the use of pre-pregs or by the use of a solid, but uncured, resin film that is laid on the mold surface, followed by dry fiber layers or a fiber preform.

Alternatively, a liquid resin can be injected into the sealed and evacuated mold cavity, as discussed later.

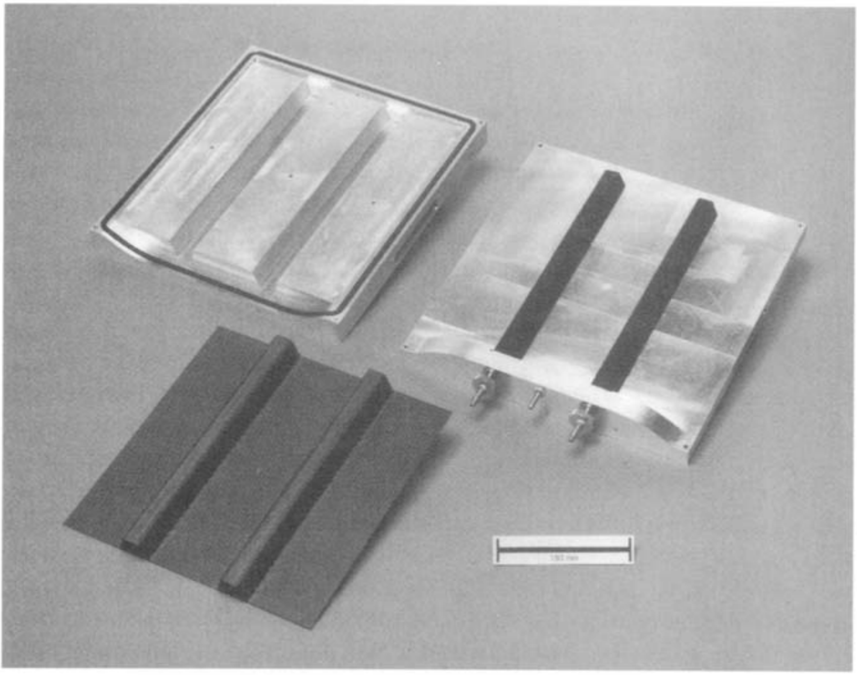


Fig. 5.1 Matched-die mold and resulting top-hat stiffened component.

5.2.3 Wrapping

Wrapping is an alternative procedure to filament winding, described later, for producing tubular components. A pre-preg sheet, either wrap sheet or cloth, is wrapped onto a removable metal mandrel and cured under pressure. Special machines are available to perform the wrapping operations. The pressure during an elevated temperature cure may be applied by the use of shrink film (applied by a tape-winding machine), vacuum bag, or autoclave. Alternatively, a silicon-rubber bladder may be placed over the mandrel before the wrapping of the laminate. Pressure is applied to the laminate through-inflation of the bladder that forces the laminate against an outer mold surface. This technique is often used to make fishing rods, golf clubs, and tennis rackets.

5.3 Laminating Procedures For Aircraft-Grade Composite Components

Major aircraft manufacturers and their subcontractors, especially in the United States, use B-staged epoxy pre-preg as their preferred material form. In this material, the reinforcement is pre-impregnated by a supplier with a resin already containing hardener.[2] This has been partially cured (B-staged) such that the resin does not flow at room temperature, but at the same time it remains tacky (sticky to the touch). B-staged epoxy pre-pregs are normally staged (partially cured) to about 15% of full cure for hand lay-up, and up to 25% for automated lay-up. To protect this material and keep it from sticking to itself, a backing or release film is added to at least one side of the pre-preg before it is rolled up for storage or transport.

5.3.1 Pre-Preg Production

A pre-preg can be made incorporating a variety of reinforcement fabrics and fiber types. Although it can be produced by the component fabricator, it is normally purchased from a materials-supply company. The following material forms are available as carbon/epoxy pre-pregs.

Woven bi-directional cloth pre-preg is most commonly made from plain weave or satin weave fabrics, 0.2–0.4 mm thick and up to 1200 mm wide. One common method of pre-impregnation is to infuse the cloth with matrix resin diluted with solvent to lower its viscosity. The pre-preg then passes through a heating tower to remove the solvent and stage the resin. The newer hot-melt method (See Fig. 5.2) involves first continuously casting a B-staged resin film on a non-stick backing film of coated paper or polymer. A doctor blade is used to control the thickness of the resin film applied (the same method used to make adhesive film). The reinforcement is then sandwiched between two of these films as it passes through a pair of heated rollers. This process has an advantage over the solvent process in that it produces lower volatile emissions.

Unidirectional pre-preg (warp sheet) is made by spreading and collimating many fiber tows (typically around 10^4 fibers in each tow) into a uniform sheet of

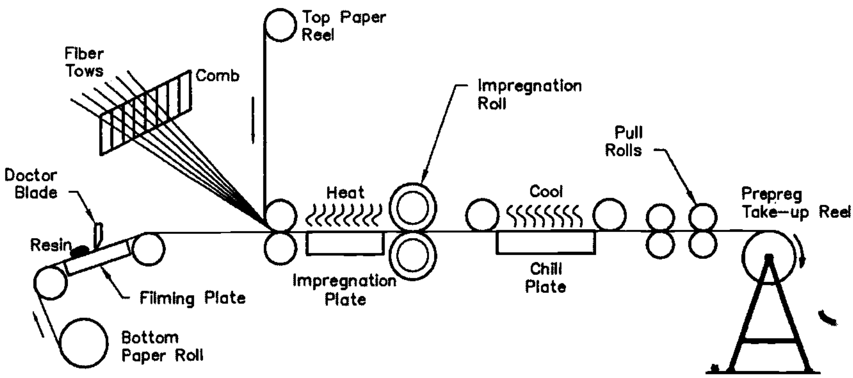


Fig. 5.2 Schematic illustration of hot-melt film pre-pregging process. Adapted from Ref. 2.

parallel fibers typically 0.125–0.25 mm thick and 300 or 600 mm wide. This is immediately pre-impregnated. Unidirectional pre-preg is the cheapest to make, and it provides laminates with the best mechanical properties. However, it may be difficult to lay into double-curved shapes. Other types of reinforcement architecture, such as multi-axial warp knit (also known as non-crimp, knitted, or stitched) fabrics can also be pre-impregnated, but the process becomes increasingly difficult as the fabric becomes thicker.

The pre-preg with its non-stick backing films is then inspected for resin content, which is typically between 34% and 42% by weight for carbon pre-pregs, wound onto a roll, and sealed to prevent the absorption of water vapor. Some pre-pregs have up to 15% more resin than is required to form a laminate with the desired fiber/volume fraction. With these pre-pregs, the resin is required to bleed out of the laminate during curing. Low-bleed or non-bleed pre-pregs with a more viscous resin are now more popular.

The standard pre-preg thickness for unidirectional materials is of the order of 0.125 mm. More recently, to cut costs, much larger tows are being used, resulting in much thicker pre-pregs; however, because it is more difficult to maintain fiber alignment in thick tows, there is some reduction in mechanical properties of the finished composite.

5.3.2 Pre-Preg Transport and Storage

The major disadvantage of pre-preg (apart from the extra cost of creating it from the fiber and resin) is that once the hardener has been added, the resin begins to react. Therefore the material normally only has a limited "shelf" (storage) life and "shop" (usage) life before the resin has reacted sufficiently for the pre-preg to become stiff and intractable for lay-up, or for the quality of the resulting composite to suffer. Most pre-pregs need to be stored in a freezer, typically at around −20°C, which halts or at least greatly slows down the curing reaction in the resin. Pre-pregs generally used in aerospace are cured at elevated temperatures, typically 120°C or 180°C for epoxy resins. Because the resin is designed to react at elevated temperature, the supplier can normally guarantee a shelf (freezer) life of 6 months to a year, and a shop life ("out" life at room temperature) of at least 2 weeks.

If the distance from the supplier to the user is long, the pre-preg will need to be shipped in refrigerated shipping containers; or for smaller lots, in insulated packages containing dry ice (frozen carbon dioxide).

5.3.3 Cutting and Kitting

When pre-preg is required for use, it is thawed to room temperature before being removed from its bag to avoid picking up condensation. The pre-preg is then moved into the cutting room, which like the lay-up room is maintained as a "clean room," free of dust and with controlled temperature (around 20°C) and humidity (e.g., between 50–70% RH). The pre-preg is then unrolled onto the cutting table, with its backing paper still in place. Plies of the required size, shape, and fiber orientation are then cut from the roll; as an example, Figure 5.3 shows a ply stack for a wing rib. This can be done by hand-using a template, or with a die in a roller press; in all but the smallest operations, this is usually done by a numerically controlled flat-bed cutter similar to those used in the textile industry. Cutting is usually achieved using an oscillating blade, but sharp "draw knife" blades as well as lasers or water jets are also used. Some cutters can cut multiple layers of fabric. Some flat-bed cutters can also label the plies automatically. The various ply shapes are then labelled, if necessary, and assembled as part of a kit containing all the plies for a component, which may be delivered directly to the lay-up room or sealed and stored in a plastic bag in the freezer for later use.

Abrasive water jet cutting uses a high-pressure water stream, perhaps up to 400 MPa, which is forced through a small sapphire orifice to produce a supersonic jet travelling at speeds up to 900 m s^{-1}, carrying abrasive particles to form a powerful cutting jet. Most materials can be machined with the water jet's ability to revolve with the robotic end effector. The critical process parameters are speed; stand-off distance; impact angle; water-jet pressure; water flow rate; orifice diameter; abrasive particle shape, hardness and size; and nozzle mixing tube geometry and material. Generally, the impact angle can be optimized to produce the maximum removal rate. The work-piece material should be softer than the abrasive compound. Oscillation of the cutting head can also influence the quality of the cut.

Laser cutting can be considered a thermal process as a portion of the beam energy is absorbed by the surface material, and this energy raises the temperature

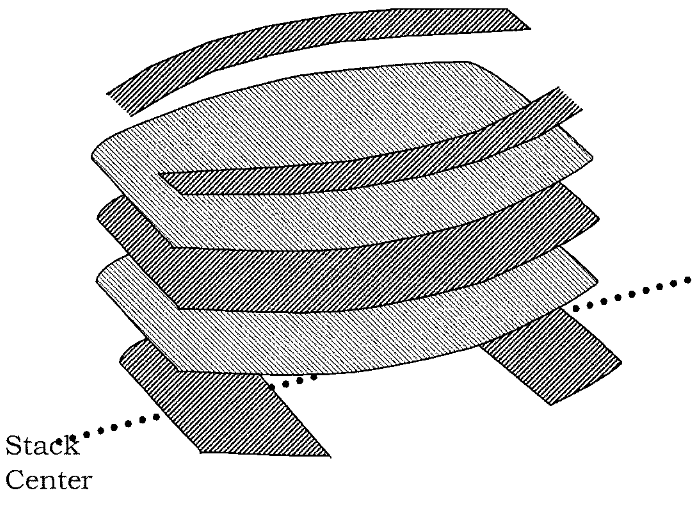


Fig. 5.3 Schematic diagram of a typical ply stack for a wing rib.

of the material. A sufficient amount of such energy will cause local decomposition of the material. Some compromise is required when focussing the laser beam as minimum spot size (a result of using short focal length lenses) is achieved at the expense of depth of field. The creation of thermal energy during cutting can produce problems in the course of dealing with standard epoxy pre-preg systems producing local cure and toxic vapors.

All methods of cutting for complex geometry flat shapes must be capable of operation with either a standard robot or gantry-type equipment.

5.3.4 Lay-Up

Most aerospace components are still laid-up by skilled labor, although considerable efforts are being made to automate or mechanize the process, as described in the subsequent sections. Hand lay-up is very versatile because human hands make excellent grippers, eyes marvellous sensors, and the brain a powerful process control and quality control unit! Any residual dust or resin from previous use is cleaned off before a thin layer of release agent is applied to the surface, where necessary. The mold will then be moved into the lay-up clean room.

The pre-preg plies are then applied to the mold in the correct position, orientation, and sequence according to a set of instructions sometimes called a ply book; these instructions may be viewed on a computer screen. The ply is located on the surface by reference to markings on the mold or with the aid of a rigid or flexible template. Many companies now have lay-up stations where an overhead projector rapidly scans a low-power laser beam to "draw" the outline of each ply on the mold surface. These machines can also project instructions for ply lay-up onto the mold.

Typically, the lower backing paper is removed by the operator before lay-up, and the upper one after positioning and consolidating using rollers or other simple tools. For larger plies, two or more operators may be required to handle and position the tacky pre-preg. Where the mold surface is doubly-curved, the pre-preg needs to be further distorted, enabling it to fit the surface.

Different types of material may be combined in the same lay-up as long as the materials are compatible. For instance, in sandwich structures, aluminium or Nomex honeycomb and adhesive films will normally be combined with carbon-epoxy pre-preg to form the structure. Different fibers such as glass and carbon may be combined to form hybrid lay-ups, and different reinforcement arrangements such as unidirectional tape and woven fabric may be combined.

5.3.5 Automated Forming of Pre-Preg Stacks

To reduce lay-up times and consequently labor costs, automated or semi-automated methods have recently been introduced to aircraft component production lines.

Instead of shaping and consolidating (laying up) each ply separately by hand, a flat stack can be assembled by manual or mechanical means. This flat stack can then be formed into the required shape using various methods; pressing, stamping, or diaphragm-forming. One version of the diaphragm-forming process is illustrated in Figure 5.4. A flat pre-preg stack is laid up and placed over a male-forming die. A diaphragm is fitted and sealed to the forming box. A vacuum is then applied to the box cavity. Because they are not extensible in the fiber direction, the plies must deform by shear to conform to the shape of the tool. It may be necessary to heat the flat pre-preg stack to a temperature above room temperature to assist forming. An infrared heating source is often used for this purpose.

This process is most attractive for deep draws, and consequently the shear deformation required can be considerable. There are three main modes of deformation: intraply shear (a trellising action in which the fiber tows pivot at the crossover points), slippage between plies, and ply out-of-plane bending. The main problem is to avoid wrinkling of the plies caused by the development of compressive residual stresses. Computer simulation to assist in predicting the optimum conditions for forming is a recent development discussed later in this chapter.

5.3.6 Automated Lay-Up

Lay-up of large components such as wing skins requires automation because, owing to the time required for hand lay-up, materials may be close to their out-life when the task is nearing completion.

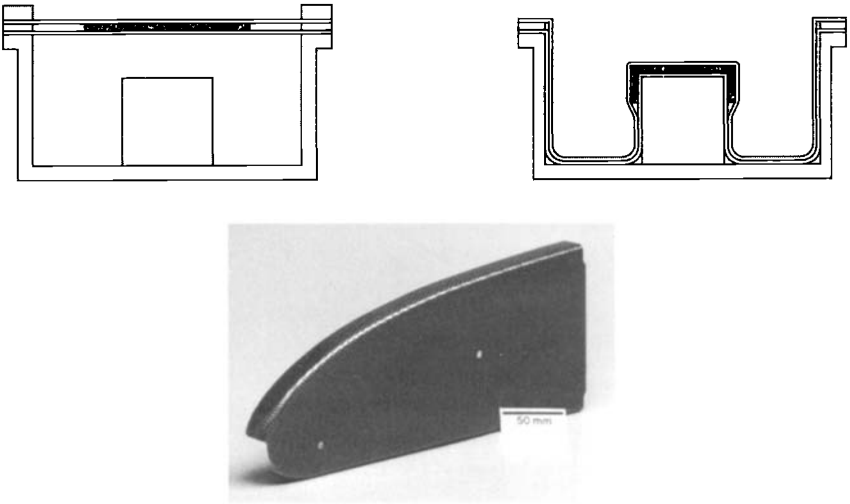


Fig. 5.4 Schematic diagram of the diaphragm-forming process; below, carbon fiber-epoxy rib made using this process.

There are two established approaches to automating the lay-up process: automated tape layers (ATL) and automated tow placement (ATP) machines. ATL machines normally consist of a gantry with a dispensing head that is free to move over the surface of the tool. Generally, unidirectional pre-preg tape is placed onto the surface (Fig. 5.5) according to a programmed routine.

As the tape is placed on the surface, the backing layer is stripped away, and the surface of the tool may be heated to aid tack of the pre-preg. Tape width is typically around 300 mm, and the lay-down rate is of the order of 50 m min^{-1}. Advanced ATLs are capable of laying tape onto a highly contoured surface. However, these machines are very costly and can be justified only where long runs of expensive components, such as tail or wing skins, are to be made.

ATLs are also being developed for use with thermoplastic pre-pregs. In this application, a gas flame or laser is used to heat the tape as it is laid down and a consolidation roller is then used to form the composite layer.

The limitations to the capability of ATL machines to manufacture more complex shapes has led to the development of automatic tow placement (ATP) systems. These machines lay down multiple pre-preg tows and are able to stop, cut, and restart individual fiber tows. A multi-axis manipulator arrays a group of pre-preg tows into a continuous band and compacts them against the surface of the lay-up tool. This allows more complex shapes to be fabricated, including lay-up onto relatively severe and complex curves and the steering of tows into curved trajectories. Heat and pressure are used to ensure proper adhesion and consolidation of the material.

ATPs offer the potential for greater structural optimization by locating fiber where it is most effective. Some systems are combined with a spindle, (Fig. 5.6) to allow lay-up of closed shapes such as ducts, combining the advantages of both filament winding and automated tape lay-up while alleviating some of the problems associated with each. However, these are, so far, even more expensive to purchase and operate and have been limited to use on military aircraft

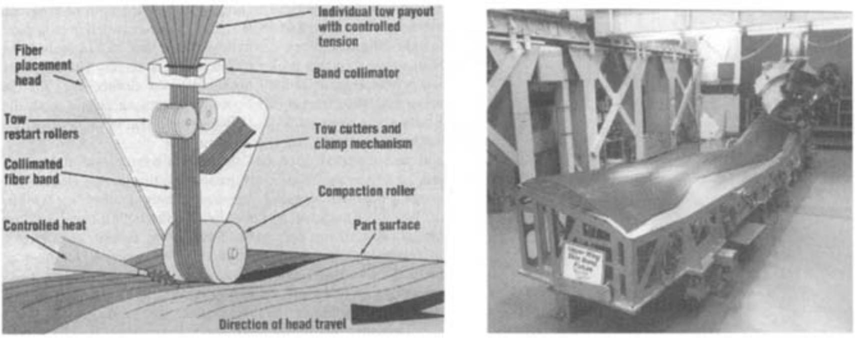


Fig. 5.5 Schematic diagram of an automatic tape-laying process (*left*) and a typical product (*right*).

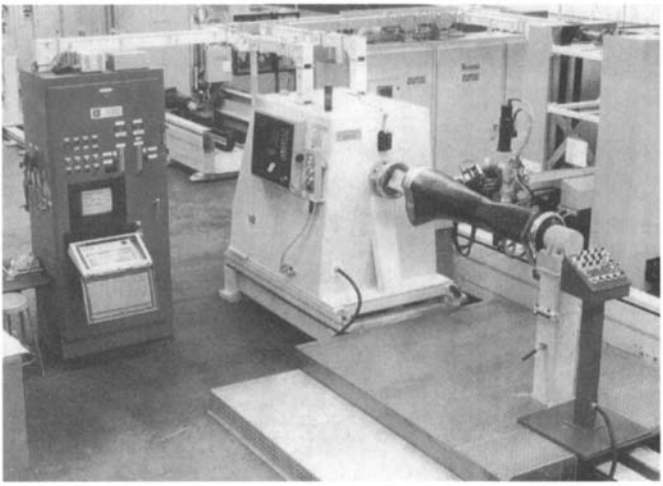


Fig. 5.6 An automatic tape placement system in use at Bell Helicopter from Automated Dynamics Corporation literature.

programs and in cases where the complexity of shape means that the part cannot be practicably fabricated in any other way.

5.3.7 Bagging

After all plies have been laid-up and inspected, the lay-up is prepared for curing. An autoclave or vacuum bag will be applied over the surface of the lay-up and sealed to the mold, so that a consolidating pressure can be applied during cure by evacuating the space under the bag, and/or by increasing the outside pressure. As illustrated in Figure. 5.7, the bagging process uses a number of different materials. These include:

- Release film—a smooth non-stick film often made from fluro-polymers, placed over the lay-up, which may be perforated to allow passage of gases or resin
- Breather fabric—transmits gases even under pressure and is used to allow gases to flow from all over the part to the vacuum fitting
- Bleeder fabric—used to soak up excess resin, especially in high-bleed pre-pregs
- Vacuum bag film, normally nylon
- Mastic tape—also called tacky tape and often made from butyl rubber; used to seal the edge of the bag to the mold

In addition, for surfaces to be bonded, a peel ply (non-bonding woven cloth, such as nylon) is placed on the surface of the lay-up. During the cure this is incorporated into the surface resin and is subsequently peeled off to create a clean, roughened surface that is ready for adhesive bonding.

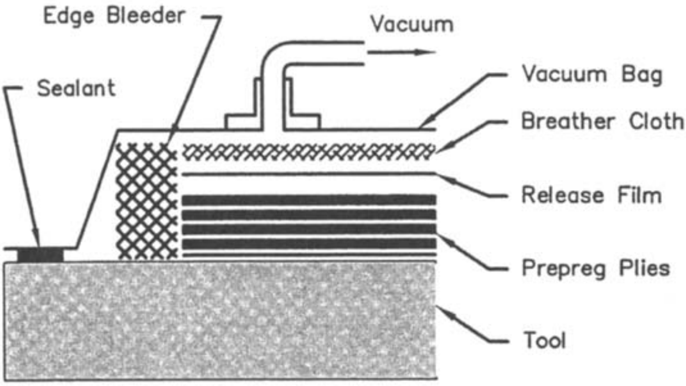


Fig. 5.7 Schematic diagram of a vacuum bag lay-up, indicating the various layers used Taken from Ref. 2.

The bagging must allow an even consolidation pressure to be applied to the part, while at the same time allowing any gases trapped in the lay-up or generated during curing to be removed from the system. The gases include volatiles from solvents left in the resin during the pre-pregging process, water, and air.

The cost of the non-reusable materials described above is considerable; many companies use permanent, shaped vacuum bags made from high-temperature elastomers. Where thermocouples are not embedded in the mold, these may be inserted into the edge of the lay-up through the edge sealant.

Vacuum bags are also applied temporarily during the lay-up process to tack the pre-preg firmly onto the mold, to consolidate previous pre-preg layers, and to allow the removal of air and volatiles. This process is often called debulking and may be required at the introduction of each ply in some complex-shaped parts, especially those with sharp corners.

Where it is critical that both surfaces of a part be smooth and of controlled dimensions, matched (usually metal) tooling can be used, as described previously. In these cases, most of the bagging materials are not required, and even the vacuum bag need not be used if the matched molds include integral seals. Careful control of tool contour, pre-preg resin content and placement, cure pressure, and resin bleed are necessary for successful matched-die molding with pre-pregs.

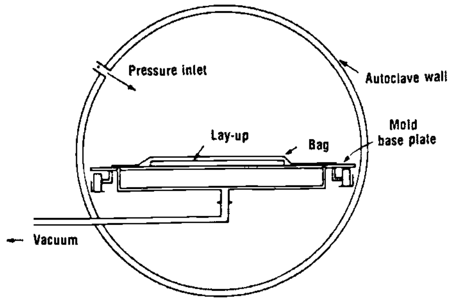
Alternatively, if a smooth outer surface is required, but control of tolerance is not required to a high level, a caul plate may be used. This is a stiff, free-floating plate or mold of the outer surface which is placed on the lay-up, just above the release film

5.3.8 *Curing*

The majority of aerospace composite parts with thermosetting matrices are cured at elevated temperatures to ensure that the service temperature of the composite is sufficiently high. As a typical example, a carbon/epoxy composite cured at 180°C for 2 hours might have a glass transition temperature (T_g) of 200°C when dry, but only 160°C when saturated with moisture. This would allow the composite to be used at a maximum service temperature of around 135°C.

As mentioned earlier, composites may be cured in an oven under a vacuum bag, but the best results come from the use of pressure above one atmosphere (compaction pressure), usually generated in an autoclave. The autoclave is basically a very large, internally heated pressure vessel, with internal connections for vacuum hoses and sensors such as thermocouples (Fig. 5.8). The autoclave is usually computer controlled, and often pressurized with nitrogen or carbon dioxide to reduce the risk of an internal fire. A standard machine for epoxy composites will be capable of temperatures over 200°C and pressures over 700 KPa. Autoclaves for processing thermoplastic composites or high-temperature thermoset composites may be capable of 400°C and 1200 KPa or more. The part is normally heated by convection of heat from the fan-forced air circulation, although electrically heated molds are sometimes used. Although more costly, there are several advantages in heating the mold, including more rapid and uniform heating and the ability to use high temperatures as the walls of the autoclave remain cool.

Normally the lay-up will be under vacuum from the time it leaves the lay-up room and while it is loaded into the autoclave, to keep the lay-up in position and help remove air and volatiles. The vacuum and sensor connections will be checked before the autoclave door is closed and the cycle commences. Pressurization and heating will begin immediately, and the target pressure will be reached in less than 30 minutes whereas, in thick parts, the target temperature may not be reached for several hours. After more than 100 KPa (gauge) pressure has been reached in the autoclave, the space under the vacuum bag is vented



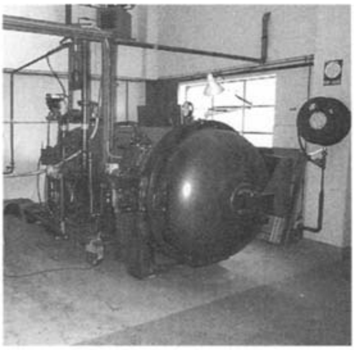


Fig. 5.8 Layout of an autoclave and, *right*, a small typical autoclave.

(connected to the atmosphere) to discourage the growth of existing bubbles and the generation of new bubbles, from entrapped gases and volatiles, in the resin as it is heated. Heat-up and cool-down rates are controlled to ensure even curing throughout the part and to reduce the possibility of residual stresses causing structural deficiencies or distortions.

The viscosity of the resin falls with increasing temperature until the resin begins to chemically cross-link (gel). It is important that full pressure is applied before gelation occurs to allow removal of entrapped gases and removal of excess resin.

Under some circumstances, a dwell is incorporated (isothermal hold), as shown in Figure 5.9, to prolong the time for consolidation and volatile removal. The hold also pre-reacts the resin and reduces the danger of large damaging exothermic reactions that can occur in thick laminates, for example, over 50 plies thick. A hold will also allow the temperature to become more uniform; this is very important in components with large variations in thickness.

The need for complex heating/pressure cycles is important for earlier, less viscous epoxy resins and high-temperature resins because this is necessary to accommodate the requirements of the chemical reactions and to ensure that the resin viscosity is optimum when pressure is increased. Most modern non-bleed epoxy pre-pregs, however, can be processed with a simple "straight-up" cure cycle, provided that the component is not too thick or complex.

If an autoclave is not available, compaction pressure may also be applied by an inflated rubber bladder or by materials with a high coefficient of thermal expansion (CTE) such as silicone rubber, used in conjunction with matched mold tooling. The expansion force generated by these arrangements requires that the

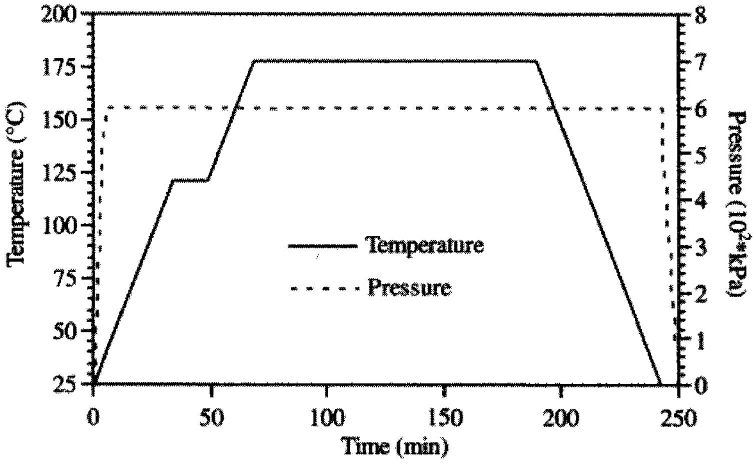


Fig. 5.9 Typical autoclave cycle incorporating a dwell to allow temperature equilibration in thick lay-ups.

tooling be stiff to resist the bending forces applied to the tool. (Bending forces are low in autoclave tooling because the pressure acts on all sides.)

Autoclave molds must be vacuum tight and free of distortions under temperature. Ideally, they should have a low thermal mass to avoid slow heating and cooling and should have a low CTE, similar to that of the laminate.

5.3.9 Cocuring of Complex Components

Complex integrally stiffened components, such as those shown in Figure 5.10, can be manufactured using internal pressurization[3] (Fig. 5.11). There are essentially two methods of applying internal pressure: thermal expansion of a rubber or metallic mandrel, and expansion under autoclave pressure of a rubber bladder. In both cases, the approach is to wrap pre-preg around the internal mandrel, which is inserted into an outer mold containing the outer skins. As shown in Figure 5.10, it may be desirable to arrange for one, usually the top outer skin, to be removable to allow equipment to be installed or for inspection purposes. This can be achieved by introducing a release film between the outer (removable) skin lay-up and the substructure. The outer skin, though cured at the same time as the substructure, can be separated, the release film removed, and the skin mechanically fastened or bonded in a secondary operation.

5.3.10 Processing Problems

The main processing problems encountered in autoclave molding include overheating (caused by excessive exothermic reactions), porosity, resin-rich

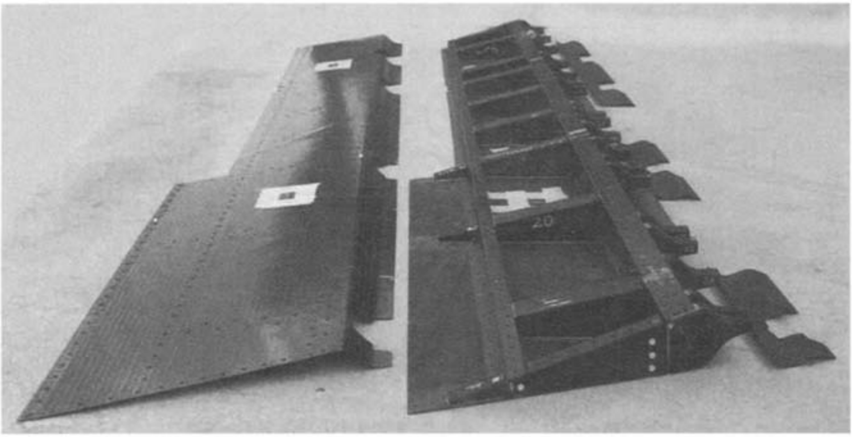


Fig. 5.10 Cocured control surface components with integral lower skin and ribs and removable top skin. Courtesy of CRC-ACS.

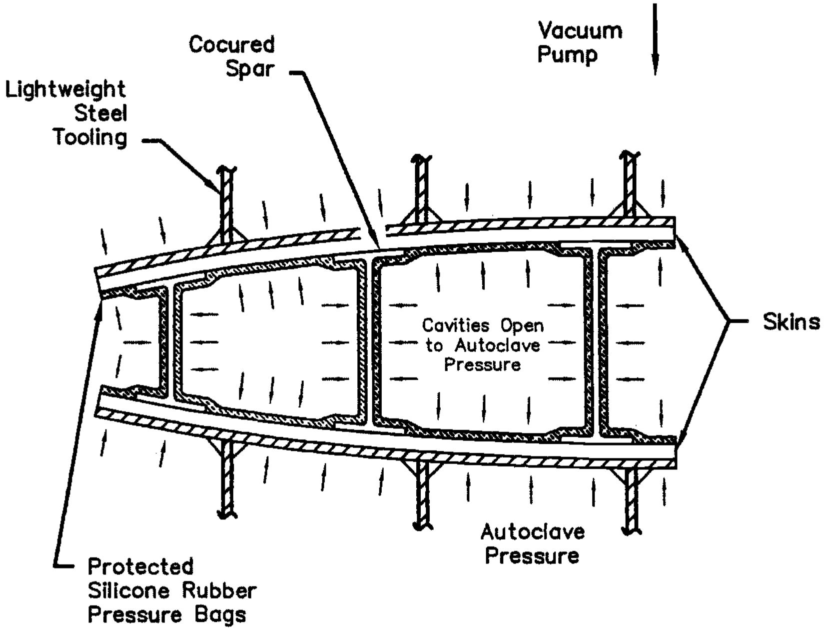


Fig. 5.11 Schematic diagram of the tooling used to make a cocured carbon/epoxy wing structure, using rubber bladder expansion for internal pressurization. Adapted from Ref. 3.

areas, resin-dry areas, poor surface finish, insufficient consolidation, uneven cure, and distortion.

Many of the problems can be resolved by correct timing of application of temperature and pressure and use of pre-preg materials with a wide processing window with (ideally) low exothermic cures.

The formation of voids is generally caused by the entrapment of volatiles, water, and air that have remained after debulking. At the high processing temperatures in the autoclave, more solvents are liberated, and the volume of the solvents and other entrapped gases increases. To avoid the formation of severe porosity, it is necessary that the hydrostatic pressure in the resin before gelation exceeds the partial pressure of the gases, allowing them to be expelled. Once the resin gels no further, void removal or consolidation is possible. Water is often considered to be the main cause of void formation so that the applied pressure needs to exceed the partial pressure of the water.[2]

While a low temperature hold is often used to increase the time at low resin viscosity for the reasons stated above, excessive pressure or over-efficient resin-bleed when the resin viscosity is low may lead to dry spots. Resin-rich areas result when areas in the lay-up have lower resistance to resin-flow and insufficient pressure is applied before gelation.

To reduce surface porosity, a surfacing resin film or fine glass/epoxy scrim ply may be placed on the mold surface before the pre-preg is placed.

The use of honeycomb core in the composite component can result in several problems, of which the most common is core-crushing. The reason for this is illustrated in Figure 5.12, which shows how a lateral force can arise in an autoclave, causing inward collapse of the core.[2] Methods for avoiding this problem include the use of reduced pressure in the autoclave (reduced from 700 to 300 KPa with a concomitant reduction in laminate quality, however) and use of friction grips to prevent the inner pre-preg skin sliding inwards. The gripped skin region must be surplus to the component and must be removed after processing.

Distortion can be a serious problem, and can arise from uneven cure, unbalanced fiber lay-ups, or the expansion differential between the composite

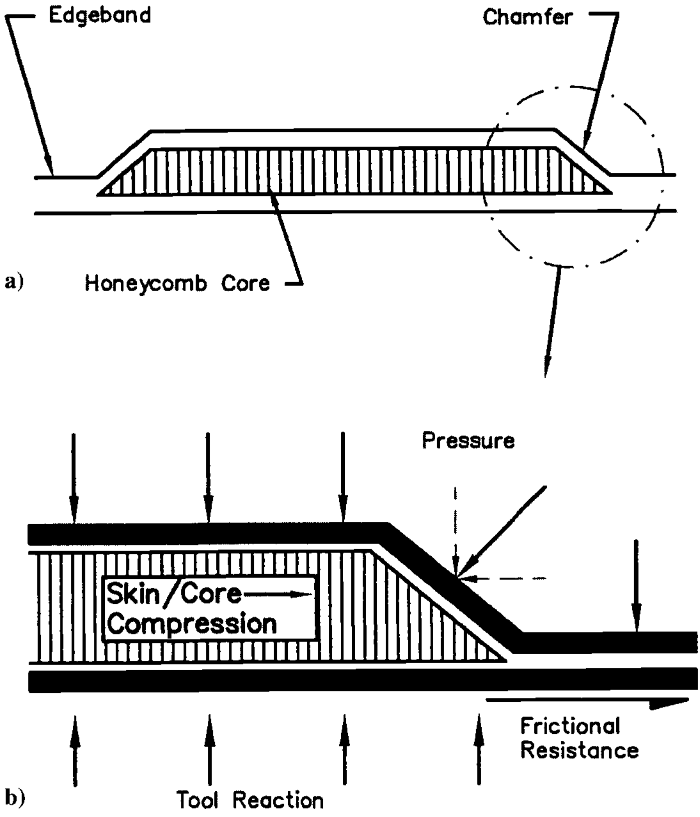


Fig. 5.12 Schematic diagram, showing *a*) a typical honeycomb arrangement incorporating a chamfer and *b*) the origin of lateral crushing forces. Adapted from Ref. 2.

part and the tooling. It will be found that long parts such as spars may appear to have "grown" with respect to the tooling, especially if this is made of a high-CTE material such as steel or aluminum. This phenomenon occurs because the resin is solidified at the curing temperature, and, compared with the tool, the composite shrinks little during cooling. This also can make it difficult to remove some complex components from their mold without damage.

Parts such as "C" sections made on male mandrels may grip the mandrel due to a condition known as *spring-in*, in which composite angles close up slightly (about 1°) during cool-down because of CTE differences between the resin and fiber. Allowance has to be made in the tool design to compensate for this.

5.3.11 Debagging, Finishing, and Painting

The part is normally cooled down to below 60°C before it is removed from the autoclave. The bagging layers are stripped off, and the part is carefully separated from the mold. If the release coating is imperfect or the mold does not have sufficient draught angle for deep parts, this may present processing difficulties.

The part should be smooth on the tool side, but unless matched molds are used, there will be some texture or roughness on the bag side of the part; however, this is minimized if a stiff caul plate is used. Due to slight variations in pre-preg fiber areal weight and resin contents, and in resin-bleed during curing, it is difficult to specify the thickness of a pre-preg part to less than about $\pm 5\%$. This becomes a serious concern in thicker parts such as wing skins, where the choice may be between having a smooth outside surface with the correct aerodynamic contour (outer mold line tooling), and controlling the inner surface dimensions (inner mold line tooling) to allow easy assembly to the substructure.

Any surface blemishes may need to be filled with special putty. For epoxy composites, a typical paint scheme is an epoxy primer coat followed by a polyurethane topcoat. Any residue from the release coating applied to the mold may cause problems with poor adhesion of the paint. For this reason, many parts may be abraded lightly on the surface before painting.

Painting may either be carried out by traditional hand-operated methods or with robots. Robotic painting is normally controlled by computer-aided-design-generated off-line process trajectories. Computer modelling and test simulations can verify the programs before production commitment. Paint application robotics can vary the paint thickness applied that would be specified to suit the service environment. Contemporary systems for automatic paint spraying can be applied to a series of small parts through to a working envelope of up to 3 million cubic feet using gantry-mounted robots.

5.3.12 Trimming and Drilling

Increasingly, trimming and drilling processes[4] are also being carried out automatically by robots.[5]

Some of the attractions of applying automation to these kind of applications are inclusion of a vision system for part recognition, elimination of jigs and templates, high speed and accuracy, and flexibility and in-process inspection.

Routing refers to the shaping of apertures or edge-trimming of components in flat and shaped panels. Robotic manipulation of routing heads with the appropriate cutting device can offer a low-cost solution, particularly when the article is of complex geometry. With automatic tool changers, a robot cell can perform a multitude of functions such as drilling holes and inserting bushes.

Trimming of the part can also be carried out using a water-jet cutter. The prime attractions of water-jet cutting of a cured composite are the negligible force on the work-piece (such that tooling is simplified) and elimination of edge delamination.

One of the more time-consuming operations in aerospace manufacture is the drilling of panels and subsequent fastener installation. Use of six-axis robots enables the most complex components such as nacelles to be automatically fastened. All the power supplies associated with any tooling, electrical and pneumatic, are automatically connected via the face-plate at the end of the robot arm. Robot-drilling and combined countersinking can be achieved in a matter of a few seconds for each hole. These systems are the same as those used for metal assemblies; however, drill-bit configuration depends on the material being drilled. Because composite structures are often attached to metal components, the bit has to be chosen such that it satisfactorily drills both materials. This is usually achieved with a carbide-tipped tool.

5.4 Liquid Resin Molding Techniques

5.4.1 *Resin Transfer Molding*

The resin transfer molding (RTM) process shown in Figure 5.13 involves first placing the dry fabric preform into the cavity of a matched mold and then filling the mold and hence the preform with liquid resin. The mold and resin are typically preheated before injection. After injection, the mold temperature is increased to cure the part. In some cases, the resin is injected into a mold that has been preheated to the cure temperature. The resin preheat, injection time, and mold temperatures are set by the characteristics of the resin being used. If the temperature(s) is too high, the resin will gel before the mold is filled; if too low, then the resin viscosity may be too high to permit flow through the preform.

A vacuum is typically applied at the exit port to evacuate air and any moisture from the mold/preform before injection. Injection pressures of around 700 KPa are usual. The application of a vacuum during injection is useful to prevent void entrapment and also supplements the injection pressure; however, care needs to be taken that the injection temperature is not above the resin boiling point when the resin is under vacuum. This will lead to high and unacceptable porosity.

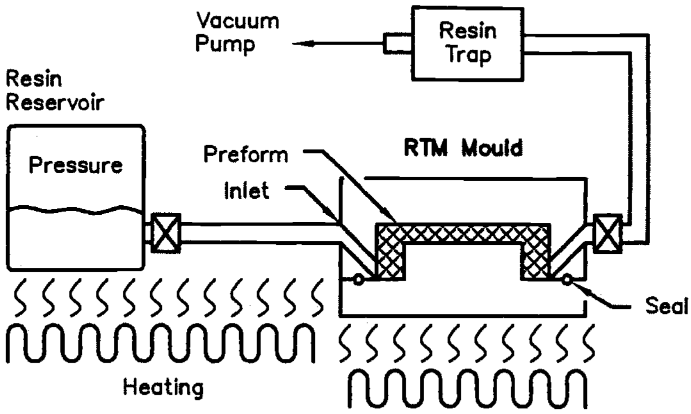


Fig. 5.13 Resin transfer molding (RTM) process.

5.4.2 Materials Systems

A large range of resins can be used for RTM, including polyesters, vinyl esters, epoxies, bismaleimides (BMIs), phenolics, and cyanate esters. Resin systems for RTM are supplied either as one-component (resin already mixed with hardener) or two-component systems.

The selection of a resin will be influenced by the suitability of its viscosity for a particular molding and the required fiber/volume fraction. For low fiber/volume moldings (around 40%), resin viscosities up to 3500 centipoise are suitable; however, for higher fiber/volume fractions, such as are usually required for aerospace structures, the viscosity should be less than 500 centipoise.

To maximize pot-life, the resin injection temperature is usually less than the preheat temperature of the mold. Material suppliers will normally provide isothermal viscosity curves for RTM resins such as those shown in Figure 5.14, allowing the optimum injection and mold temperatures to be selected by the molder.

Preforms may be made up of various reinforcements such as fabrics, braids, and other advanced textiles. Preforms are usually fabricated by using a “tackifier” or binder in the reinforcement at around 2–5% by volume. The shape is formed and consolidated on a mandrel with the application of heat and pressure (usually vacuum pressure) before it is loaded in the mold. The action of closing the mold will increase the compaction and, correspondingly, the final achievable fiber/volume fraction. Fiber/volume fractions up to 70% are achievable with certain “high-nesting” reinforcements.

When high injection pressures are used, the possibility of fiber-wash (i.e., reinforcement distortion) exists. Loose weaves and unidirectional reinforcements will have a greater tendency to fiber-wash than tightly woven performs, such as plain weaves. Additionally, high injection pressures will cause an increase in resin flow speed between tows, without complete fiber wetting, leading to voids

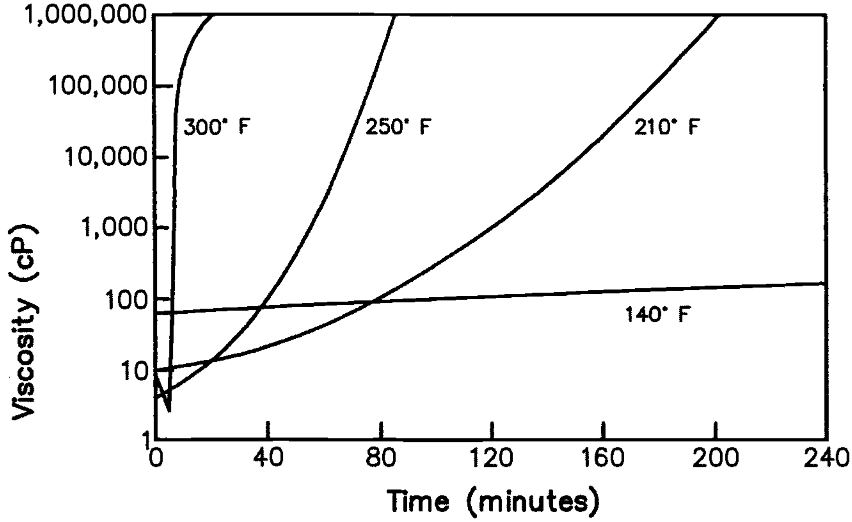


Fig. 5.14 Typical isothermal dynamic viscosity curves for an RTM resin.

within the tow bundles. Alternatively, a pressure that is too low can result in voids between tows.

The flow of the resin through the preform can be simulated using computer models. These help to establish the optimum injection pressures and predict irregular flow fronts that can trap air and cause dry spots. Generally, the highest pressure that can be used without causing significant mold deflections is sought. The models treat the flow through the preform as flow through a porous medium. In such a material, the flow velocity ν and the pressure in fluid p are coupled via the generalized Darcy's law:

$$\nu = -\left(\frac{K}{\eta}\right) \cdot (\Delta p) \tag{5.1}$$

Here η is the resin viscosity and K is the preform permeability.[6]

5.4.3 Tooling Systems

Tooling for RTM is similar to other closed (matched die) molds in many respects. The mold determines both the inside and outside geometry of the part. For most composite components, the outside mold line may not be critical and may be uncontrolled. However, in RTM, the cavity always needs to be controlled, otherwise processing difficulties can be experienced. Too much "pinch" on the preform will affect permeability and hence resin flow and may lead to dry spots. For this reason, all mold surfaces of aerospace RTM tooling must be accurately machined.[7]

Due to the relatively high injection pressures, the mold halves must be securely clamped and reinforced to prevent expansion of the cavity. Alternatively, the mold halves can be held in a press.

Gating refers to the resin distribution system that is used to transfer the resin uniformly into the preform from the resin inlet position(s) to the outlet(s). The aim of the gating is to ensure that a smooth and predictable infusion takes place without the flow front becoming distorted by local variations in permeabilities or by geometric features and without air entrapment. Line gates, point gates, and perimeter gates are all methods employed, each having its advantage under different circumstances (Fig. 5.15).

Race-tracking describes a situation in which the resin tracks the perimeter of the part (between a trimmed preform and the cavity wall), usually in an uncontrolled manner. It can lead to trap-off of air with resulting dry spots in the cured part. This condition needs to be guarded against when the gating is designed. Figure 5.15 shows how dry spots can result from a point gate arrangement and (in the example shown) are eliminated through the use of a line gate. Perimeter inlet gates will typically be combined with one or more outlet point gates. This method provides the quickest means of filling a part as well as eliminating race-tracking concerns because the resin is planned to fill first the perimeter before migrating into the part.

5.4.4 Applications

Advantages of RTM include excellent dimensional control, good surface finish, reproducibility, reduced material cost, reduced labor cost, net or near-net

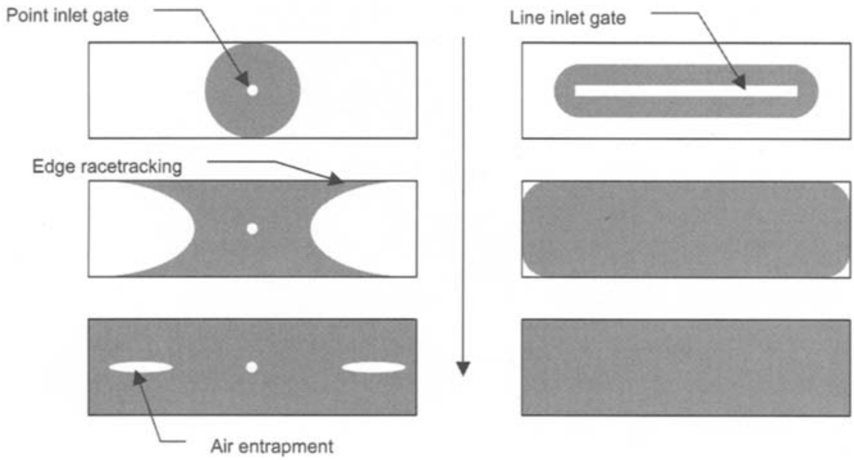


Fig. 5.15 Alternative gating arrangements for the RTM process, showing possible defects.

shape fabrication and elimination of the use of an autoclave. Consequently, the process is often used for smaller parts of complex geometry that requires good dimensional control on both inner and outer surfaces.

Other advantages include the ability to use preforms with through-thickness reinforcement and to mold inserts integrally with the part. A further advantage over pre-preg processing is that the materials need not be limited by shelf-life; however, preforms with some thermosetting binder materials can lose some drapability if excessively exposed to room temperature.

Figure 5.16 shows an example of a component that realizes many of the benefits of RTM. The component is a section of a helicopter door pillar designed as two mating Z-section details that are bonded together to make a hollow section with two flanges or lands for the transparency and door seal. The complex shape of this component would require time-consuming pre-preg hand lay-up. In the RTM process, two dry fabric stacks are draped into each half of the mold before closure over a mandrel. The individual stacks are separated by a film to allow the mold to be opened and the two parts and the mandrel removed after curing. The molding is carried out in a single operation. The two halves mate exactly at the film-line and are bonded together in a secondary operation.

The interest in RTM for larger parts has led to some novel design concepts such as multi-spar flaps and spoilers. These contain no ribs and are made with multiple internal mandrels onto which the dry preforms are laid before loading

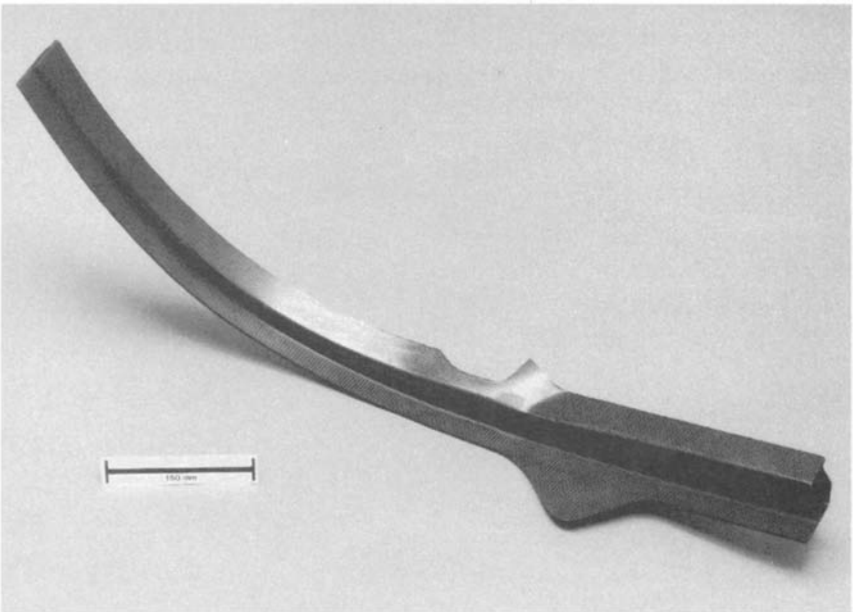


Fig. 5.16 Complex hollow section RTM part. Courtesy of CRC-ACS.

into an outer shell mold set. After resin fill and cure, the mandrels are removed to leave a multi-cell open-ended box structure.

5.4.5 Resin Film Infusion

In the resin film infusion (RFI) process illustrated in Figure 5.17, a film of resin is placed onto a mold either beneath or above the dry reinforcement. A vacuum bag is then placed over the assembly. This is then loaded into an autoclave and subjected to heat and pressure. The temperature is increased to a level such that the resin viscosity reduces and a low-level pressure is applied to force the resin into the reinforcement. Once the infusion has been completed, the pressure and temperature are increased to compact and cure the part. The appropriate viscosity-temperature-time profile must be established for each particular resin system so that complete saturation is obtained.[8]

Two areas are particularly critical to the success of this process: preform design and placement within the tool, and tool design and dimensional control throughout the process.[8]

Higher viscosity resin systems (such as Hexcel 3501-6) can be used for RFI because the resin travel distance is shortened considerably compared with that of a RTM part. The RFI process is ideally suited to the infusion of large relatively flat areas and has been used successfully to manufacture stiffened skins and rib-type structures. In these cases, the majority of the flow is one-dimensional (through the thickness); however, race-tracking around the perimeter of the reinforcement can occur, resulting in additional in-plane flow. If this is controlled (by careful design and trimming of the preform), flow distances can be advantageously increased. Quite large box-section structures have been produced by these means. However, extreme care is required to avoid trap-off and consequent dry spots.

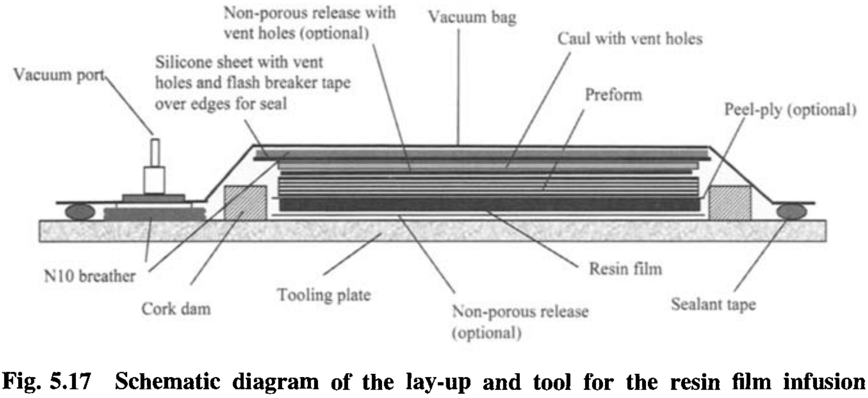


Fig. 5.17 Schematic diagram of the lay-up and tool for the resin film infusion process.

The consistency (tackiness) of the film is similar to that of pre-preg. The film is usually supplied on a roll and is available in several areal weights. In some cases, several plies will be required for thicker parts or the film can be fabricated in sections by casting or pressing the resin to the desired thickness. Resin film made using this technique may be either solid or slightly flexible, depending on the degree of staging.

RFI is more suitable than RTM for large structures (over 3 m) because it becomes difficult to handle the weight of large RTM molds. Additionally, being a single-sided tooling process, tooling costs will be considerably less for an RFI component; however, as there is inevitably some "float" of the mandrels, tool design and set-up are more complicated.

5.4.6 Vacuum-Assisted RTM

The vacuum-assisted RTM (VARTM) process, shown in Figure 5.18, is also a single-sided tooling process. It involves laying a dry fiber preform onto a mold, then placing a permeable membrane on top of the perform, and finally vacuum bagging the assembly. Inlet and exit feed tubes are positioned through the bag, and a vacuum is pulled at the exit to infuse the preform. The resin will quickly flow through the permeable material across the surface, resulting in a combination of in-plane and through-thickness flow and allowing rapid infusion times. The permeable material is usually a large open-area woven cloth or plastic grid. Commercial "shade-cloth" is often used for this purpose.

In foam-cored sandwich structures, the resin can be transported through grooves and holes machined in the core, eliminating the need for other distribution media. However, foam-cored structures are rarely selected for aerospace structures with the exception of some light aircraft and sailplanes.

The VARTM process results in lower fiber/volume fractions than RTM or RFI because the preform is subjected to vacuum compaction only. Reductions in the order of 5% can be expected depending on the form of the reinforcing. Hence, VARTM has in the past generally been used for lower-performance composite structures, such as ship hulls, and superstructures, where the advantages of lower tooling costs and the ability to cure under vacuum without the need of an autoclave outweigh the slightly reduced performance. However, some aerospace companies are overcoming this problem by pre-compacting or stitching the preform before lay-up. Although the infusion is conducted at room temperature in the manufacture of commercial grade parts, VARTM for aerospace structures involves the use of high-temperature resin systems and therefore the process will require a heating oven.

As noted, the advantage of VARTM over RTM is in the reduced tooling costs and compared with RFI or pre-preg processing, the elimination of the need for an autoclave is a significant consideration.

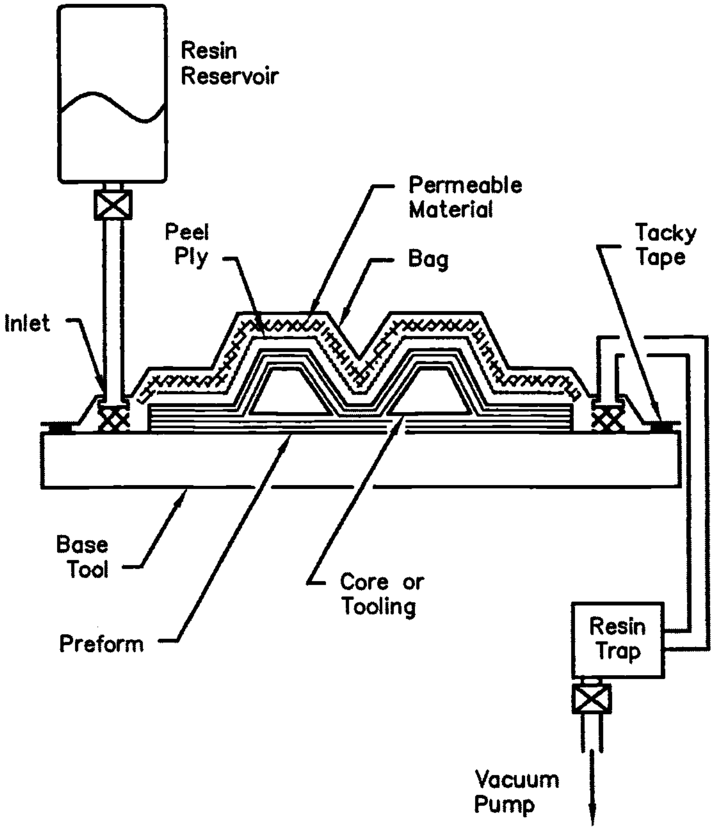
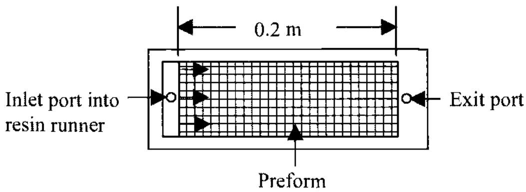


Fig. 5.18 Schematic diagram of the vacuum-assisted resin-transfer molding process.

Example 5.1

Simple calculations can determine the time to fill a rectilinear RTM mold for validation of a flow simulation model. The length of the preform is 0.20 m. The permeability is $3.5 \times 10^{-11}\ \mathrm{m}^2$ for a 54% fiber/volume fraction, 8 harness carbon fabric preform. The resin is injected at 200 KPa and room temperature where the viscosity of the resin is 400 centipoise.



Rectilinear RTM Mold. The one-dimensional Darcy's law is:

$$Q = -\frac{KA}{\eta}\frac{\mathrm{d}P}{\mathrm{d}x} \tag{5.2}$$

where Q is the volume flow of resin per unit time.

Assuming $-(dP/dx)$ constant:

$$Q = vA(1 - V_f) = \frac{KA}{\eta}\frac{P}{x} \tag{5.3}$$

$$\textbf{average velocity:}\quad v = \frac{\mathrm{d}x}{\mathrm{d}t} = \frac{KP}{\eta(1 - V_f)}\frac{1}{x} \tag{5.4}$$

Solve for time by integrating the equation (5.4), where
K is the permeability
P is the injection pressure
V_f is the fiber/volume fraction
x is the mold length
η is the resin viscosity
t is the time to fill
A is the mold cross-sectional area (width $\times$ thickness)

$$\text{Answer: } t = \frac{\eta(1 - V_f)}{KP}\frac{x^2}{2} = \frac{0.4(1 - 0.54)}{3.5E^{-11} \times 200{,}000}\frac{(0.2)^2}{2} = 526 \text{ seconds}$$

5.5 Filament Winding

5.5.1 General

Filament winding[9,10] is a composite-material manufacturing process that enables continuous reinforcement to be laid down at high speed and precision in predefined (generally, geodesic) paths. The process basically involves the winding of continuous fiber, impregnated with resin, over a rotating or stationary mandrel. The mandrel, whose geometry cannot include any re-entrant curvature, is subsequently removed after cure. By varying process parameters, such as winding tension, winding angle, and resin content, during the laying of the fiber, the desired part thickness, ply lay-up, and fiber/volume fraction can be achieved.

Filament winding is considered to be less versatile than other composite manufacturing techniques, particularly for complex shapes with varying thickness and fiber orientation. The process is better suited to parts with simple surfaces of revolution, although developments of the process with the introduction of multi-axis machines and sophisticated control software has enabled more complex-shaped components that are non-axisymmetric to be produced.

5.5.2 Winding Process

The basic filament-winding machine (Fig. 5.19) comprises a mandrel, fiber feed head and carriage, drive systems, and control box. The mandrel is motor driven such that it rotates about its longitudinal axis. As it rotates, it takes up fiber from the feed head. The feed head is attached to a carriage that is located onto a track, enabling the head to traverse back and forth in a direction parallel to the longitudinal axis of the mandrel. The speeds at which the mandrel rotates and the feed carriage traverses determine the orientation of the fiber being laid down. Basic winding machines can be programmed simply by changing the gearing between the mandrel and feed carriage. Ancillary devices are also used to maintain tension in the fiber as it is being taken off supply spools or creels. The tension in the fiber controls the level of compaction in the wound part.

In the wet-winding procedure, the fibers pass through a heated resin bath before reaching the feed head and are then deposited onto the mandrel. In this situation, rollers are used to remove excess resin, to force remaining resin into the fibers and flatten the tows. A variation to this is the controlled wet procedure, in which resin is metered onto the fiber. In the case of pre-preg winding, the resin bath and rollers are not required, the pre-impregnated fiber being fed directly into

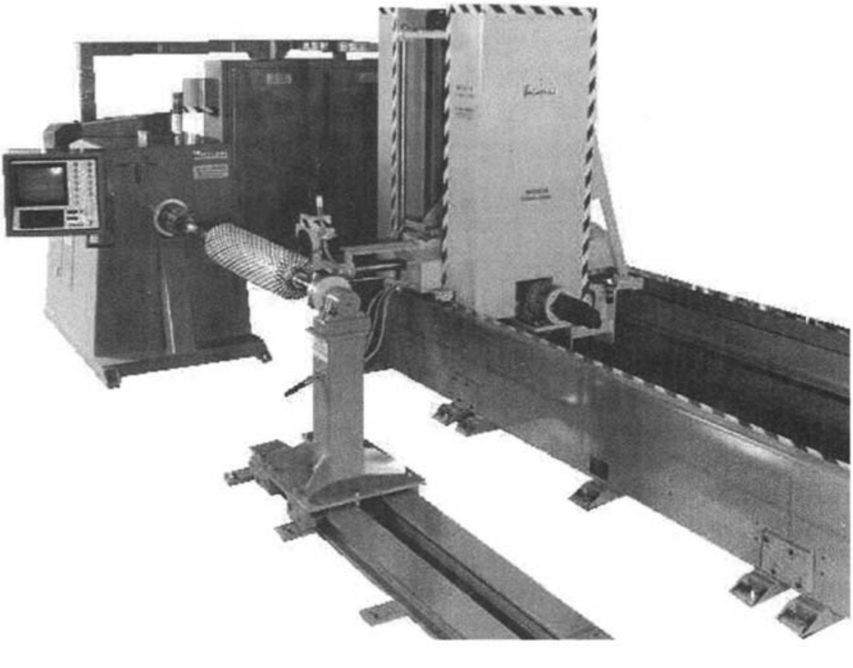


Fig. 5.19 Filament winding machine. Courtesy McClean-Anderson, Schofield, Wisconsin.

the feed head from the spools, then laid onto the mandrel. For pre-preg winding, the mandrel is generally heated to promote resin tack and flow. The fully wound part is then cured either at room temperature in an oven or in an autoclave, depending on the resin system.

The design of the mandrels used in filament winding is highly dependent on the winding machine capabilities, the structural requirements of the part, and the processing characteristics. Mandrels are generally constructed of steel or aluminum, and for situations in which the mandrel forms part of the structure or simple extraction of the mandrel is possible, the mandrel is in one piece. Where simple withdrawal is not possible, various types of removable mandrels are required. This may involve segmented metal mandrels, or mandrels constructed of materials that are soluble, fusible, inflatable, or collapsible.

5.5.3 Winding Patterns

There is a range of winding patterns used in filament winding, with the three primary classes being hoop, helical, and polar (See Fig. 5.20). The simplest is *hoop* winding, which comprises a mandrel rotating continuously about its longitudinal axis while the fiber feed carriage advances one fiber bandwidth after each mandrel axis of rotation. Consequently, fibers are deposited almost normal to the longitudinal axis. *Helical* winding, which is most commonly used, is achieved when the mandrel rotates continuously about a horizontal axis while the fiber feed carriage traverses back and forth. Winding angles ranging between 25–80° can be achieved with this method. In *polar* winding, the mandrel is rotated perpendicular to its longitudinal axis and remains stationary while the fiber feed arm rotates about the longitudinal axis, inclined at a slight angle. After each revolution of the feed arm, the mandrel is indexed to rotate about its longitudinal axis by one fiber bandwidth. A variation to polar winding is *whirling* winding, whereby the mandrel is rotated about a vertical longitudinal axis.

The basic winding patterns enable continuous fiber to be laid down onto the mandrel in the hoop, longitudinal, and bias directions. The ability to achieve these patterns is dependent on the type of filament winder being used. Basic filament winding machines have only two axes, thus limiting the patterns and shapes that can be wound. More sophisticated machines, such as robotic CNC filament winders, can have up to 10 axes of movement, which enables a greater range of patterns and more complex-shaped parts to be wound. These CNC machines have computerized servo-controls that allow complex winding procedures to be defined before their automatic execution.

5.5.4 Materials

The fibers used in the filament winding process typically come in two forms. Wet winding uses dry fibers that are impregnated with a low-viscosity resin during the winding process. In some cases, the part may be wound entirely with

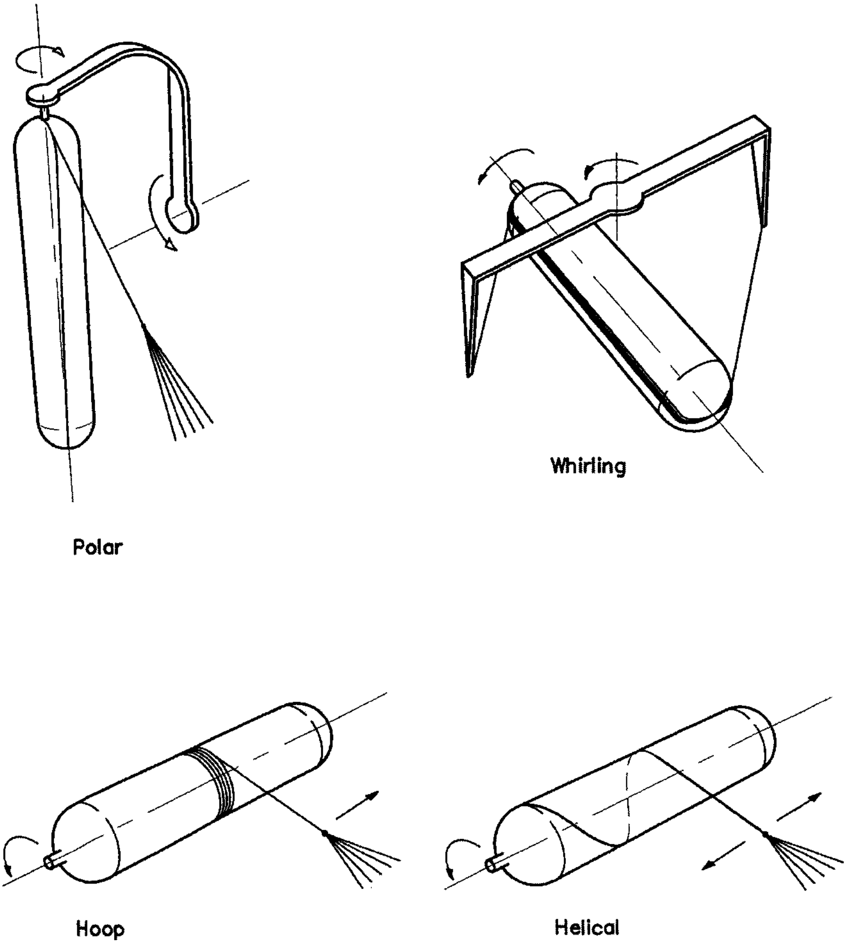


Fig. 5.20 Schematic diagram of the various filament winding machines and patterns. Adapted from Reference 18.

dry fiber then impregnated with resin under pressure. Pre-preg winding utilizes fibers that have been encapsulated within a B-staged resin. The advantages of wet winding are that it uses materials in the lowest cost form having no shelf life limits, and also that it requires fewer compaction cycles during the winding process. Pre-preg systems, on the other hand, can produce parts with higher quality and consistency, reduce winding times, minimize the chance of fiber slippage, and require less consolidating after winding.

Thermosetting resins are most commonly used in filament winding, where consolidation of the material takes place after the winding has been completed. More recently, thermoplastic resins have been used in the form of pre-preg and consolidation takes place as the material is being laid down.

Further discussion of filament winding of thermoplastic composites appears later in this chapter.

5.5.5 Design and Properties

The analysis of filament-wound structures is usually carried out using a netting approximation. This assumes that the fibers are uniformly loaded in tension and provide all the longitudinal stiffness and strength while the resin provides only the shear stiffness. This is a conservative approach; a more realistic procedure is to use techniques such as composite laminate theory (See Chapter 6).

The properties of filament-wound structures are generally inferior to composites made by conventional methods. This can be attributed to the higher void contents that can be as high as 7% for wet-wound material. If the fiber tension is too high, air will be entrapped at crossover points and within the tows that are unable to spread. If the resin viscosity is too high, the entrapped air is also unable to escape. To some extent, excessive voiding may be reduced by control of fiber tension and use of low-viscosity resins, however, autoclave processing with prior vacuum treatment is a more effective method of minimizing voids.

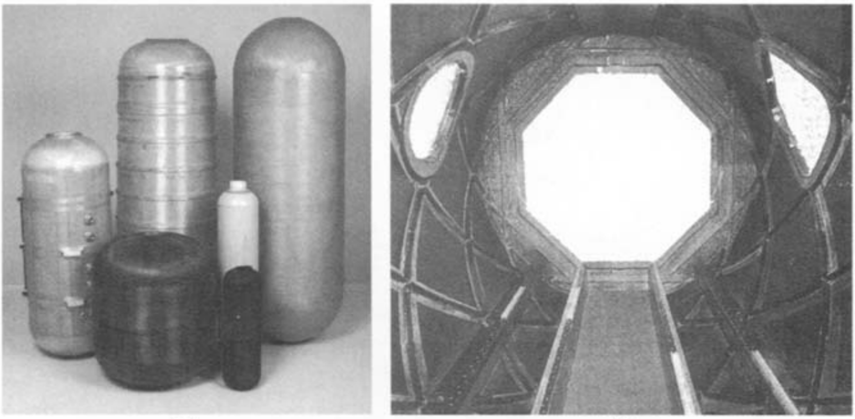
The winding pattern can also contribute to variations in the mechanical properties. Helical winding patterns produce fiber tow crossovers that result in crimping of the fiber and increase stress concentrations at these points. However, interweaving does result in improved interlaminar performance.

One of the most significant problems occurring in filament-wound structures is layer or fiber waviness, which can result in a significant loss of strength and stiffness. The waviness is mainly caused by volumetric changes during resin bleed-out in thick wound structures. It can therefore be avoided by minimizing the amount of resin that needs to be removed and maintaining the correct level filament tension during winding.

5.5.6 Applications

The advantages of the filament winding process are best exploited on components with simple surfaces of revolution. Examples of aerospace parts that have been fabricated using filament winding include rocket-motor cases, pressure vessels, missile launch tubes, and drive shafts. Some of these components, especially rocket-motor cases, can be very large (exceeding 4 m in diameter). Metal end-closures and metal or rubber internal liners are commonly incorporated into the design of filament-wound pressure vessels. These additions are placed onto the mandrel before winding. Filament winding is also commonly used for non-aerospace applications, such as storage and processing tanks, reinforced pipe, crane booms, automotive drive shafts, springs, golf shafts, fishing rods, and paddle shafts.

Filament winding has also been shown to be an ideal method for making geodesic composite structures. These structures utilize reinforcement in an



a) b)

Fig. 5.21 Parts made by filament winding; *a*) pressure vessels, *b*) geodesic structure Reference 18.

efficient manner, achieving ultra-lightweight components with high stiffness and strength. Examples of this include an isogrid helicopter blade and an orthogrid fuselage barrel (Fig. 5.21b).

Filament winding can be combined with a secondary molding process, whereby the winding process is used as a means of rapid and high-precision lay-up. Hollow cylinders are wound up onto mandrels and removed before curing. The uncured lay-up is then loaded into a tool and press-molded. This approach has been used to produce I-beams and helicopters blades. In the case of the latter, inflatable mandrels are used, where the uncured winding is placed into a mold with the deflated mandrel, and the mandrel is then reinflated to apply a consolidation pressure to the lay-up.

5.6 Pultrusion

Pultrusion is a highly automated, continuous, linear process for manufacturing constant cross-sectional profiles of fiber-reinforced polymeric materials. In its simplest form, continuous unidirectional fibers (in the form of tows or rovings) are impregnated with a thermosetting resin and pulled through a heated die to shape and cure the composite into a finished product (Fig. 5.22). As the material progresses through the die, the applied heat triggers the cure reaction, and the resulting solid product is pulled through the die by a set of mechanically or hydraulically driven grippers. Further details are given elsewhere.[11,12]

The aim of the process is to produce a cured part before the product exits the die. The pulling speed is therefore related to the curing kinetics of the resin

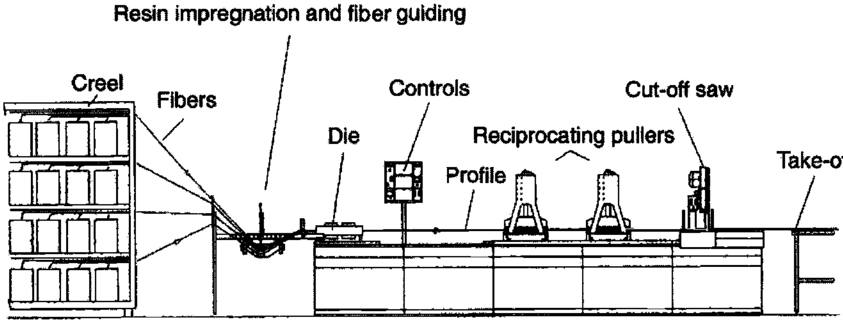


Fig. 5.22 Schematic diagram of basic pultrusion machine (Reference 11).

system being used and the die length. Dies are typically 1 m long and pulling speeds vary between 200 mm min^{-1} for epoxy-based products to 3000 mm min^{-1} for commercial, polyester-based products. With epoxy-based systems, full cure is not normally achieved before the part exits the die, and post-curing operations need to be considered (either on- or off-line).

5.6.1 Reinforcements

Almost all reinforcement material and forms can be processed by the pultrusion technique, including glass, aramid, polyethene (polyethylene), and carbon fibers. One intrinsic requirement of the process is the need for a high percentage of fibers aligned parallel to the pulling direction. With need for off-axis fibers, as is the case for aerospace products, there is a fundamental requirement to have sufficient zero degree fibers to withstand the pulling forces required to draw the array of collimated fibers and fabrics through the die. When off-axis reinforcement is required, such as at 90° or $\pm 45°$, stitched non-crimp fabrics (NCF) can be used. However, these fabrics are effectively incompressible and can give rise to rapid pressure rise at the die entrance.

5.6.2 Resins

With transient times of typically 0.5–5.0 minutes in the heated section of the die, it is essential to use a resin system that gels and/or cures very rapidly.

The majority of commercial pultrusions are manufactured with polyester resin. This is because it is inexpensive and is the easiest resin to process. In applications in which the fire resistance is of primary importance, phenolic resin is normally selected. However, there are certain considerations that must be taken into account when pultruding phenolic-based products. First, the compatibility of the phenolic resin with conventional sizing on glass fibers is poor, and second, in some systems? water, in the form of steam, is generated as a by-product of the curing reaction. Without careful management, the water can remain trapped in the product, resulting in a severely voided laminate. The mechanical properties of phenolic laminates are typically lower than those having polyester or vinyl ester resin systems, and the production rates are also slower.

Epoxy resins are selected for applications where the mechanical properties need to be maximized, such as in aggressive environments and military or aerospace applications. However, epoxies are notoriously difficult to process by pultrusion because the curing mechanism of epoxies is significantly different to that of polyesters and vinyl esters. Epoxies cure very slowly and take a long time to reach their gel point; it may not occur until just before the die exit. Also, the degree of cure at the die exit may be as low as 70–80%.

To maximize the transient time, pulling speeds are normally very low when processing epoxy-based products. Epoxies also have very low cure shrinkages and are exceptional adhesives, which in combination can lead to a surface-roughening phenomenon called *micro-sloughing*.

5.6.3 Pultrusion Process

The process can be separated into three key stages:

- Fiber in-feed system—includes fiber-dispensing, impregnation, collimation, and forming
- Forming system—includes external heating, die design, and the curing reaction
- Pulling system—includes pulling mechanism and the cut-off station

5.6.4 In-Feed System

Of the three stages listed above, the in-feed system, an example of which is shown in Figure 5.23, is by far the most important to the smooth and successful operation of the pultrusion process.

The reinforcing fibers are usually used in a combination of rovings and broadgoods. The rovings are traditionally stored on multi-layer racks called creels, and the fabric is slit to the required widths and dispensed from rolls. The fibers and fabrics can be impregnated with resin either collectively, toward the end of the forming process, or individually at intermediate stations, located throughout the in-feed system. Once impregnated, and before final collimation, the fabrics pass through a series of shaped formers that squeeze-off excess resin. This stage also encourages thorough infiltration of the resin and wet-out of all fibers.

5.6.5 Tooling System

The tooling system consists of a pair of closed, matched dies that are about 1 m in length. The die cavity forms the shape of the finished part and, apart from

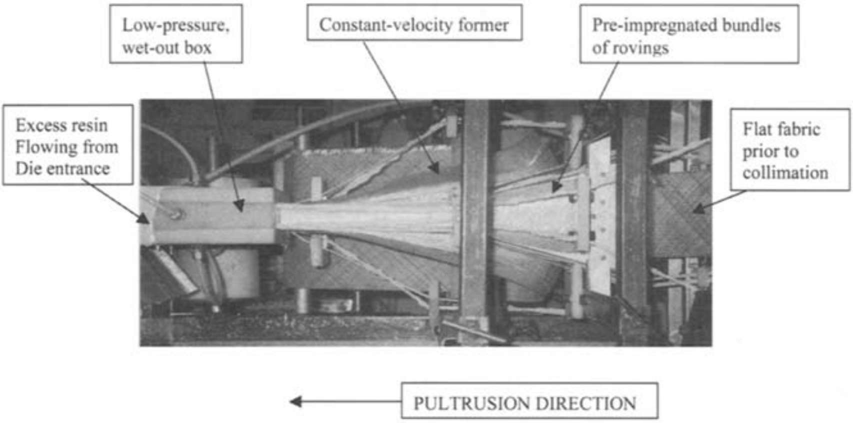


Fig. 5.23 Infeed system for a pultrusion process.

having a bell-mouthed entrance, is normally of constant dimensions along the length of the tool. The dies, which are normally manufactured from tool steel or medium-strength steel with chrome-plated internal surfaces, are then usually placed between a set of heated platens and anchored to the machine.

To achieve thermal equilibrium, additional heaters such as strip heaters can be positioned along the length of the die at strategic locations. Cartridge heaters can be inserted in mandrels, which are otherwise cold because they are isolated from the main external heat source. Heat pipes, which are very efficient thermodynamic devices with extremely high thermal conductivity, can be used to transfer heat from the exit end to the front end. Sometimes when dealing with a reactive resin mix or a complex profile, the mouth of the die is water-cooled to avoid premature gelation. Tooling design is of paramount importance and is normally achieved with the aid of three-dimensional numerical models, such as TOPDIE, which is available from Pultrusion Dynamics Technology Center.[13]

5.6.6 *Pulling and Docking Systems*

The motive force to draw the solid product from the die is generally supplied by one of two means; either 1) by reciprocating clamps that oscillate in a hand-to-hand motion or 2) by using a pair of caterpillar tracks that continuously clamp and draw the product.

The process is completed when the product reaches the cut-off station where a flying cut-off saw clamps onto the product and cuts the profile to the desired length. The pultrusion process offers the inherent advantage that any transportable length can be produced. This may typically be 6 m for standard construction type profiles (tees, angles, etc.) but may be as long as 2000 m for fiber optic cable core, which is 0.002 m diameter and wound onto a spool mounted at the end of the pultrusion machine.

5.6.7 Aerospace Applications

Starr[11] gives a comprehensive overview of the ever-increasing number of applications of pultrusion from cable-trays and window lineals to full-scale bridge decks and railway bridge constructions.

Within the aerospace market, however, successful examples of the use of structural pultrusions are relatively few. This is due primarily to the limited production runs required for aerospace products; demands are usually too short for the pultrusion process to be viable. Production runs of aircraft are usually measured in hundreds, spread over several years. It is also due in part to the difficulty in reaching the quality of product achievable with other aircraft-molding techniques. This arises both from the unsuitability of most high-performance resins and the difficulty of achieving high-volume fractions when using off-axis reinforcement. Nevertheless, through the development of special resins, high-performance aerospace quality pultrusions with relatively high V_f have been produced, an example of which is shown in Figure 5.24.

5.7 Process Modelling

One of the main barriers to more widespread application of advanced composite structures is their relatively high cost compared with parts made of

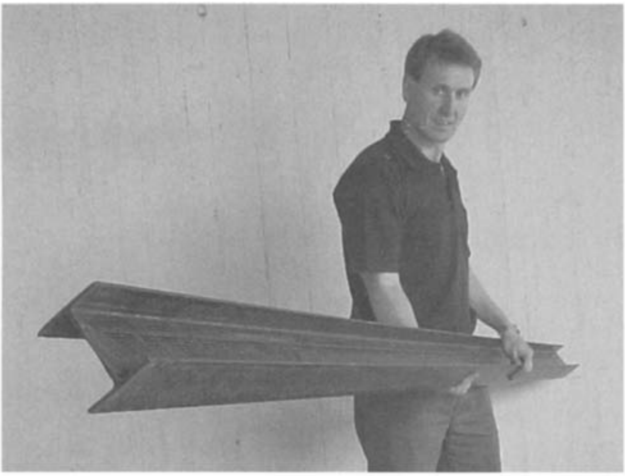


Fig. 5.24 Prototype, structural I-beam, produced using carbon fiber tows and NCFs with an epoxy resin system. Courtesy of CRC-ACS Ltd, Australia.

conventional aluminum alloys. The high cost of composite manufacturing is partly due to the trial-and-error philosophies adopted in the manufacturing tooling design and process development. It is therefore very desirable to be able to predict the material and tooling responses during manufacturing through the use of *process modelling* or simulation. Process modelling may help to reduce the manufacturing cost and time on two different scales. First, it is possible to optimize the tooling and process design for a manufacturing process through process modelling if the fundamental response of the materials involved can be characterized relatively accurately. Second, and more broadly, process modelling can be used to predict a desired tooling and process design window within which a reduced number of trials can be conducted.

The processing of advanced composites involves a number of coupled physical and chemical phenomena. These include heat and mass transfer in the two-phase media (reinforcement and matrix), resin cure reactions, and deformation caused by temperature changes, resin cure shrinkage, and applied forces. These phenomena are governed by the well-known conservation rules, such as conservation of energy, conservation of resin mass, and conservation of momentum. Process modelling is used to solve the relevant governing equations under a set of given initial and/or boundary conditions to predict the process variables such as temperature, degree of cure, pressure, flow front positions, and deformation of composite part and tooling. Due to the general complexity of both the process and the part geometry, an analytical solution is usually not possible and therefore a numerical method, such as the finite difference method or the finite element method, has to be used.

5.7.1 Forming of Reinforcement Stacks

Forming a stack of reinforcement layers, whether they be pre-preg plies or "dry" fabric plies for use in RTM, involves transforming a flat stack of reinforcement into a three-dimensional shape. However, the deformation behavior of pre-preg is more complicated than that of the dry reinforcement, making it much more difficult to model.

Two approaches are commonly used to model forming: the kinematic mapping approach and the mechanics approach.

In the mapping or kinematic approach, forming is considered purely as a process of geometrical transformation: the initially flat sheet of material is mapped onto the three-dimensional surface of the forming tool. The material is assumed to be inextensible in the fiber direction and the draping is achieved through shear deformation. Any forces required to shear the fabric are ignored. Consequently, the mapping approach provides only geometrical or strain information on forming, such as fiber orientation in the formed part and the total shear strain experienced by the part. The mapping approach is a good initial tool for investigating forming requirements, and may be all that is required for predicting the formed shape in hand lay-up of single layers of pre-preg or dry fabrics, or preforming of stacks of dry fabric layers with the same orientation. Figure 5.25 shows fiber paths in a woven fabric draped over an aircraft rib shape, predicted by the software Drape from the Technical University of Delft.

The mechanics approach solves equilibrium equations balancing the forces within the material against the applied loads, and the constitutive equations describing how the stress in the material is related to strain and/or strain rate. The transient forming process is modelled by time stepping. Such a model is usually complicated due to the complex deformation modes of composite sheets. It has to be solved by the finite element method and requires large computing power. However, a mechanics model can provide not only more detailed geometrical information, but also the transient strain and stress states in the material, which is needed to predict forming defects. Therefore, much recent development in the modelling of composite sheet forming has used this approach. Figure 5.26 shows the predicted forming behavior of a cross-plied stack of woven pre-preg formed over the same rib shape. The software used is PAMFORM from Engineering Systems International.

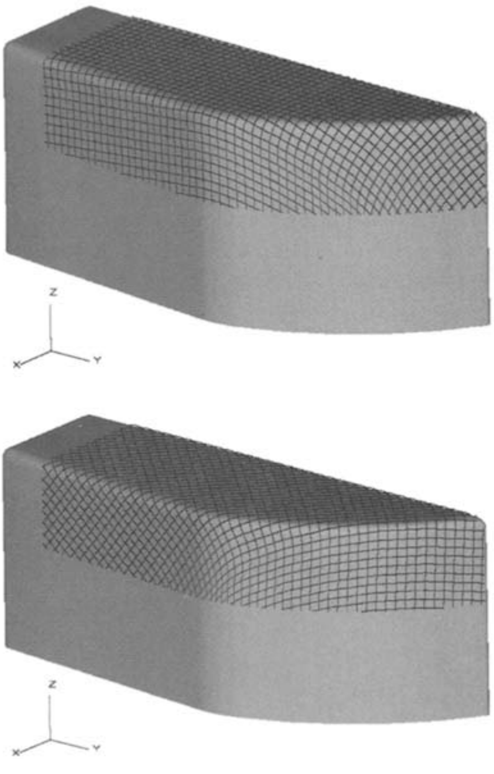


Fig. 5.25 Kinematic draping predictions for different fabric orientations.

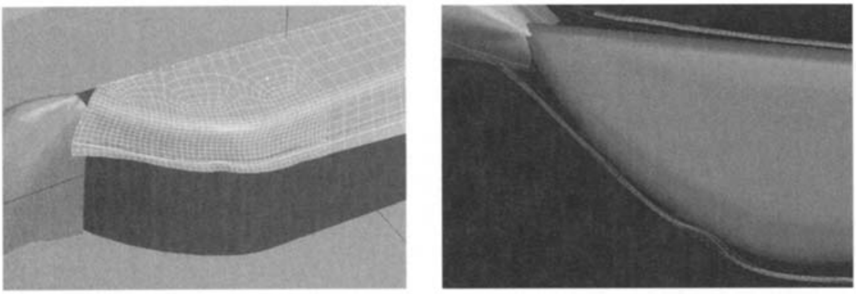


Fig. 5.26 PAM FORM predictions for forming a ply stack over a rib shape.

5.7.2 Heat Transfer and Resin Cure

Advanced composites are usually cured at the relatively high temperature of about 180°C. During a composite curing process, heat transfer and cure in composites are governed by the following equations:

$$\overline{\rho c}_p \frac{\partial T}{\partial t} + V_r\rho_r c_{pr}\left(u_x\frac{\partial T}{\partial x} + u_y\frac{\partial T}{\partial y} + u_z\frac{\partial T}{\partial z}\right)$$

$$= \bar{\kappa}_x\frac{\partial^2 T}{\partial x^2} + \bar{\kappa}_y\frac{\partial^2 T}{\partial y^2} + \bar{\kappa}_z\frac{\partial^2 T}{\partial z^2} + V_r\rho_r H_r R_r \tag{5.5}$$

$$\frac{\partial \alpha}{\partial t} + u_x\frac{\partial \alpha}{\partial x} + u_y\frac{\partial \alpha}{\partial y} + u_z\frac{\partial \alpha}{\partial z} = R_r \tag{5.6}$$

where $\bar{\rho}$ and $\bar{c}_p$, respectively, are density and specific heat of the composites; $\bar{\kappa}_x$, $\bar{\kappa}_y$ and $\bar{\kappa}_z$ are the directional thermal conductivity of the composites; ρ_r, c_{pr}, and κ_r, respectively, are density, specific heat, and conductivity of the resin; V_r is the resin volume fraction; u_x, u_y, and u_z are the components of resin flow velocity; H_r and R_r are the total heat of reaction and the rate of reaction of the resin, respectively; and α is the degree of cure.

For a thermoset resin, the rate of reaction (R_r) at various temperatures can be experimentally determined by differential scanning calorimetry (DSC). The results are then fitted to an equation expressing R_r as a function of temperature T and α. The following Arrhenius-type equation is most frequently used:

$$R_r = \frac{d\alpha}{dt} = K_0\exp\left(-\frac{E}{RT}\right)\alpha^m(1-\alpha)^n \tag{5.7}$$

where R is the universal gas constant, K_0, E, m, and n are the parameters to be determined by the fitting.

The existence of resin flow velocity (u_x, u_y, u_z) in equations (*5.1*) and (*5.2*) means that modelling of heat transfer and cure in composites is normally coupled with simulation of resin flow. This is often referred to as non-isothermal flow simulation. However, some manufacturing processes, such as autoclave curing and the curing stage of RTM, involve insignificant resin flow. For these processes, the above equations can be simplified by setting the relevant velocity components to zero and can be solved to predict the temperature and curing profiles.

Pultrusion is considered as a special case for which the resin flow relative to the reinforcement can be ignored and hence a coupling with flow simulation is also not needed. However, heat transfer and cure modelling for pultrusion is still somewhat complicated owing to the constant movement of the pultruded part in the pulling direction. The governing equations for a pultrusion process can be written as follows:

$$\overline{\rho c_p}\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=\bar{\kappa}_x\frac{\partial^2 T}{\partial x^2}+\bar{\kappa}_y\frac{\partial^2 T}{\partial y^2}+\bar{\kappa}_z\frac{\partial^2 T}{\partial z^2}+V_r\rho_r H_r R_r \tag{5.8}$$

$$\frac{\partial \alpha}{\partial t}+u\frac{\partial \alpha}{\partial x}=R_r \tag{5.9}$$

where u is the pulling speed.

The above equations can be solved using the finite difference or the finite element method to predict the temperature and curing profiles in pultrusion. Figure 5.27 shows the temperature and curing profiles at the die exit for the pultrusion of a fiberglass-vinyl ester composite I beam, predicted by using the finite element method. Owing to the symmetry in the die, only one quarter of the section need be modelled.

5.7.3 Resin Flow Through Fiber Reinforcement

The flow of resin through fiber reinforcement is considered to obey Darcy's law that states that the velocity of the flow is proportional to the pressure gradient in the resin. Combined with the assumption of resin incompressibility, one can derive the following resin pressure equation:

$$\frac{\partial}{\partial x}\left(\frac{S_x}{\mu}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{S_y}{\mu}\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{S_z}{\mu}\frac{\partial P}{\partial z}\right)=0 \tag{5.10}$$

where S_x, S_y, and S_z are the directional permeability of the reinforcement and μ is the viscosity of the resin.

The above equation can be solved analytically for the simple cases of isothermal, one-dimensional flow and isothermal radial flow. The solutions have been used to process results of tests to determine the permeability of reinforcement.

To solve these equations for any more complex case, the finite element/control volume method is most frequently used. In this method, the reinforcement is divided into elements/control volumes. A fill factor between 0 and 1 is assigned to each of the control volumes, with 0 indicating an empty volume and 1 for a

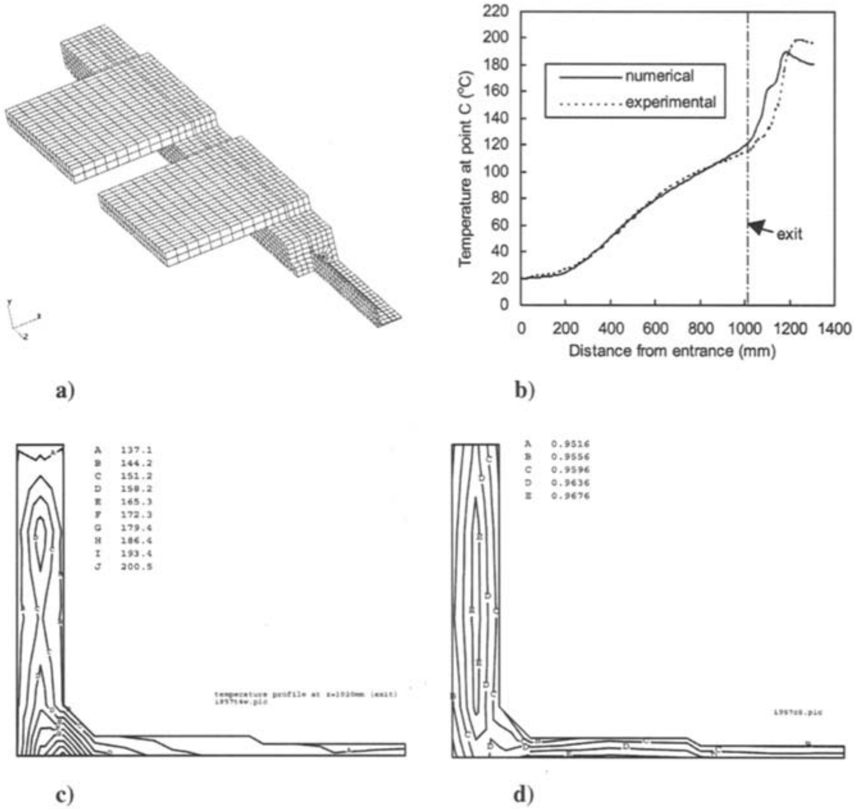


Fig. 5.27 Heat transfer and cure modelling for a pultruded composite I-beam.

resin-saturated one. The flow front is identified as joining those control volumes with fill factors that are neither 0 nor 1. The transient process of resin flow is divided into time steps. Within a step, the pressure equation is first solved by the finite element method. Darcy's law is then used to calculate the net flow into the control volumes at the flow front, and the relevant fill factors and the pressure boundary conditions are updated.

Because the components produced by liquid composite molding are often thin shell structures, the flow model can be simplified as two-dimensional. However, two-dimensional modelling assumes no flow in the through-thickness direction, which may lead to significant errors in the modelling of flow in thick parts, as illustrated in Figure 5.28.

The resin flow in a composite manufacturing process is usually non-isothermal and the viscosity of the resin is affected by its temperature and curing state. To simulate these conditions requires a coupling between flow simulation and heat transfer and cure modelling. Such a non-isothermal flow simulation is

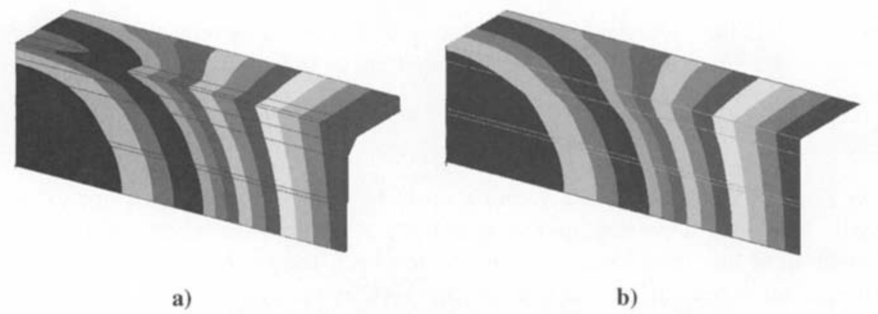


Fig. 5.28 Sequential predicted flow fronts for RTM of a composite I-beam (quarter section). Resin inlet is at lower left. a) Three-dimensional flow simulation; b) two-dimensional flow simulation.

needed for a "fast" liquid molding process such as structural reaction injection molding (SRIM), and high-temperature infusion processes such as resin film infusion during which significant cure reaction occurs simultaneously with resin flow. RTM processes are often operated at a temperature at which the viscosity is lowest and little cure occurs. An isothermal flow simulation can be used for such an operation.

5.7.4 Consolidation of Reinforcement

In general, consolidation can be considered as a phenomenon during which the fiber/volume fraction, and hence the thickness, of the reinforcement stack changes as a result of applied pressure and/or resin flow. This could occur, for example, during compression molding, resin film infusion, or the autoclave processing of thick composites. The change in the fiber/volume fraction presents a number of challenges to process modelling. It results in a moving boundary in the thickness direction. It affects the permeability of the reinforcement significantly, which has a direct impact on flow simulation. Additional models are needed to describe fiber/volume fraction as a function of the fiber compaction stress and to relate the stress to the total applied pressure.

In a consolidation model, it is generally assumed that the applied pressure is balanced by the effective fiber compaction stress p and the resin pressure P:

$$\sigma = p + P \tag{5.11}$$

To account for the compaction of the reinforcement in the thickness direction, the resin pressure equation is modified to:

$$\frac{\partial}{\partial x}\left(\frac{S_x}{\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{S_y}{\mu}\frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{S_z}{\mu}\frac{\partial P}{\partial z}\right) = m_v\left(\frac{\partial P}{\partial t} - \frac{\partial \sigma}{\partial t}\right) \tag{5.12}$$

where m_v is the coefficient of volume change, which can be related to the fiber/volume fraction and the fiber compaction stress as follows:

$$m_v = \frac{1}{V_f}\frac{dV_f}{dp} \tag{5.13}$$

The relationship between V_f and p needs to be determined by a compaction test. It is also necessary to experimentally determine the permeability as a function of the fiber/volume fraction. It has been shown that the results of the permeability test can be fitted to the Kozeny-Carman equation:

$$S = \frac{r_f^2}{4K_z}\frac{(1 - V_f)^3}{V_f^2} \tag{5.14}$$

where r_f is the fiber radius and K_z the Kozeny constant.

Consolidation modelling has been used for some time to simulate autoclave consolidation of thick pre-preg composites in which the resin flow is predominantly one-dimentional in the thickness direction. More recently, it has been used in other situations such as the simulation of compression RTM and of vacuum bag resin infusion.

5.7.5 *Process-Induced Distortion and Residual Stress*

Five main factors have been identified as responsible for process-induced part distortion and residual stress in composite structures. These are thermal strains, resin cure shrinkage strains, gradients in temperature and resin degree of cure, resin pressure gradients, and tooling mechanical constraints. To fully model the development of the part distortion and residual stress during a manufacturing process, it is necessary to include the transient temperature, resin flow and cure, and the tooling and part deformation under load. Therefore, modelling of process-induced part distortion and residual stress is one of the most complex process modelling tasks, requiring modelling of heat transfer and cure, flow simulation, and consolidation analysis as sub-models.

Fortunately, aerospace composite structures are often thin panels cured in an autoclave or oven. For these panels, it is reasonable to assume that the gradients in temperature and resin degree of cure are small and can be ignored. Furthermore, the majority of resin cure shrinkage may occur very early in the curing process, when the resin behaves as a viscous fluid or is at least highly viscoelastic. Therefore, the cure shrinkage strains will be relaxed in the subsequent curing and contribute little to the final part distortion. This suggests that the thermal strains caused by the thermal mismatch between different directions/different plies are often the only major source of residual stress. Consequently, prediction of the process-induced distortion and residual stress can often be simplified to a structural analysis of the composite panel loaded thermally by cooling down from the curing temperature. Figure 5.29 illustrates the predicted distortion of a tray-shaped part with a curved flange by considering the thermal loads only.

5.7.6 Experimental Validation

Process modelling should not, and cannot, replace experimentation completely. On the contrary, it should be applied jointly with experimentation for the following two reasons.

First, experimental measurement is needed to obtain various material properties and derive constitutive models to be used in process modelling. Owing to developments in numerical techniques and ever-increasing computing power, there is often little difficulty in solving numerically the macroscopic governing equations for composite manufacturing processes. However, very often process modelling cannot be conducted meaningfully because the required material properties are not available or are not accurate. This is particularly true for modelling of transient processes in which it is often necessary to know the material properties as functions of the process variables, such as temperature, fiber/volume fraction, and pressure.

Second, a process model should always be verified experimentally before it can be confidently used to guide process development. A relatively large amount of process modelling work has been published in the last 20 years. However, comparatively little experimental verification of this modelling has been reported.

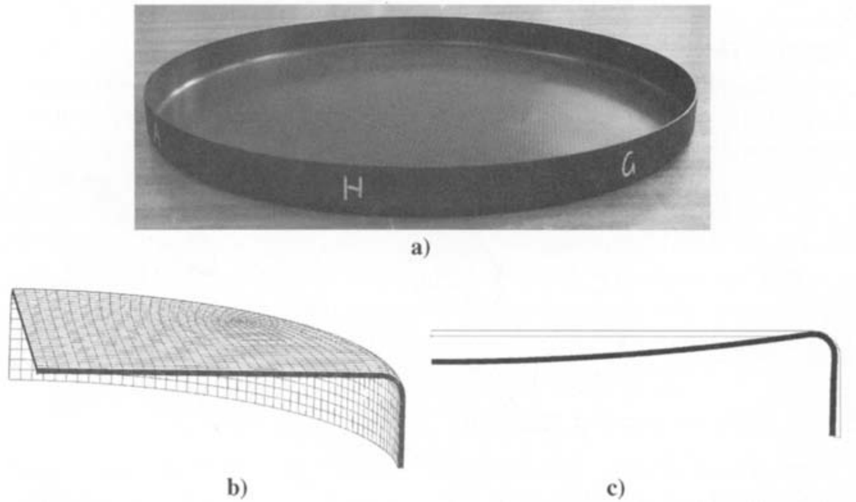


Fig. 5.29 Distortion of a curved composite flange: *a*) manufactured part; *b*) finite element mesh; *c*) distorted shape of cross-section.

5.8 Tooling

The fabrication of composite parts requires tooling that can be described as either closed-mold or open-mold. Closed-mold tooling is used for components produced by the RTM method, and these tools are matched with a cavity whose dimensions are controlled to achieve the specified fiber and resin volume fractions. These tools are usually made from steel due to the high pressures inside the mold required for injection and compaction. Pressure on the mold is usually achieved by a press, but for large parts an autoclave can be used. Small molds can be bolted together and are satisfactory provided that deflections can be minimized. Open-mold tooling is used for manufacture with pre-preg materials, RFI, or vacuum bag resin infusion (VBRI) and consists of a hard tool providing the shape of the required component (or outer mold line; OML) with compaction provided through a flexible bag or bladder. The tooling materials for open-mold tools can be metallic or non-metallic, the choice of which is largely driven by initial cost and the numbers of parts required from the tool. For large production runs, hard metals such as steel, nickel, or invar are preferred. Composite tools are lighter and can be produced by casting from a master shape. Although they are less durable, they can be easily repaired. Wood can also be used for materials with curing temperatures less than 100°C (these materials may require a post-cure that can be undertaken off the tool).

Other factors that need to be considered in the selection of tooling materials are dimensional stability, coefficient of thermal expansion, and specific heat.

Composite tools may be unstable at elevated temperatures if cross-linking has not been sufficiently completed during manufacture. Wooden tools will be unstable if not completely dried. The tendency for uptake of moisture by wooden tools requires they be sealed with an epoxy or similar gel coat.

Carbon fiber composites have very low coefficients of thermal expansion compared with steel and aluminum. Because the part will be cured into shape at an elevated temperature, allowance has to be made for the expansion of the tool at that temperature. Subsequent contraction of the composite part can then usually be neglected, however, care must be taken to ensure that the part does not lock or is cracked due to contraction of the tool on cool-down. This is a particular concern for closed-mold tools.

A high specific heat is desirable to improve the heat-up rate of the tool. This means less energy is required through the curing process and, additionally, cycle times can be reduced.

5.8.1 Metallic Tooling Materials

The most commonly used metallic materials are aluminum alloy, steel, electroformed nickel, and invar.

Aluminum alloy is attractive due to its relatively low cost, ease of machining, and low density. It also has a high specific heat. Unfortunately, because of the low hardness, aluminum tools are easily scratched and damaged. The high CTE (aluminum CTE is twice that of steel) requires considerable compensation be allowed for the dimensions of the tool. This is used to advantage, however, when aluminum is used for internal mandrels where the higher expansion acts to compact the composite against the walls of a steel cavity mold. Cast aluminum tools have proved to have poor vacuum integrity due to the porosity in the casting, and hence they are not usually used.

Steel is a low-cost material, although machining rates are slower than for aluminum, negating the cost advantage. Its specific heat and CTE are half those of aluminum, whereas its density is three times greater. As a consequence, heat-up rates are much slower. The main advantages are its hardness and consequent durability. Steel is usually preferred where high production volumes are expected.

Electroplated or electroformed nickel has a CTE close that of steel, and its specific heat and density are both approximately 10% higher. Electroforming is a rapid electroplating process wherein nickel is deposited from a solution (generally nickel sulphamate) onto a conductive or conductive-coated master. Plating thicknesses up to 6 mm are usual. Because there is no heat generated during the process, the master can be fabricated from materials with low thermal stability such as wax, rubber, or polymer compounds. At the completion of the process the master is removed, leaving a hard, dense shell structure. Vacuum integrity on these tools is very good. They are often used for large surfaces such as wing skins.

Invar is a very dimensionally stable material. It is highly durable and has a CTE very close to carbon fiber composite materials. Thus makes it a very suitable choice for closed-cavity molds. It is however very expensive and cannot be welded.

5.8.2 Composite Tooling Materials

Normally, composite aircraft components are cured in the higher temperature ranges, typically at around 180°C, and in an autoclave under a pressure of up to 700 KPa. Therefore composite tooling, if used, must be able to withstand these conditions and have a glass transition temperature at least 15°C above the curing temperature. The high cross-link densities and high concentrations of polar molecular groups of such polymers result in a cured resin of high brittleness with susceptibility for moisture absorption. Repeated thermal cycling causes micro-cracks leading to eventual loss of vacuum integrity. In extreme cases, blistering occurs from the presence of trapped moisture. With care, however, production runs of over 100 can be achieved, and because they can be produced economically from a master, they are still popular among many manufacturing organizations. Composite tool material suppliers have in some cases developed complete systems for composite tooling that assure good tool durability, an example of which is shown in Figure 5.32. Naturally, there are no concerns from differing CTEs.

Composite tools are taken from a master model that is usually machined from computer-aided design data. Carving or splining by hand were alternative methods used in the past, however these have now largely been discarded. A variety of materials can be used for the master including polyurethane modelling board, hardwood, and medium-density fiberboard (MDF) (Fig. 5.30). The master is a positive of the component shape so that the tool can be cast directly from the surface without a transfer mold. The masters need to be handled and stored carefully because it may be intended to produce replacement tooling at some later date. Contact with moisture must be avoided because these materials are hygroscopic and will not be stable in the presence of moisture.

The tool can be a solid fiber laminate construction that is sometimes reinforced with a backing to increase stiffness. This backing may be in the form of a laminated "egg-crate" or a thick tooling compound sandwiched between the laminations. Cast epoxy can be used for smaller tools where stiffness is not a

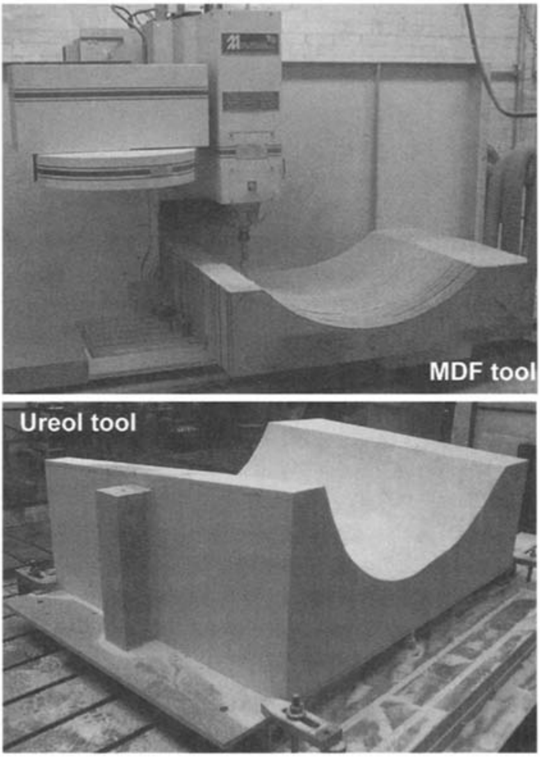


Fig. 5.30 Medium-density fiberboard (MDF) and Ureol tooling.

concern. These are usually filled with aluminum to increase thermal conductivity and modulus.

More recently, tooling pastes have been used whereby the paste is dispensed onto a foam or honeycomb backing structure followed by machining to the desired shape. These are suitable for manufacture of lower-temperature curing materials.

The tools will be surfaced with a high-temperature gel-coat. These sometimes contain fillers such as aluminum, ceramic, or silicone carbide to improve abrasion resistance.

5.8.3 Mandrels

The interest in part integration has led to the concept of cocuring. With this concept, detail laminates are laid-up onto individual mandrels that are loaded together into an assembly mold. An example of this is the Airbus A300 fin box, which is made with pre-preg material and cured in a single autoclave cycle. The key issues for design of the mandrel system are how the mandrels will be removed after cure and how to ensure the correct compaction across all surfaces. Either flexible or rigid mandrels can be used.

Flexible mandrels can be solid or can be inflatable bags that are pressurized internally through a vent to the autoclave chamber. They are usually constructed from a polyacrylic elastomer such as Airpad. This is an uncured non-silcone rubber that can be molded into shape. The sidewalls of inflatable bag mandrels are stiffened with a reinforcing fabric such as woven carbon fiber. This produces a semi-rigid box on which the composite plies can be laid-up (Fig. 5.31). There is sufficient compliance in the mandrel to expand when exposed to internal pressure, forcing the plies against the adjacent surfaces. Removal of the mandrel

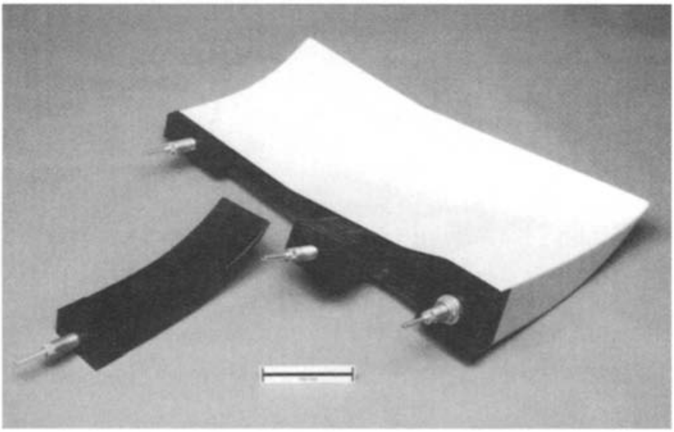


Fig. 5.31 Airpad brand inflatable tooling.

after cure can be achieved by applying a partial vacuum whereupon the bag collapses sufficiently for it to be withdrawn.

The durability of the Airpad material is limited, and often a replaceable nylon film is cured onto the surfaces to extend the useful life of the mandrel.

Metal mandrels are an alternative and have an advantage in terms of durability. Aluminum is often used and, in conjunction with a steel mold, provides compaction through differential expansion. Great care has to be taken to control the dimensions such that the correct compaction and hence the correct fiber/volume fraction is achieved. Removal of metal mandrels is less simple and even though an aluminum mandrel will shrink away from the cured part on cool-down, depending on the geometry, this may be insufficient to release it. In these circumstances it is necessary to use a segmented or split mandrel. These segments are joined with an adhesive that holds the mandrel together during lay-up but breaks down at the cure temperature to allow the segments to be removed individually after cure.

For complex geometries when either of the above solutions would still not allow mandrel removal, mandrels made of a soluble plaster are used. These are cast to shape for each part and melted or washed-out under high-pressure water after use. Removal rates of the plaster tend to be low, and the economics of this restrict it to small items or where no other choice is possible.

5.9 Special Thermoplastic Techniques

5.9.1 Intermediate Forms

Because of their very high viscosity at low to moderate temperatures, it is significantly more difficult to impregnate a reinforcement with a thermoplastic

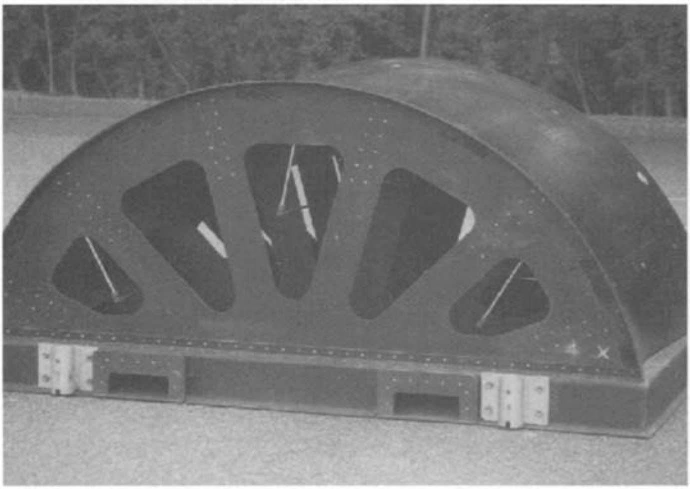


Fig. 5.32 ACG "Toolbrace" tooling.

material than with a thermoset resin. Thermoplastic composites are therefore supplied in a variety of different ready-to-use intermediate forms that may be processed through a number of standard production techniques[14] (Fig. 5.33). Considerable work has gone into developing these intermediates over the past decade. Typically, this has centred on the development of materials that have some form of a "partial impregnation," such as solvent or melt pre-pregs, film stacked pre-pregs, commingled fibers (carbon and thermoplastic fibers in a bundle or woven cloth), and powder-impregnated bundles that can be used in conjunction with contemporary thermoplastic manufacturing technology. The latter two intermediates bring fibers and matrix together in the non-molten state and are arranged such that fibers and matrix are already well mixed before processing. The comingled fibers and powder/sheath fiber bundles can be easily converted to a woven fabric by the standard weaving processes. An advantage of these two intermediates is that they are highly drapable.

5.9.2 Processing Technology of Thermoplastic Composites

The conversion of the intermediate into a final product requires only heat and pressure. No chemical conversion takes place as with thermosetting composites. The economic advantages of thermoplastic composites can be

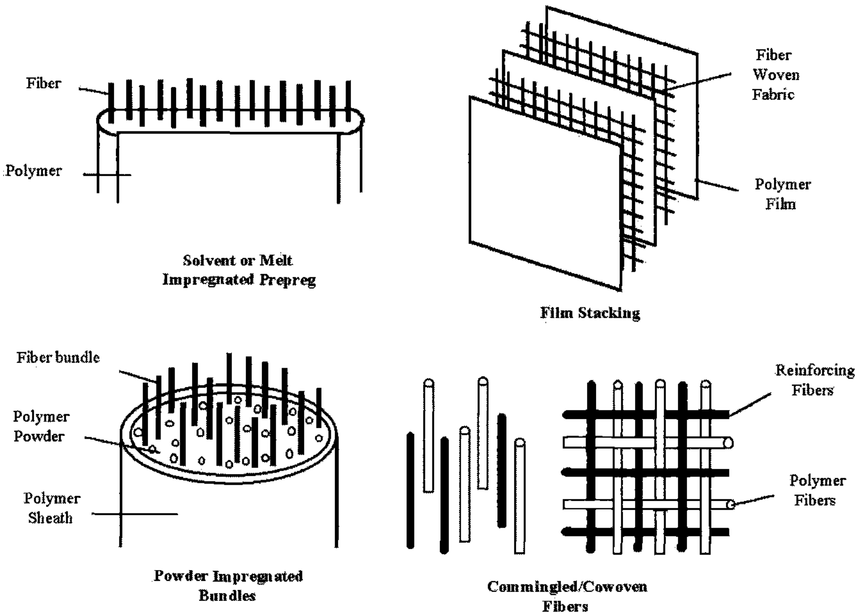


Fig. 5.33 Intermediate material forms for thermoplastic composites.

realized through high-rate, automated, manufacturing technologies that exploit the inherent rapid processibility of the material. The processing methods that are currently being developed for continuous fiber-reinforced thermoplastic composite parts are essentially adapted either from conventional thermoset composite technology or from existing sheet-metal-forming technology. These technologies include roll-forming, filament winding, pultrusion, diaphragm-forming, compression molding, stamping, deep drawing, and folding. Some of these techniques are briefly reviewed in the following subsections. A comprehensive review of various processing operations can be found in Ref. 15 and 16.

5.9.2.1 Roll-Forming. Figure 5.34 shows a schematic diagram of roll-forming.[17] The method employs consecutive roll stations to progressively deform the pre-consolidated sheet into some desirable shape. The process consists of an infrared preheating station designed to bring the sheet up to the molding temperature, followed by a series of rolling stations to form and consolidate the parts. Normally, several shaping rolls are required. The first one may be heated, but at least the last one must be cool enough to solidify the composite parts. The alignment of the rollers and the tolerance of their spacing are among several critical features that affect the quality of the product.

5.9.2.2 Filament Winding. The advantage of using a thermoplastic material in the filament winding process is that in situ consolidation can be effected that avoids the lengthy post-winding cure cycle required when using

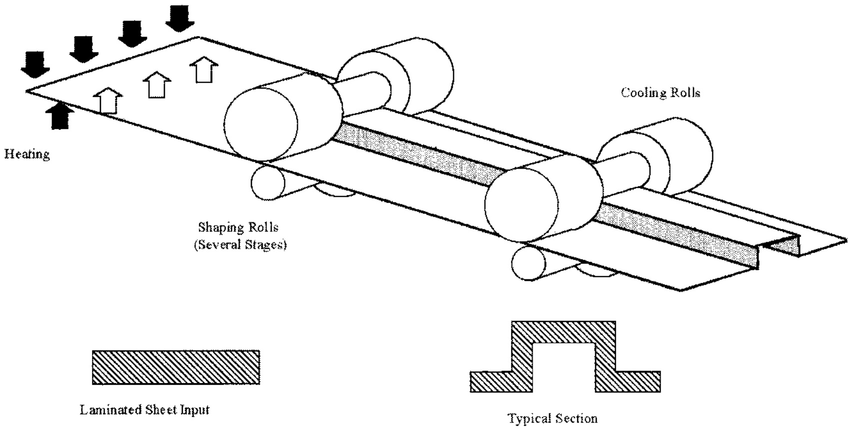
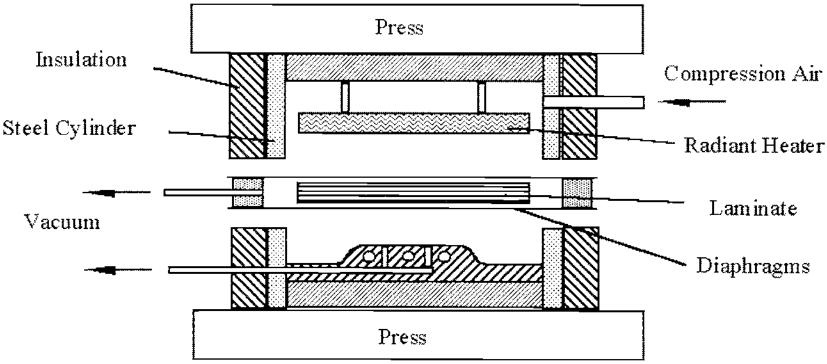


Fig. 5.34 Schematic diagram of roll-forming a thermoplastic composite part.

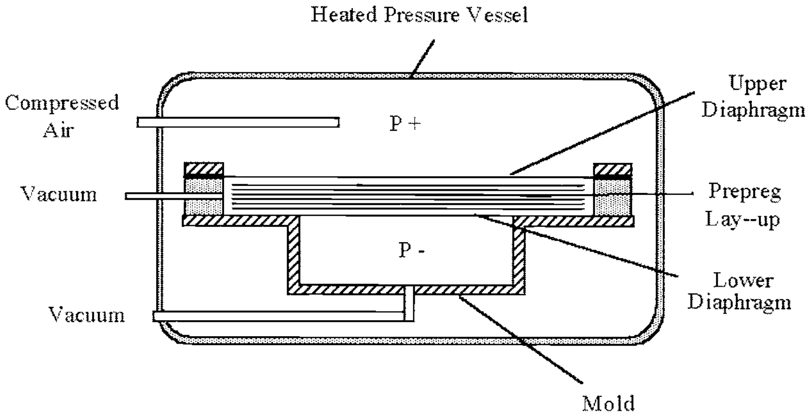
thermosetting composites. The same basic winding equipment used for thermoset composite systems discussed earlier in this chapter can be used for thermoplastics. Modifications require the addition of a heat source to heat the pre-preg tow above its melting/softening point and a consolidation mechanism to fuse the incoming tape to the face of previously wound material. The key steps are identified as tow preheating, tow guiding, contact point heating, mandrel heating, and post-consolidation. Heating techniques such as ultrasonic, laser beam, focused infrared, conduction, and convection heating have been investigated as methods to introduce localized heating into the process. Tow tension, heated roller, and sliding devices are possible consolidation methods that can be used. Because welding and consolidation take place immediately in the local contact area, composite parts having a re-entrant shape can be made. This is not possible with a filament-wound thermosetting composite.

5.9.2.3 Pultrusion. Although the pultrusion process is primarily associated with thermoset polymer composites, it is also possible to process continuous fiber-reinforced thermoplastic composites in this way. Pre-impregnated tape or commingled fiber bundles are the most usual intermediate forms that can be used in the pultrusion process. Significantly higher die temperatures are required than are necessary for thermoset pultrusion. Furthermore, while thermosets are allowed to exit the die at high temperatures (because they are chemically cross-linked and cured), thermoplastic pultruded profiles must pass through a cooling die to avoid deconsolidation on exit. The dies for thermoplastic composite pultrusion have tapering die cross-sections from entrance to exit to facilitate consolidation whereas thermoset pultrusion dies have constant cross-sections. In addition, the resin content of the material entering the die is more critical for thermoplastics than thermosets. Thermoset pultrusions enter the die with excess resin, which under these conditions is at a low viscosity, allowing it to be squeezed off at the die entrance. Thermoplastic materials, on the other hand (due to their much higher viscosity), must enter the die with a net resin content. The pultrusion of thermoplastics does not rely on a chemical reaction within the die that is time-dependent. Consequently, pultrusion speeds for thermoplastics will be faster than for thermosets.

5.9.2.4 Diaphragm Forming of Thermoplastic Composites. Diaphragm forming is also used to form thermoplastic composites, being particularly applicable to the forming of large areas with double curvature. Because the process requires far higher temperatures and pressures than the forming of thermoset pre-pregs described earlier in this chapter, the operation needs to be carried out in an autoclave or in a hydraulic press (Fig. 5.35). In the latter case, a split pressure chamber is mounted between the upper and lower platens. The unconsolidated pre-preg lay-up is sandwiched between two sealed, plastically deformable diaphragms. The diaphragms are clamped to a vacuum ring. After creating a vacuum within the composite lay-up, the entire sandwich is heated



a)



b)

Fig. 5.35 Diaphragm forming a thermoplastic composite part: *a*) in autoclave; *b*) in mold.

above the polymer melting/softening point, and pressure is applied to force the sandwich against the mold. During the processing, the diaphragms undergo a stretching action that supports the pre-preg layers and prevents wrinkling. Once forming is complete, the mold is cooled below the melting temperature of the thermoplastic resin. The diaphragms are then stripped off, and the component can be trimmed and finished. The stiffness of the diaphragm is a critical factor in achieving an optimum process. A typical cycle time of heating, pressurization, forming, and cooling might range from 40 minutes to 2 hours, depending on the tooling, heating, and cooling methods used. The actual time to shape the lay-up is typically 1–5 minutes.

5.9.2.5 Compression Molding. The process of compression molding can be applied to all the various intermediate material forms. Figure 5.36a illustrates the compression molding of a flat panel. The pre-preg lay-up is heated to melt the thermoplastic matrix; pressure is then applied to consolidate the plies together, and the laminate is cooled under pressure. The laminates can either be cooled directly within the molding press or quickly transferred to a cold-press with pressure reapplied. The latter procedure can effectively shorten the cycle time because it eliminates the period required to heat and cool the hot-press during forming. Specific profile shapes instead of flat laminates can also be produced using this technique (Fig. 5.36b). The laminate is supported in a frame or ring that allows the heated laminate to slip between the frame under the drawing forces generated as the mold closes.

5.9.2.6 Stamp-Forming. Stamp-forming is a variation of compression molding, which is similar to the sheet-metal stamp-forming process. This technology is best suited to the forming of simply-folded shapes requiring only a minimum of deformation in the material. In this process, a consolidated flat laminate is heated in an external heater to a temperature above the melting/ softening temperature of the thermoplastic matrix. The hot laminate is then quickly transferred into an unheated mold, where it is stamped to conform to the mold geometry and allowed to cool under pressure to a temperature below the melting point of the polymer matrix (Fig. 5.37). The typical cycle time is about 2–3 minutes. Because the heated laminate is exposed to a lower environmental temperature before forming, the use of high closing speeds is important to successfully stamp-form the part. Either mechanical or hydraulic presses can be used.

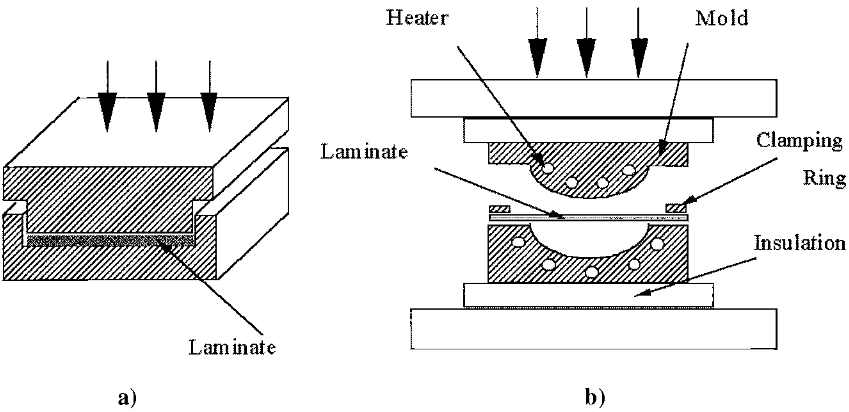


Fig. 5.36 Schematic diagram of compression molding of a thermoplastic composite part: a) flat panel molding; b) shaped panel molding.

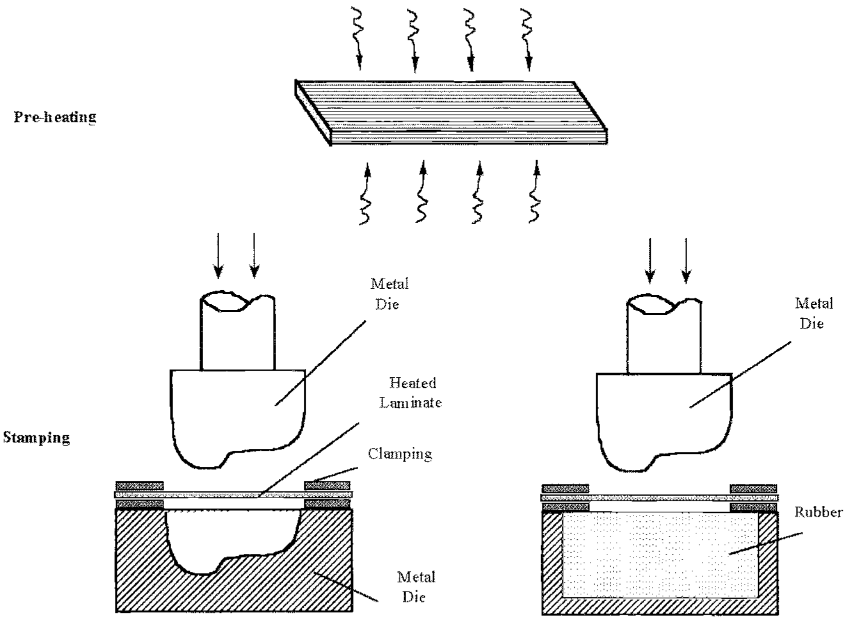


Fig. 5.37 Schematic diagram of stamp-forming a thermoplastic composite part.

The dies can be matched metal or single metal with a conforming rubber block. The use of matched metal dies provides improved dimensional control and surface quality on both sides of the part. Metal dies can apply higher pressures and can also be internally heated, further enhancing the quality of the final product. However, their rigidity creates a non-uniform pressure over the laminate during the forming process that makes it difficult to control wrinkling. Furthermore, it can result in varying fiber/volume fractions through the product and consequently non-uniform mechanical properties. To overcome these disadvantages, one of the metal dies can be replaced with a flexible rubber block. The remaining rigid metal die determines the final shape of the product and gives a good surface quality on the contacting face of the product, and the rubber block generates a homogeneous pressure distribution on the composite material. The flexibility of the rubber will account for any thickness mismatch or thickness variation of the product. To facilitate molding of more complex geometries, the rubber may be contoured to approximately match the shape of the rigid metal mold half. Sometimes it is beneficial to under- or over-shape the rubber die to avoid or create certain high local pressures that can improve the quality of the product. Silicone rubber is usually used as the block material, which allows a relatively high processing temperature range (up to 320°C).

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