PMC PROCESSING

1. Forming Processes for Thermosetting matrix composites:
   - Hand layup and sprayup techniques.
   - Filament winding.
   - Pultrusion.
   - Resin transfer moulding.
   - Autoclave moulding.

2. Forming Processes for Thermoplastic matrix composites:
   - Injection moulding.
   - Film stacking.
   - Diaphragm forming.
   - Thermoplastic tape laying.

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Hand Layup

- Hand layup process:
  - Gel coat is applied to open mold.
  - Fiberglass reinforcement is placed in the mold.
  - Base resin mixed with catalysts is applied by pouring and brushing.

Layup is made by building layer upon layer to obtain the desired thickness.
Hand Layup

Advantages:
- Widely used.
- Low tooling cost.
- Custom shape.
- Larger and complex items can be produced.

Potential Problems:
- Labour intensive.
- Low-volume process.
- Styrene emission.
- Quality control is entirely dependent on the skill of labourers.

Hand layup products:

SPRAYUP

In Sprayup process liquid resin matrix and chopped reinforcing fibers are sprayed by two separate sprays onto the mold surface. The fibers are chopped into fibers of 1-2" (25-50 mm) length and then sprayed by an air jet simultaneously with a resin spray at a predetermined ratio between the reinforcing and matrix phase. The Sprayup method permits rapid formation of uniform composite coating, however the mechanical properties of the material are moderate since the method is unable to use continuous reinforcing fibers.
A spray gun supplying resin in two converging streams into which roving is chopped. Automation with robots results in high rate of production. Labor costs are lower.

**SPRAYUP**

In Sprayup process, chopped fibers and resins are sprayed simultaneously into or onto the mold. Applications are lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, small boats, etc.

**Hand and Spray Layup**

- In both the cases the deposited layers are densified with rollers.
- Catalysts and Accelerators are used.
  - **Catalyst** - substance added to the gel coat or resin to initiate the curing process.
  - **Accelerator** - A compound added to speed up the action of a catalyst in a resin mix.
- Curing at room temperature or at a moderately high temperature in an oven.

**Advantages of Hand Layup and Sprayup**

- Tooling cost is low.
- Semiskilled workers are easily trained.
- Design Flexibility.
- Molded-in inserts and structural changes are possible.
- Sandwich constructions are possible.
- Large and Complex items can be produced.
- Minimum equipment investment is necessary.
- The startup lead time and the cost are minimal.
**Disadvantages of Hand Layup and Sprayup**

- Labor intensive.
- Low volume process.
- Longer curing times.
- Production uniformity is difficult.
- Waste factor is high.

**PREPREG**

- Prepreg is the composite industry's term for continuous fiber reinforcement. Pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite form most widely used for structural applications.

**PREPREG PROCESS**

- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to provide for its thorough impregnation of the fibers.
- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin.

**PREPREG**

- Prepared for packaging by winding onto a cardboard core.
- Typical tape thicknesses range between 0.08 and 0.25 mm.
- Tape widths range between 25 and 1525 mm.
- Resin content lies between about 35 and 45 vol%.
PREPREG

* The prepreg is stored at 0°C (32°F) or lower because matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.

* Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.

* Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.

* The layup can be by hand or automated.

Easily obtained with epoxies.

Filament Winding

Filament Winding method involves a continuous filament of reinforcing material wound onto a rotating mandrel in layers at different layers. If a liquid thermostelling resin is applied on the filament prior to winding the, process is called Wet Filament Winding. If the resin is sprayed onto the mandrel with wound filament, the process is called Dry Filament Winding. Besides conventional curing of molded parts at room temperature, Autoclave curing may be used.

Filament Winding Process

• For Round or Cylindrical parts
  • A tape of resin impregnated fibers is wrapped over a rotating mandrel to form a part.
  • These windings can be helical or hooped.
  • There are also processes that use dry fibers with resin application later, or prepregs are used.
  • Parts vary in size from 1" to 20"
  • Winding direction
    • Hoop/helical layers
    • Layers of different material
  • High strengths are possible due to winding designs in various direction
  • Winding speeds are typically 100 m/min and typical winding tensions are 0.1 to 0.5 kg.

Demolding

• To remove the mandrel, the ends of the parts are cut off when appropriate, or a collapsible mandrel (e.g., low melt temperature alloys) is used.
• Curing in done in an Autoclave for thermoset resins (polyester, epoxy, phenolic, silicone) and some thermoplastics (PEEK).
• Fibers are E-glass, S-glass, carbon fiber and aramids (toughness and lightweight).
• Inflatable mandrels can also be used to produce parts that are designed for high pressure applications, or parts that need a liner, and they can be easily removed.

Advantages

• Good for wide variety of part sizes
• Parts can be made with strength in several different directions
• Very low scrap rate
• Non-cylindrical parts can be formed after winding
• Flexible mandrels can be left in as tank liners
• Reinforcement panels, and fittings can be inserted during winding
• Due to high hoop stress, parts with high pressure ratings can be made

Disadvantages

• Viscosity and pot life of resin must be carefully chosen
• NC programming can be difficult
• Some shapes can't be made with filament winding
• Factors such as filament tension must be controlled
Filament Winding

The filament winding process has the following advantages:
1. The process may be automated and provides high production rates.
2. Highest-strength products are obtained because of fiber placement control.
3. There is versatility of sizes.
4. Control of strength in different directions possible.

The following are limitations of filament winding:
1. Winding reverse curvatures is difficult.
2. Winding at low angles (parallel to rotational axis) is difficult.
3. Complex (double-curvature) shapes are difficult to obtain.
4. There is poor external surface.

Filament winding - applications

• pressure vessels, storage tanks and pipes
• rocket motors, launch tubes
  – Light Anti-armour Weapon (LAW)
    • Hunting Engineering made a nesting pair in 4 minutes with ~20 mandrels circulated through the machine and a continuous curing oven.
• drive shafts
• Entec “the world’s largest five-axis filament winding machine” for wind turbine blades
  – length 45.7 m, diameter 8.2 m, weight > 36 tonnes.

FILAMENT WINDING CHARACTERISTICS

* The cost is about half that of tape laying
* Productivity is high (50 kg/h).
* Applications include: fabrication of composite pipes, tanks, and pressure vessels. Carbon fiber reinforced rocket motor cases used for Space Shuttle and other rockets are made this way.

Filament winding

- Tensioner
- Roving
- Resin bath
- Shuttle
- Motor
- Gearbox
- Drive link chain
- Stroke
- Chain
- Track
- Part
- Dwell
Filament winding - winding patterns

- **hoop (90°)** - girth or circumferential winding
  - angle is normally just below 90° degrees
  - each complete rotation of the mandrel shifts the fibre band to lie alongside the previous band.

- **helical**
  - complete fibre coverage without the band having to lie adjacent to that previously laid.

- **polar**
  - domed ends or spherical components
  - fibres constrained by bosses on each pole of the component.

- **axial (0°)**
  - beware: difficult to maintain fibre tension

Filament wound pressure bottles for gas storage
Pultrusion

Description:

Pultrusion is a process where composite parts are manufactured by pulling layers of fibres/fabrics, impregnated with resin, through a heated die, thus forming the desired cross-sectional shape with no part length limitation.

Pultrusion process is characterized by the following features:

- High productivity.
- The process parameters are easily controllable.
- Low manual labor component.
- Precise cross-section dimensions of the products.
- Good surface quality of the products.
- Homogeneous distribution and high concentration of the reinforcing fibers in the material is achieved (up to 80% of roving reinforcement, up to 50% of mixed mat + roving reinforcement).
- Pultrusion is used for fabrication of Fiber glass and Carbon fiber reinforced polymer composites and Kevlar (aramid) fiber reinforced polymers.
Pultrusion

- Manufacturing
  - Fibers are brought together over rollers, dipped in resin and drawn through a heated die. A continuous cross section composite part emerges on the other side.

production of constant cross-section profiles
Pultrusion

• Design
  - Hollow parts can be made using a mandrel that extends out the exit side of the die.
  - Variable cross section parts are possible using dies with sliding parts.
  - Two main types of dies are used, fixed and floating. Fixed dies can generate large forces to wet fiber. Floating dies require an external power source to create the hydraulic forces in the resin. Multiple dies are used when curing is to be done by the heated dies.
  - Very low scrap. Up to 95% utilization of materials (75% for layup).
  - Rollers are used to ensure proper resin impregnation of the fiber.
  - Material forms can also be used at the inlet to the die when materials such as mats, weaves, or stitched material is used.
  - For curing, tunnel ovens can be used. After the part is formed and gelled in the die, it emerges, enters a tunnel oven where curing is completed.
  - Another method is, the process runs intermittently with sections emerging from the die, and the pull is stopped, split dies are brought up to the sections to cure it, they then retract, and the pull continues. (Typical lengths for curing are 6” to 24”)
  - Shapes such as rods, channels, angle and flat stocks can be easily produced.
  - Production rate is 10 to 200 cm/min.
  - Profiles as wide as 1.25 m with more than 60% fiber volume fraction can be made routinely.
  - No bends or tapers allowed (continuous molding cycle)

• Materials
  - Most fibers are used (carbon, glass, aramids) and Resins must be fast curing because of process speeds. (polyester and epoxy)
  - Processing
    - speeds are 0.6 to 1 m/min; thickness are 1 to 76 mm; diameters are 3 mm to 150mm
    - double clamps, or belts/chains can be used to pull the part through. The best designs allow for continuous operation for production.
    - diamond or carbide saws are used to cut sections of the final part. The saw is designed to track the part as it moves.
  - Advantages
    - good material usage compared to layup
    - high throughput and higher resin contents are possible
  - Disadvantages
    - part cross section should be uniform.
    - Fiber and resin might accumulate at the die opening, leading to increased friction causing jamming, and breakup.
    - when excess resin is used, part strength will decrease
    - void can result if the die does not conform well to the fibers being pulled
    - quick curing systems decrease strength

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Pultrusion - applications

- panels – beams – gratings – ladders
- tool handles - ski poles – kites
- electrical insulators and enclosures
- light poles - hand rails – roll-up doors
- 450 km of cable trays in the Channel Tunnel

Resin Transfer Molding

- In the RTM process, dry (i.e. non-impregnated) reinforcement is pre-shaped and oriented into skeleton of the actual part known as the preform which is inserted into a matched die mold.
- The heated mold is closed and the liquid resin is injected.
- The part is cured in mold.
- The mold is opened and part is removed from mold.

Resin Transfer Moulding

Close mold low pressure process.
A dry preform is placed in a matched metal die.
A vacuum pulls the low – viscosity resin through a flow medium that helps impregnate the preform.
Resin may also be forced by means of a pump.
Resin Transfer Moulding

Transfer Molding (Resin Transfer Molding) is a Closed Mold process in which a pre-weighed amount of a polymer is preheated in a separate chamber (transfer pot) and then forced into a preheated mold filled with a reinforcing fibers, taking a shape of the mold cavity, impregnating the fibers and performing curing due to heat and pressure applied to the material.

- The picture below illustrates the Transfer Molding Process.
- The method uses a split mold and a third plate equipped with a plunger mounted in a hydraulic press.
- The method combines features of both Compression Molding - hydraulic pressing, the same molding materials (thermosets) and Injection Molding - ram (plunger), filling the mold through a sprue.
- Transfer Molding cycle time is shorter than Compression Molding cycle but longer than Injection Molding cycle.
- The method is capable to produce very large parts (car body shell), more complicated than Compression Molding, but not as complicated as Injection Molding.

RTM

RTM process involves the following steps:

- The mold cavity is filled with preformed reinforcing fibers.
- A pre-weighed amount of a polymer mixed with additives and fibers (catalyst) is placed into the transfer pot.
- The charge may be in form of pastes, pellets, putty-like masses or pre-formed blanks.
- The charge is heated in the pot where the polymer softens.
- The plunger, mounted on the top plate, moves downwards, pressing on the polymer charge and forcing it to fill the mold cavity through the sprue and impregnate the fibers.
- The mold, equipped with a heating system, provides curing (cross-linking) of the polymer (if thermoset is processed).
- The mold is opened and the part is removed from it by means of the ejector pin.
- If thermosetting resin is molded, the mold may be opened in hot state – cured thermosets maintain their shape and dimensions even in hot state.
- If thermoplastics is molded, the mold and the molded part are cooled down before opening.
- Following steps are the same as in the case of thermostets, and the chemistry is reversed. Scope of transferring polymers is not recoupled.

Advantages of RTM

- Large complex shapes and curvatures can be made easily.
- High level of automation.
- Layup is simpler than in manual operations.
- Takes less time to produce.
- Fiber volume fractions as high as 60% can be achieved.
- Styrene emission can be reduced to a minimum.
- Cost effective High volume process for large-scale processing.

Disadvantages of RTM

- Mold design is complex and requires mold-filling analysis.
- Fiber reinforcement may "wash" or move during resin transfer.
Resin Transfer Moulding

Advantages:
- Low skill labour required
- Low tooling cost
- Low volatile emission
- Required design tailorability

Potential Problems:
- Control of resin flow
- Kinking of fibres
- Criticality in mould design

RTM Products:

Autoclave moulding
- Autoclave Curing is a method in which a part, molded by one of the open molding methods, is cured by a subsequent application of vacuum, heat and inert gas pressure.
- The molded part is first placed into a plastic bag, from which air is exhausted by a vacuum pump. This operation removes air inclusions and volatile products from the molded part.
- Then heat and inert gas pressure are applied in the autoclave causing curing and densification of the material.
- Autoclave Curing enables fabrication of consistent homogeneous materials. The method is relatively expensive and is used for manufacturing high quality aerospace products.
Autoclave

- An oven that allows for high pressures to be used.
- Composites cure under heat and pressure provides a superior part because the voids are reduced due to the pressure.
  - Process
    - The part is placed in the pressure vessel, and heated, pressure is applied simultaneously.
    - Vacuum bagging can be used in an autoclave.
    - Thermoset composites are crosslinked.
    - Thermoplastics are melted.
  - Advantages
    - The pressure helps bond composite layers, and remove more voids in the matrix.
    - Very large parts can be made with high fiber loadings.
    - Properties are improved.
    - Many different parts can be cured at the same time.
  - Disadvantages
    - Autoclaves are expensive

Autoclave process - Characteristics

- Very high quality product
- Generally prepregs are used
- Chopped fibres with resin can also be used
- Hybrid composites can be produced
- High fibre volume fractions can be obtained
- Simultaneous application of high temperature and pressure helps in:
  * Consolidating the laminate.
  * Removing the entrapped air.
  * Curing the polymeric matrix.

Autoclave Moluding

- a) Autoclave process to make a laminated composite
- b) Prepregs of different orientations stacked to form a laminated composite
- Higher fiber volume fractions (60 – 65%) can be obtained
Injection moulding

- **Injection Molding** is a Closed Mold process in which molten polymer (commonly thermoplastic) mixed with very short reinforcing fibers (10-40%) is forced under high pressure into a mold cavity through an opening (sprue).
- Polymer-fiber mixture in form of pellets is fed into an Injection Molding machine through a hopper. The material is then conveyed forward by a feeding screw and forced into a split mold, filling its cavity through a feeding system with sprue gate and runners.
- Screw of injection molding machine is called reciprocating screw since it not only rotates but also moves forward and backward according to the steps of the molding cycle.
- It acts as a ram in the filling step when the molten polymer-fibers mixture is injected into the mold and then it retracts backward in the molding step.
- Heating elements, placed over the barrel, soften and melt the polymer.
- The mold is equipped with a cooling system providing controlled cooling and solidification of the material.

Injection moulding machine

- The injection molding machine comprises of:
  - The plasticating and injection unit: The major tasks of the plasticating unit are to melt the polymer, to accumulate the melt in the screw chamber, to inject the melt into the cavity and to maintain the holding pressure during cooling.
  - The clamping unit: Its role is to open and close the mold, and hold the mold tightly to avoid flash during the filling and holding. Clamping can be mechanical or hydraulic.
  - The mold cavity: The mold is the central point in an injection molding machine. Each mold can contain multiple cavities. It distributes polymer melt into and throughout the cavities, shapes the part, cools the melt and ejects the finished product.
The Injection Mold

The mold consists
• Sprue and runner system
• Gate
• Mold cavity
• Cooling system (for thermoplastics)
• Ejector system

Features of injection molding:
- Direct path from molding compound to finished product
- Process can be fully automated
- High productivity & quality

Injection molding machine

Injection Molding Machine
Injection Molding

Injection molding involves two basic steps:
- Melt generation by a rotating screw
- Forward movement of the screw to fill the mold with melt and to maintain the injected melt under high pressure

Injection molding is a "cyclic" process:
- Injection: The polymer is injected into the mold cavity.
- Hold on time: Once the cavity is filled, a holding pressure is maintained to compensate for material shrinkage.
- Cooling: The molding cools and solidifies.
- Screw-back: At the same time, the screw retracts and turns, feeding the next shot in towards the front

Injection molding is the most important process used to manufacture plastic products. It is ideally suited to manufacture mass produced parts of complex shapes requiring precise dimensions.

It is used for numerous products, ranging from boat hulls and lawn chairs, to bottle cups. Car parts, TV and computer housings are injection molded.

Thermoplastics: Polystyrene, PE, PP, ABC, PC, PMMA etc

Thermosets: Unsaturated polyester resin, Phenol formaldehyde etc

Reaction injection moulding

- Reaction injection moulding (RIM): Two reactive ingredients are pumped at high speeds and pressures into a mixing head and injected into a mold cavity where curing and solidification occur due to chemical reaction.
**Reinforced reaction injection molding**

*Reinforced reaction injection moulding (RRIM)* - similar to RIM but includes reinforcing fibers, typically glass fibers, in the mixture.

- Advantages: similar to RIM (e.g., no heat energy required, lower cost mold), with the added benefit of fiber reinforcement.
- Products: auto body, truck cab applications for bumpers, fenders, and other body parts.

**Film stacking**

- Stack of laminate consists of fibers, impregnated with insufficient thermoplastic matrix, and polymer films of complementary weight to give the desired fiber volume fraction in the end product. These are then consolidated by simultaneous application of heat and pressure.
- Generally, a pressure of 6-12 MPa, a temperature between 275 and 350°C, and dwell times of up to 30 mins are appropriate for thermoplastics such as polysulfones and polyetheretherketone (PEEK).

**DIAPHRAGM FORMING**

- This process involves the sandwiching of freely floating thermoplastic prepreg layers between two diaphragms.
- The air between the diaphragms is evacuated and thermoplastic laminate is heated above the melting point of the matrix.

**DIAPHRAGM FORMING**

- Pressure is applied to one side, which deforms the diaphragm and makes them take the shape of the mold.
- The laminate layers are freely floating and very flexible above the melting point of the matrix, thus they readily conform to the mold shape.
DIAPHRAGM FORMING

• After the completion of the forming process, the mold is cooled, the diaphragms are stripped off, and the composite is obtained. The diaphragms are the key to the forming process, and their stiffness is a very critical parameter.

• For very complex shapes requiring high molding pressures, stiff diaphragm are needed. At high pressures, a significant transverse squeezing flow can result, and this can produce undesirable thickness variations in the final composite.

ADVANTAGES:

• Components with double curvatures can be formed.
• Compliant diaphragm do the job for simple components.

Thermoplastic tape laying (Automated Layup)

• In this method layers of prepreg (reinforcing phase impregnated by liquid resin) tape are applied on the mold surface by a tape application robot.
• Cost is about half of hand lay-up.
• used for thermoset or thermoplastic matrix.
• limited to flat or low curvature surfaces.
• Extensively used for products such as airframe components, bodies of boats, truck ,tanks, swimming pools and ducts.

Automated tape-laying machine (photo courtesy of Cincinnati Milacron).

Automated tape-laying machines operate by dispensing a prepreg tape onto an open mold following a programmed path .
Typical machine consists of overhead gantry to which the dispensing head is attached.
The gantry permits x-y-z travel of the head, for positioning and following a defined continuous path.