

Composites Manufacturing



ME 338: Manufacturing Processes II
Instructor: Ramesh Singh; Notes: Prof. Singh/ Ganesh Soni

Composites



What is a composite Material?

- Two or more chemically distinct materials combined to have improved properties
 - Natural/synthetic
 - Wood is a natural composite of cellulose fiber and lignin.
 - Cellulose provides strength and the lignin is the "glue" that bonds and stabilizes the fiber.
 - Bamboo is a wood with hollow cylindrical shape which results in a very light yet stiff structure. Composite fishing poles and golf club shafts copy this design.
 - The ancient Egyptians manufactured composites!
 - Adobe bricks are a good example which was a combination of mud and straw



COMPOSITES

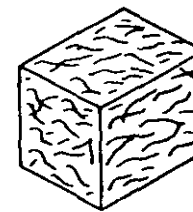
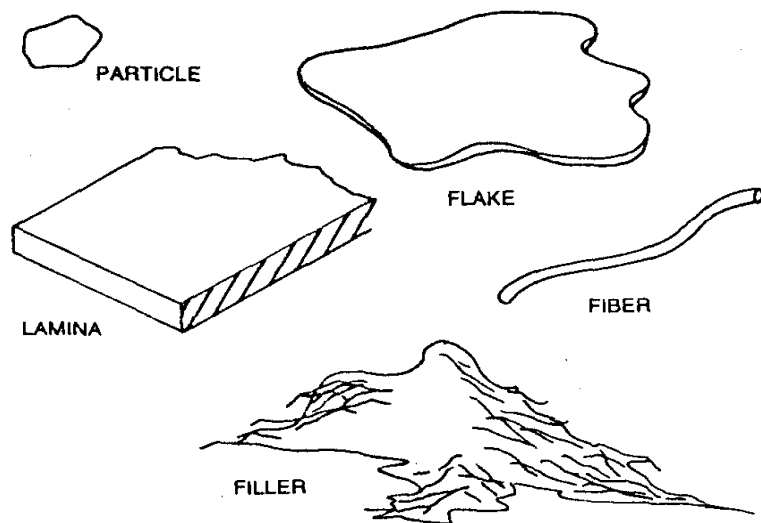
A composite material consists of two phases:

- Primary
 - Forms the matrix within which the secondary phase is imbedded
 - Any of three basic material types: polymers, metals, or ceramics
- Secondary
 - Referred to as the imbedded phase or called the reinforcing agent
 - Serves to strengthen the composite (fibers, particles, etc.)
 - Can be one of the three basic materials or an element such as carbon or boron

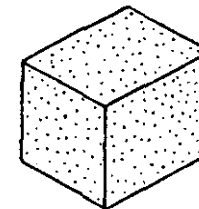


Types of composite materials

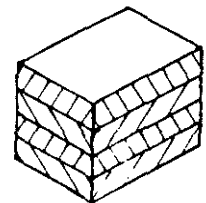
There are five basic types of composite materials: **Fiber**, **particle**, **flake**, **laminar** or layered and **filled** composites.



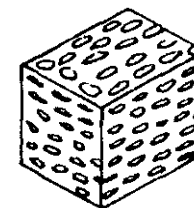
FIBER COMPOSITE



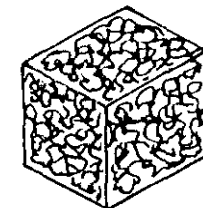
PARTICLE COMPOSITE



LAMINAR COMPOSITE



FLAKE COMPOSITE



FILLED COMPOSITE



Classification of composite material

- **Metal Matrix Composites (MMCs)**
 - Mixtures of ceramics and metals, such as cemented carbides and other cermets
 - Aluminum or magnesium reinforced by strong, high stiffness fibers
- **Ceramic Matrix Composites (CMCs)**
 - Least common composite matrix
 - Aluminum oxide and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications
- **Polymer Matrix Composites (PMCs)**
 - Thermosetting resins are the most widely used polymers in PMCs.
 - Epoxy and polyester are commonly mixed with fiber reinforcement



Classification of composite material

- Matrix material serves several functions in the composite
 - Provides the bulk form of the part or product
 - Holds the imbedded phase in place
 - Shares the load with the secondary phase



The reinforcing phase

- The imbedded phase is most commonly one of the following shapes:
 - Fibers, particles, flakes
- Orientation of fibers:
 - **One-dimensional:** maximum strength and stiffness are obtained in the direction of the fiber
 - **Planar:** in the form of two-dimensional woven fabric
 - **Random or three-dimensional:** the composite material tends to possess isotropic properties



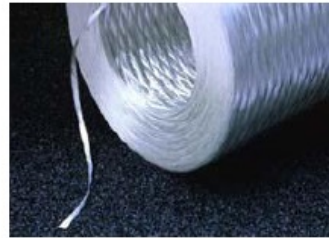
The reinforcing phase

Types of phases

- Currently, the most common fibers used in composites are glass, graphite (carbon), boron and Kevlar 49.
 - Glass – most widely used fiber in polymer composites called glass fiber-reinforced plastic (GFRP)
 - E-glass – strong and low cost, but modulus is less than other (500,000 psi)
 - S-glass – highest tensile strength of all fiber materials (650,000 psi). UTS~ 5 X steel ; $\rho \sim 1/3$ x steel



- Rovings
 - continuous
 - bulk



- Continuous strand mat
- Chopped strand mat



- Surface veils



The reinforcing phase

- Carbon/Graphite –Graphite has a tensile strength three to five times stronger than steel and has a density that is one-fourth that of steel.
- Boron – Very high elastic modulus, but its high cost limits its application to aerospace components
- Ceramics – Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are the main fiber materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low- modulus metals such as aluminum and magnesium
- Metal – Steel filaments, used as reinforcing fiber in plastics



Polymer matrix composites

- Fiber Reinforced Plastics (FRP) are most closely identified with the term composite.

FRP

- A composite material consisting of a polymer matrix imbedded with high-strength fibers
- Widely used in rubber products such as tires and conveyor belts
- Principle fiber materials are: glass, carbon, and Kevlar
- Advanced composites use boron, carbon, Kevlar as the reinforcing fibers with epoxy as the matrix



Polymer matrix composites

Hybrids

When two or more fibers materials are combined in the composite.

- **Intraply hybrids** (within) - Alternate strands of different fibers in a single layer or ply
- **Interply hybrid** (across) – Different plies of different fibers
- The most widely used form is a laminar structure, made by stacking and bonding thin layers of fiber and polymer until the desired thickness is obtained.



Rule of mixtures for composites



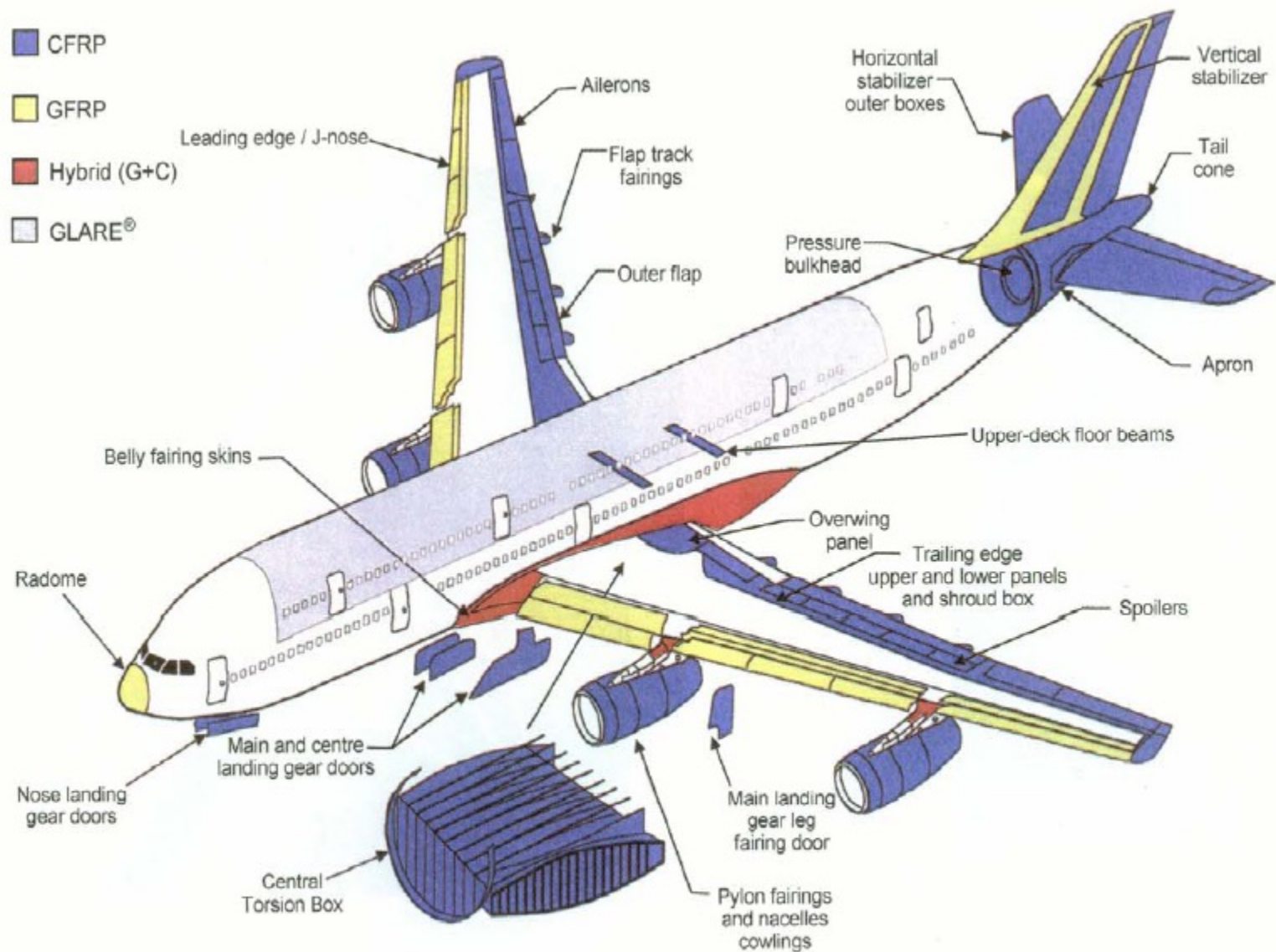


Plate 1: A380 composite materials application. Not shown: CFRP passenger floor panels and struts. *Some composite parts are bonded others are not.* Several metal parts are also bonded in modern civil and military aircrafts.

Automotive sectors





All composite bus
(Compobus). North American
Bus Industries (Anniston,
Alabama) delivered 200th bus.

Body and
chassis are
produced using
glass and carbon
fiber composites

Light weight,
good damage
tolerance and
corrosion
resistant



Composite "flying" trimaran
(France), l'Hydroptere fastest
sailing boat on the planet
(59.1 mph) over 500 m

Carbon fiber
composites w/
Titanium at keel
locations. Only
14,300 lbs

At a certain
speed, its
submerged
foils can lift the
hulls above the
water surface



Light weight,
good damage
tolerance and
corrosion
resistant



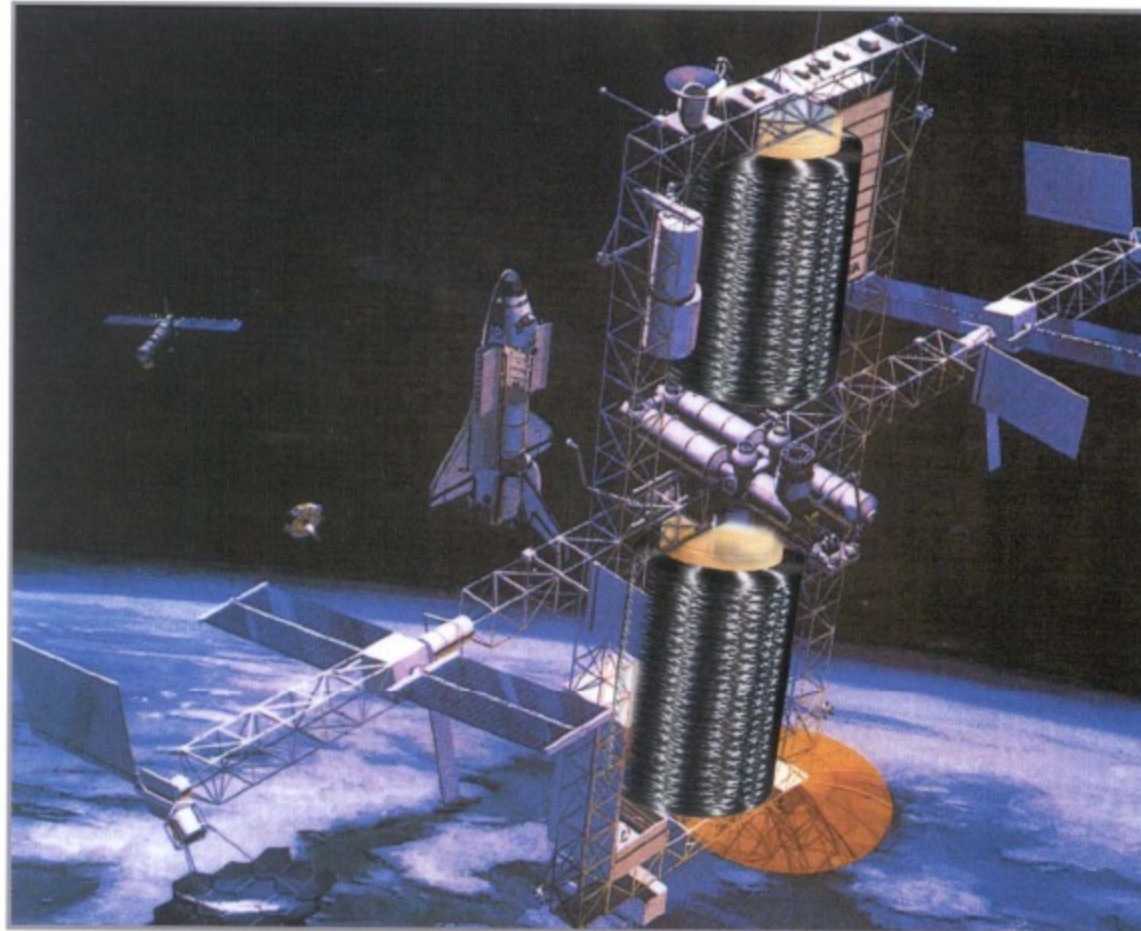
Wind mill blades
are made of
composite
materials.



Lifting tanks onto the ship.

Fiber Reinforced Plastic tanks for storing acids and corrosives (Reinforced Plastics Magazine, May 2009)

Communication and Space



Sports and recreational sectors:



Aft flaps

- Outboard (graphite)
- Inboard (graphite fiberglass)

Flap support fairings

- Fwd segment (graphite/Kevlar + non-woven Kevlar mat)
- Aft segment (graphite/fiberglass)

Rudder (graphite)

Tip fairings (fiber glass)

Fixed trailing edge panels (graphite/Kevlar + non-woven Kevlar mat)

Engine strut fairings (Kevlar/fiberglass)

Environmental control system ducts (Kevlar)

Elevators (graphite)

Nose landing gear doors (graphite)

Fixed trailing edge panels upper (graphite/fiberglass) lower (graphite/Kevlar + non-woven Kevlar mat)

Wing-to-body fairings (graphite/Kevlar fiberglass) and (graphite/Kevlar + non-woven Kevlar mat)

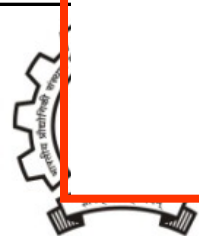
Spoilers (graphite)

Fixed trailing edge panels (graphite/Kevlar + non-woven Kevlar mat)

Cowl components (graphite)

Wing leading edge lower panels (Kevlar/ fiberglass)

- Body main landing gear doors (graphite)
- Trunnion fairings and wing landing gear doors (graphite/Kevlar)
- Brakes (structural carbon)



Application of Composites in Aircraft Industry

Boeing 777	Boeing 787/Dreamliner
<i>Launched in 2000</i>	<i>To be launched in 2007</i>
11% composites	50% composites
70% aluminum	20% aluminum
7% titanium	15% titanium
11% steel	10% steel
1% other	5% other

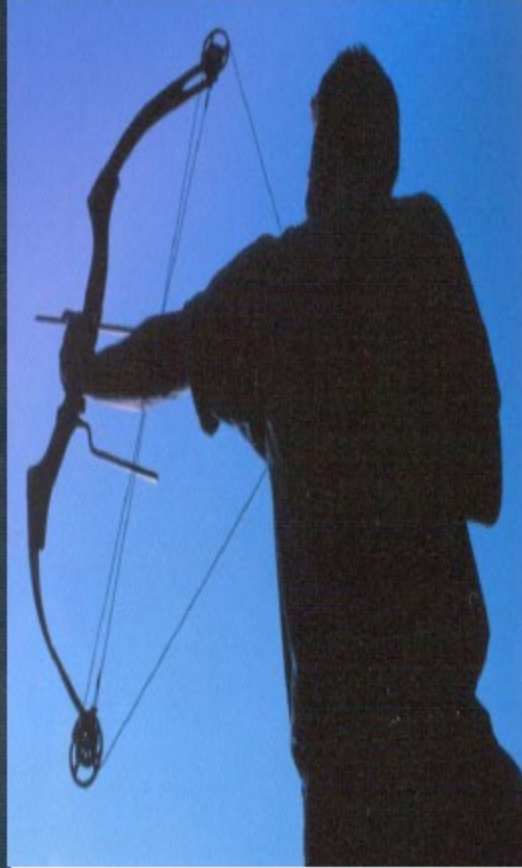
20% more fuel
efficiency and 35,000
lbs. lighter

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Sports applications



Application of Composites



Pedestrian bridge in
Denmark, 130 feet
long (1997)

Lance Armstrong's 2-
lb. Trek bike, 2004
Tour de France

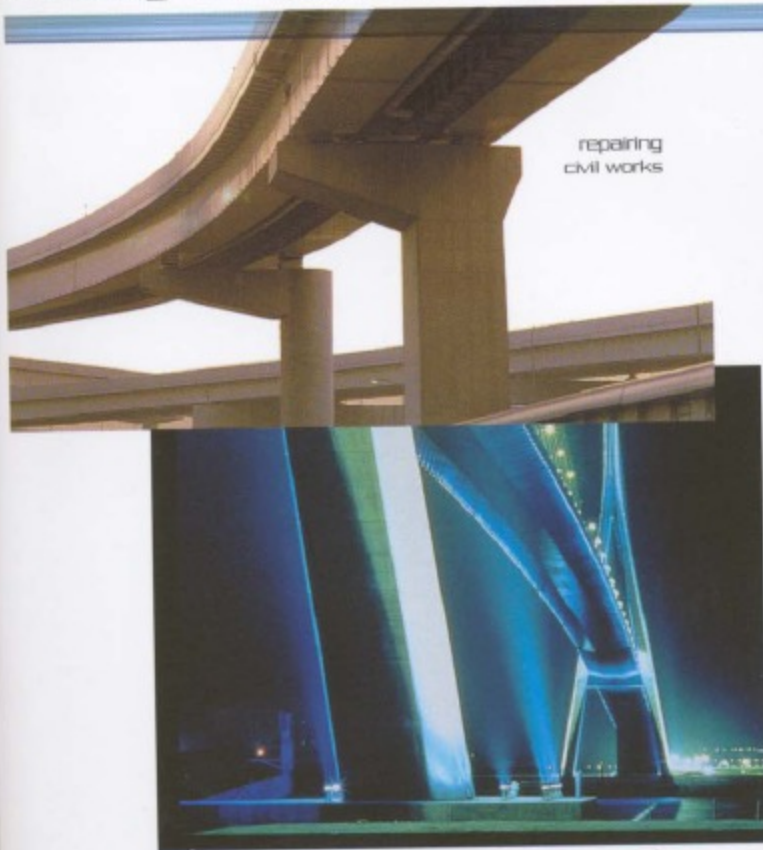


Swedish Navy,
Stealth (2005)



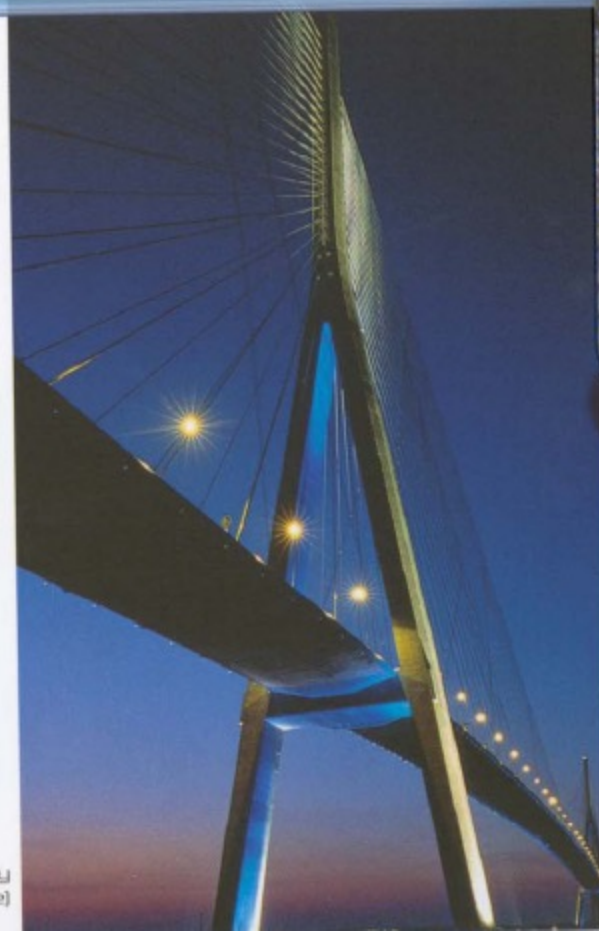
Civil Infrastructure sectors:

building and public works



repairing
civil works

Pont de Normandie (Normandy
Bridge, France)



Why Composites are Important

- Composites can be very strong and stiff, yet very light in weight, so ratios of strength-to-weight and stiffness-to-weight are several times greater than steel or aluminum
- Fatigue properties are generally better than for common engineering metals
- Toughness is often greater than most of the metals
- Composites can be designed that do not corrode like steel
- Possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone



Disadvantages and Limitations of Composite Materials

- Properties of many important composites are anisotropic
- Many of the polymer-based composites are subject to attack by chemicals or solvents
- Composite materials are generally expensive
- Manufacturing methods for shaping composite materials are often slow and costly



Disadvantages of Composites

In November 1999, America's Cup boat "Young America" broke in two due to debonding face/core in the sandwich structure.



Manufacturing of composites

1. **Open Mold Processes-** some of the original FRP manual procedures for laying resins and fibers onto forms
2. **Closed Mold Processes-** much the same as those used in plastic molding
3. **Filament Winding-** continuous filaments are dipped in liquid resin and wrapped around a rotating mandrel, producing a rigid, hollow, cylindrical shape
4. **Pultrusion Processes-** similar to extrusion only adapted to include continuous fiber reinforcement
5. **Other PMC Shaping Processes**

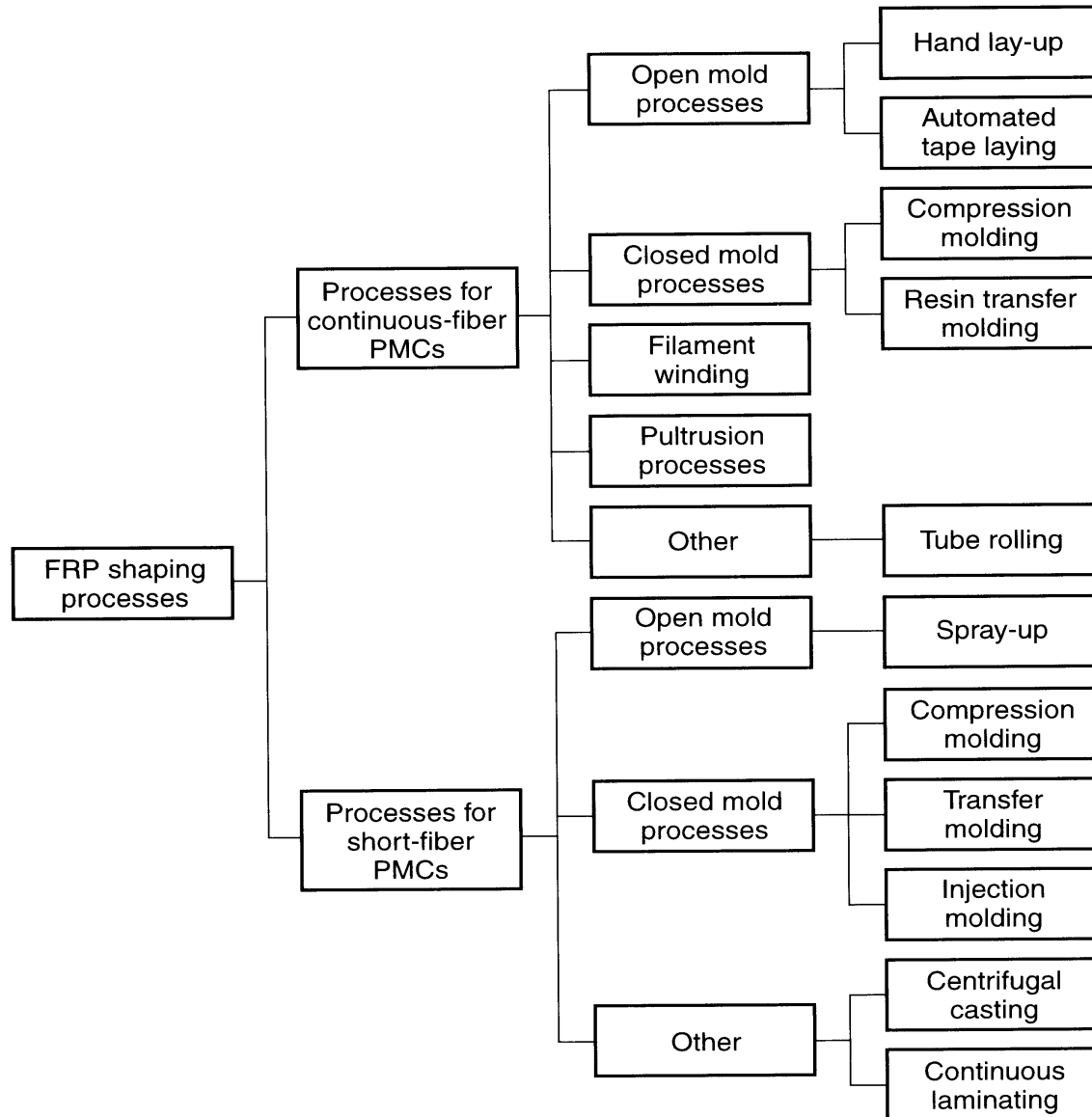


Overview of polymer matrix composite

- A *polymer matrix composite* (PMC) is a composite material consisting of a polymer imbedded with a reinforcing phase such as fibers or powders
- FRP composites can be designed with very high strength-to-weight and modulus-to-weight ratios
- These features make them attractive in aircraft, cars, trucks, boats, and sports equipment



Classification of FRP Processes



Polymer Matrix

- Thermosetting (TS) polymers are the most common matrix materials
- Principal TS polymers are:
 - Phenolics – used with particulate reinforcing phases
 - Polyesters and epoxies - most closely associated with FRPs
- Thermoplastic molding compounds include fillers or reinforcing agents
- Nearly all rubbers are reinforced with carbon black



Fibers as the Reinforcing Phase

- Common fiber materials: glass, carbon, and Kevlar (a polymer)
- In some fabrication processes, the filaments are continuous, while in others, they are chopped into short lengths
- The most familiar form of continuous fiber is a *cloth* - a fabric of woven yarns



Mats and Pre-forms as Reinforcements

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



Combining Matrix and Reinforcement

1. The starting materials arrive at the fabrication operation as separate entities and are combined into the composite during shaping
 - Filament winding and pultrusion, in which reinforcing phase is continuous fibers
2. The two component materials are combined into some starting form that is convenient for use in the shaping process
 - Molding compounds
 - Prepregs



Molding Compounds

FRP composite molding compounds consist of the resin matrix with short randomly dispersed fibers, similar to those used in plastic molding

- Most molding compounds for composite processing are thermosetting polymers
- Since they are designed for molding, they must be capable of flowing
 - Accordingly, they have not been cured prior to shape processing
 - Curing is done during and/or after final shaping



Prepregs

Fibers impregnated with partially cured TS resins to facilitate shape processing

- Available as tapes or cross-plyed sheets or fabrics
- Curing is completed during and/or after shaping
- Advantage: prepregs are fabricated with continuous filaments rather than chopped random fibers, thus increasing strength and modulus



Open Mold Processes

Family of FRP shaping processes that use a single positive or negative mold surface to produce laminated FRP structures

- The starting materials (resins, fibers, mats, and woven rovings) are applied to the mold in layers, building up to the desired thickness
- This is followed by curing and part removal
- Common resins are unsaturated polyesters and epoxies, using fiberglass as the reinforcement



Open Mold FRP Processes

1. Hand lay-up
2. Spray-up
3. Vacuum Bagging – uses hand-lay-up, uses atmospheric pressure to compact laminate.
4. Automated tape-laying machines

The differences are in the methods of applying the laminations to the mold, alternative curing techniques, and other differences



Hand Lay-up/Spray-up

- MAX SIZE: Unlimited
- PART GEOMETRY: Simple - Complex
- PRODUCTION VOLUME: Low - Med
- CYCLE TIME: Slow
- SURFACE FINISH: Good - Excellent
- TOOLING COST: Low
- EQUIPMENT COST: Low



Hand Lay-Up Method

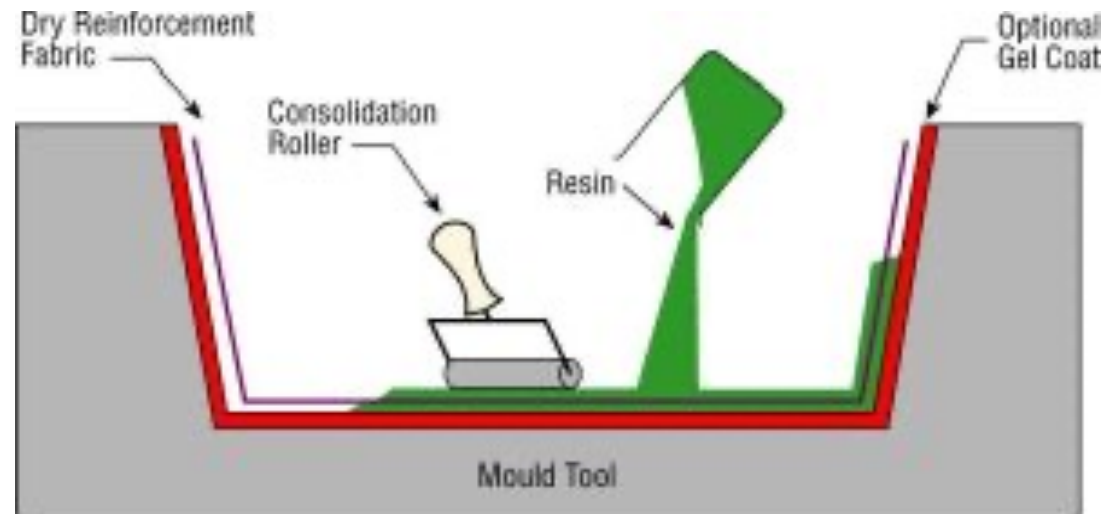
Open mold shaping method in which successive layers of resin and reinforcement are manually applied to an open mold to build the laminated FRP composite structure

- Labor-intensive
- Finished molding must usually be trimmed with a power saw to size outside edges
- Oldest open mold method for FRP laminates, dating to the 1940s when it was first used for boat hulls

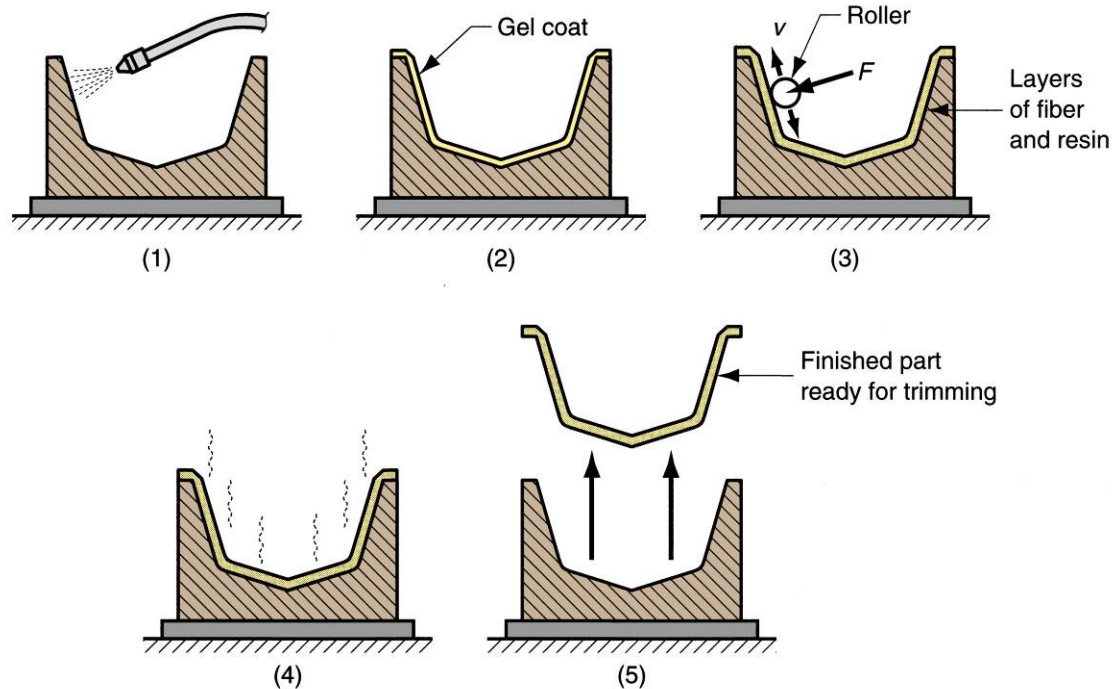


Hand Lay-up

Hand lay-up, or *contact molding*, is the oldest and simplest way of making fiberglass-resin composites. Applications are standard wind turbine blades, boats, etc.)



Hand Lay-Up Method schematic



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



Products Made by Hand Lay-Up

- Generally large in size but low in production quantity - not economical for high production
- Applications:
 - Boat hulls
 - Swimming pools
 - Large container tanks
 - Movie and stage props
 - Other formed sheets
- The largest molding ever made was ship hulls for the British Royal Navy: 85 m (280 ft) long



Spray-Up Method

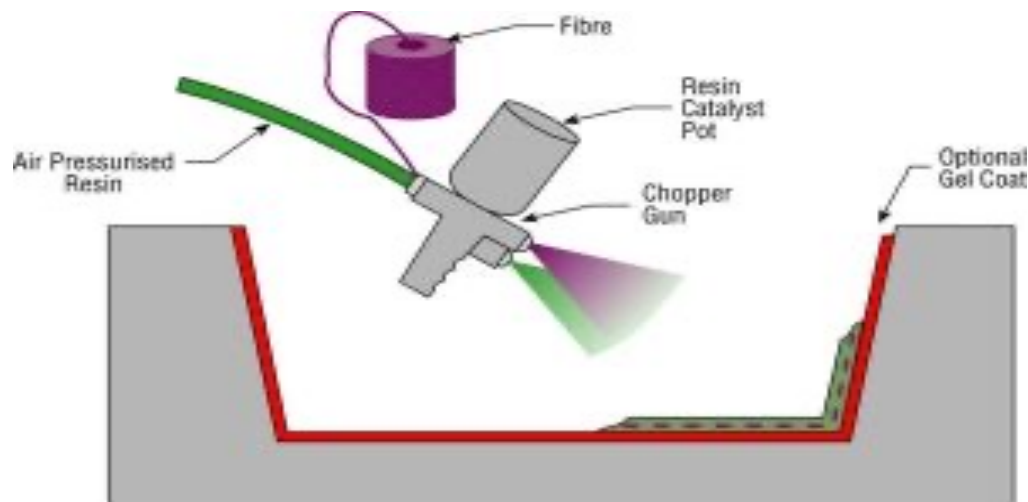
Liquid resin and chopped fibers are sprayed onto an open mold to build successive FRP laminations

- Attempt to mechanize application of resin-fiber layers and reduce lay-up time
- Alternative for step (3) in the hand lay-up procedure

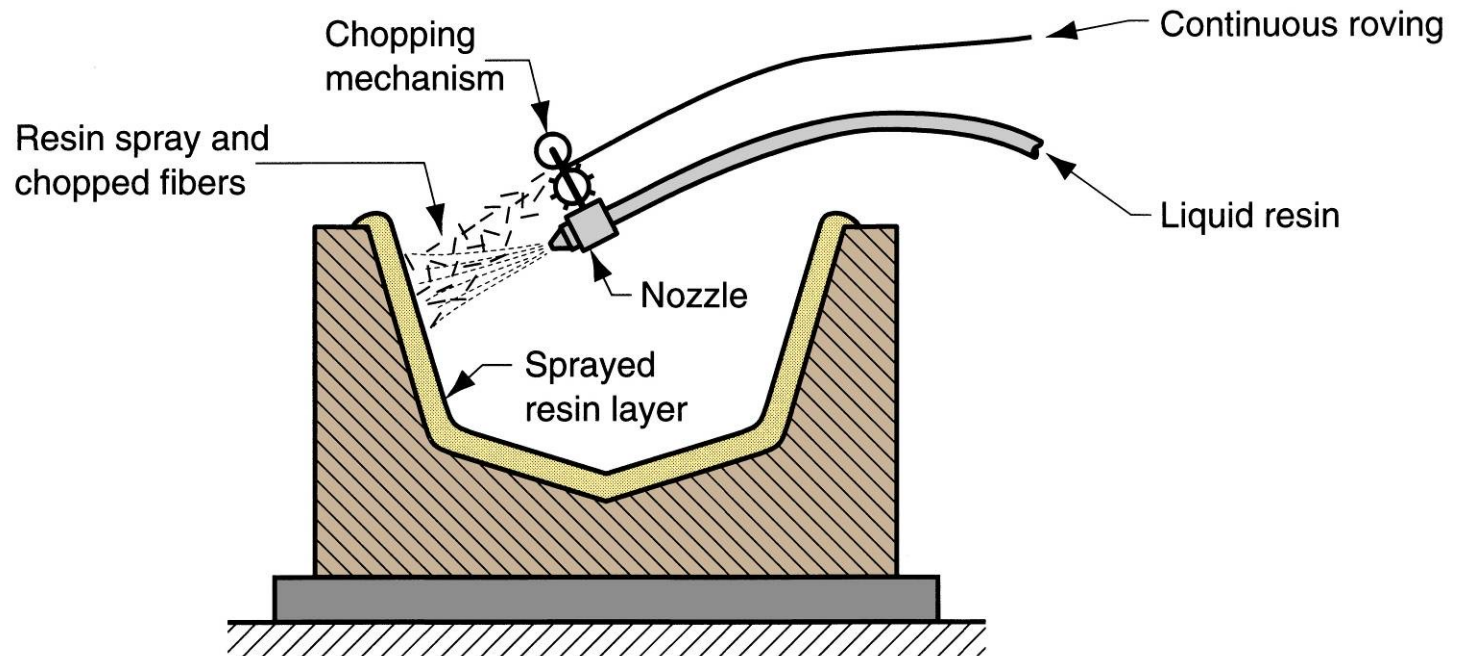


Spray-up Method

In Spray-up 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.



Spray-Up Method Schematic

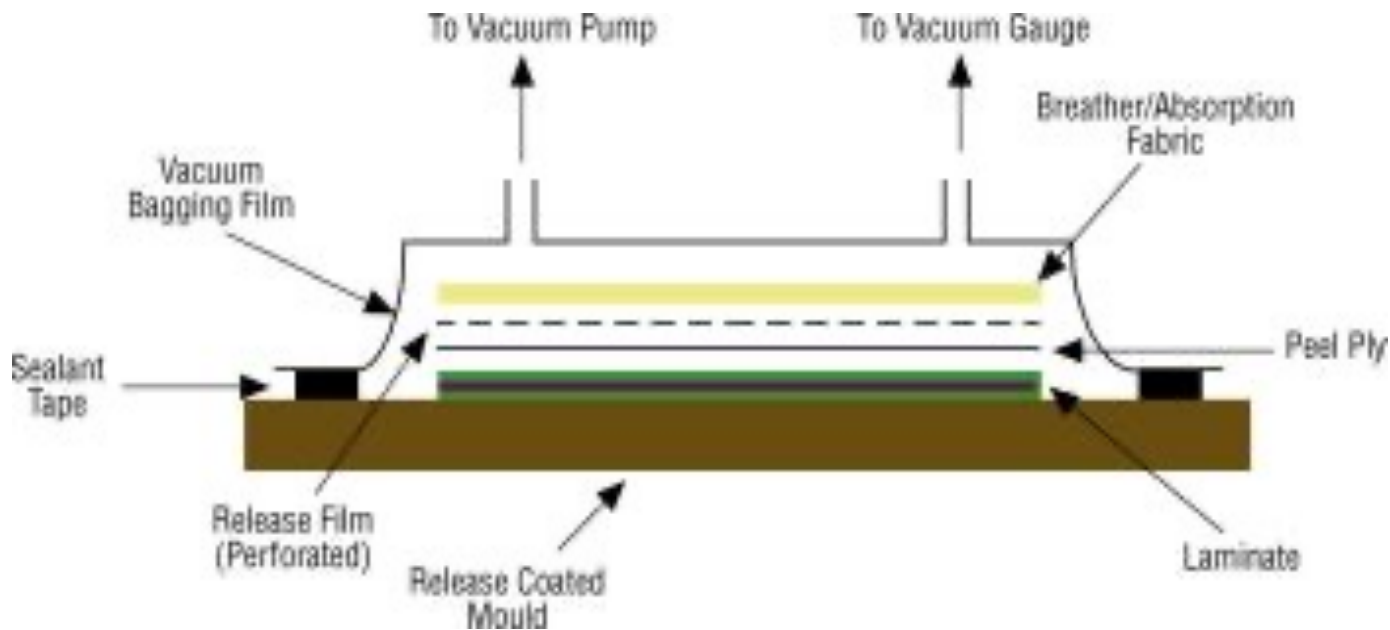


Spray-up method

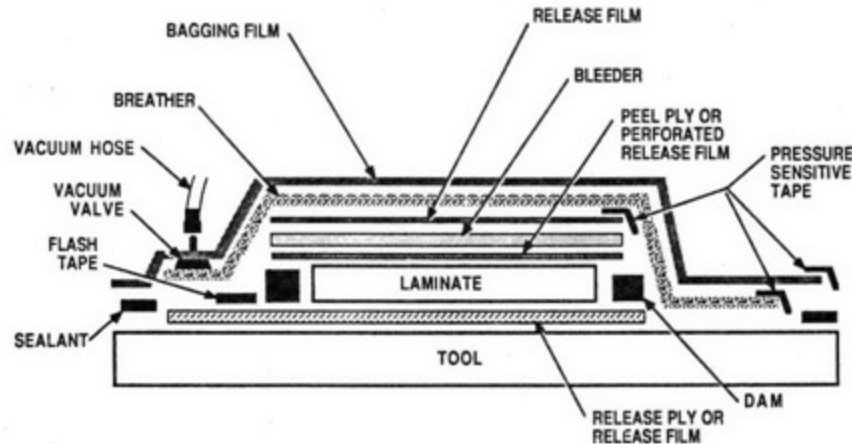


Vacuum-Bag Molding

The **vacuum-bag** process was developed for making a variety of components, including relatively *large parts with complex shapes*. Applications are large cruising boats, racecar components, etc.



Vacuum Bagging Schematic



Lay up sequence for bagging operation

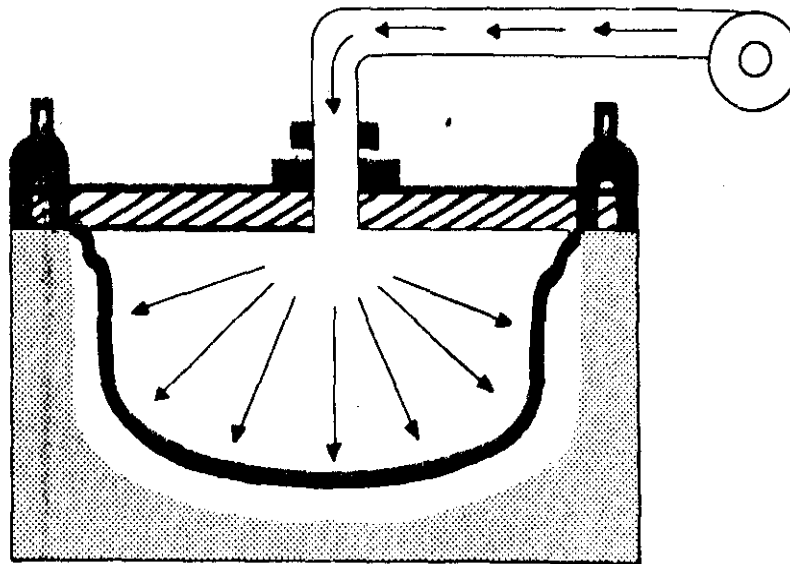
Use atmospheric pressure to suck air from under vacuum bag, to compact composite layers down and make a high quality laminate

- Layers from bottom include: mold, mold release, composite, peel-ply, breather cloth, vacuum bag, also need vacuum valve, sealing tape.



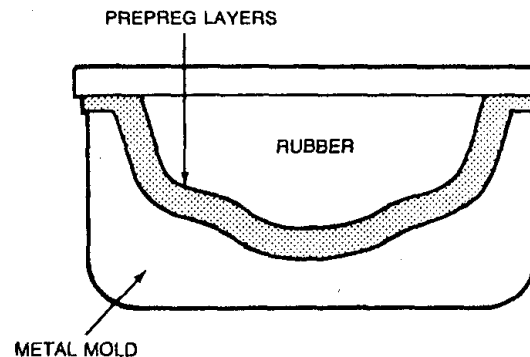
Pressure-Bag Molding

Pressure-bag process is virtually a mirror image of vacuum-bag molding. Applications are sonar domes, antenna housings, aircraft fairings, etc.



Thermal Expansion Molding

- Prepreg layers are wrapped around rubber blocks and then placed in a metal mold.
- As the entire assembly is heated, the rubber expands more than the metal, putting pressure on the laminate.
- Complex shapes can be made reducing the need for later joining and fastening operations



Autoclave Molding

Autoclave molding is similar to both vacuum–bag and pressure–bag molding. Applications are lighter, faster and more agile fighter aircraft, motor sport vehicles.



Automated Tape-Laying Machines

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





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



Curing in Open Mold Processes

- Curing is required of all thermosetting resins used in FRP laminated composites
- Curing cross-links the polymer, transforming it from its liquid or highly plastic condition into a hardened product
- Three principal process parameters in curing:
 1. Time
 2. Temperature
 3. Pressure



Curing at Room Temperature

- Curing normally occurs at room temperature for the TS resins used in hand lay-up and spray-up procedures
 - Moldings made by these processes are often large (e.g., boat hulls), and heating would be difficult due to product size
 - In some cases, days are required before room temperature curing is sufficiently complete to remove the part



Closed Mold Processes

- Performed in molds consisting of two sections that open and close each molding cycle
- Tooling cost is more than twice the cost of a comparable open mold due to the more complex equipment required in these processes
- Advantages of a closed mold are: (1) good finish on all part surfaces, (2) higher production rates, (3) closer control over tolerances, and (4) more complex three-dimensional shapes are possible



Classification of Closed Mold Processes

- Three classes based on their counterparts in conventional plastic molding:
 1. Compression molding
 2. Transfer molding
 3. Injection molding
- The terminology is often different when polymer matrix composites are molded



Compression Molding PMC Processes

A charge is placed in lower mold section, and the sections are brought together under pressure, causing charge to take the shape of the cavity

- Mold halves are heated to cure TS polymer
 - When molding is sufficiently cured, the mold is opened and part is removed
- Several shaping processes for PMCs based on compression molding
 - The differences are mostly in the form of the starting materials



Transfer Molding PMC Processes

A charge of thermosetting resin with short fibers is placed in a pot or chamber, heated, and squeezed by ram action into one or more mold cavities

- The mold is heated to cure the resin
- Name of the process derives from the fact that the fluid polymer is transferred from a pot into a mold



Injection Molding PMC Processes

- Injection molding is noted for low cost production of plastic parts in large quantities
- Although most closely associated with thermoplastics, the process can also be adapted to thermosets
- Processes of interest in the context of PMCs:
 - Conventional injection molding
 - Reinforced reaction injection molding



Conventional Injection Molding

- Used for both TP and TS type FRPs
- Virtually all TPs can be reinforced with fibers
- Chopped fibers must be used
 - Continuous fibers would be reduced by the action of the rotating screw in the barrel
- During injection into the mold cavity, fibers tend to become aligned as they pass the nozzle
 - Part designers can sometimes exploit this feature to optimize directional properties in the part



Reinforced Reaction Injection Molding

Reaction injection molding (RIM) - two reactive ingredients are mixed and injected into a mold cavity where curing and solidification occur due to chemical reaction

Reinforced reaction injection molding (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



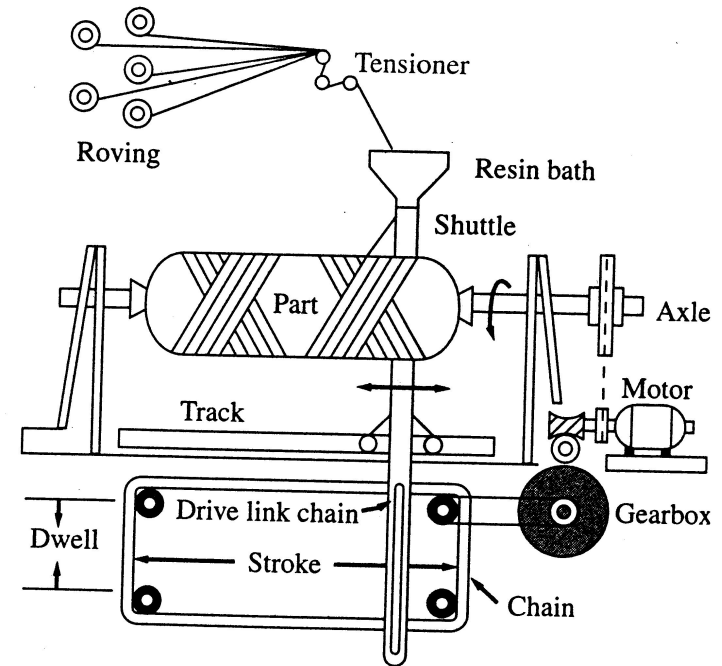
Filament Winding

- Resin-impregnated continuous fibers are wrapped around a rotating mandrel that has the internal shape of the desired FRP product; the resin is then cured and the mandrel removed
- The fiber rovings are pulled through a resin bath immediately before being wound in a helical pattern onto the mandrel
- The operation is repeated to form additional layers, each having a criss-cross pattern with the previous, until the desired part thickness has been obtained

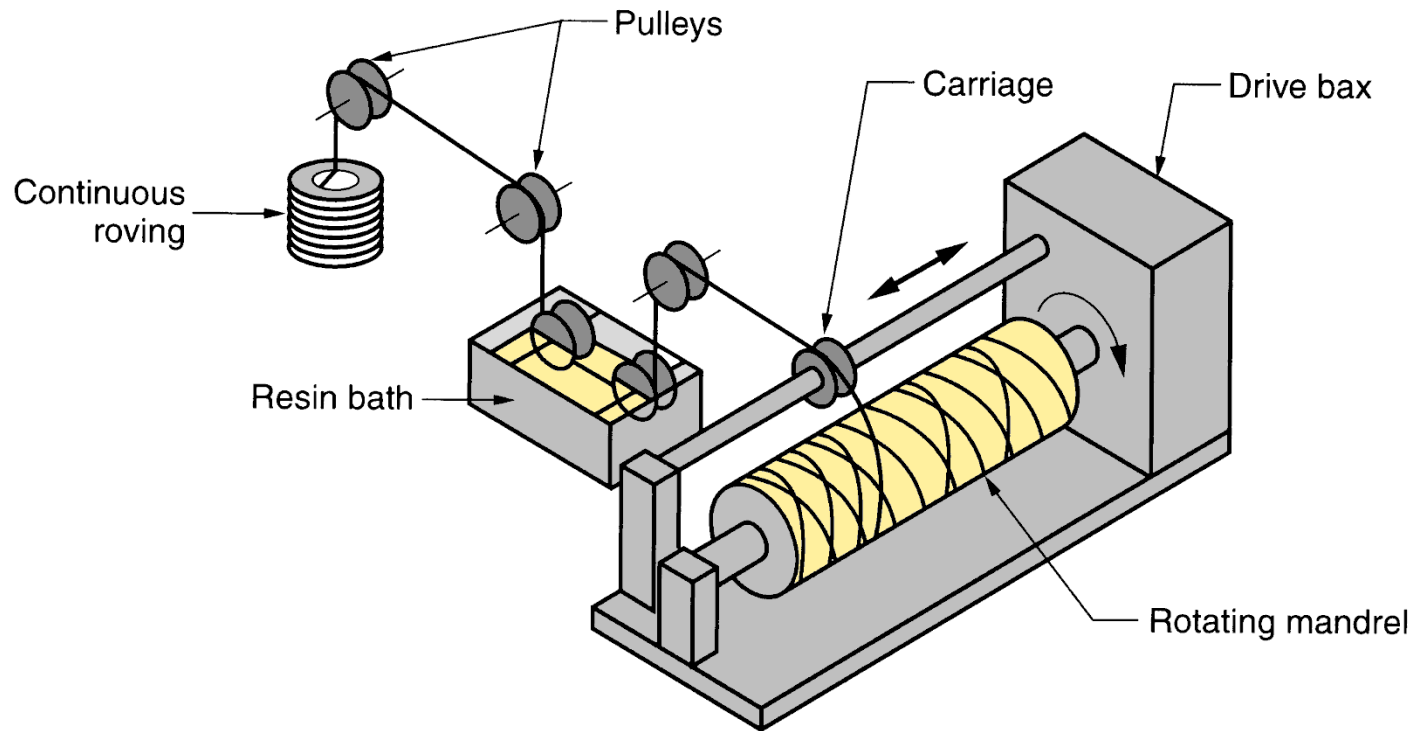


Manufacturing - Filament Winding

- Highly automated
 - low manufacturing costs if high throughput
 - e.g., Glass fiber pipe, sailboard masts



Filament Winding



Filament winding.

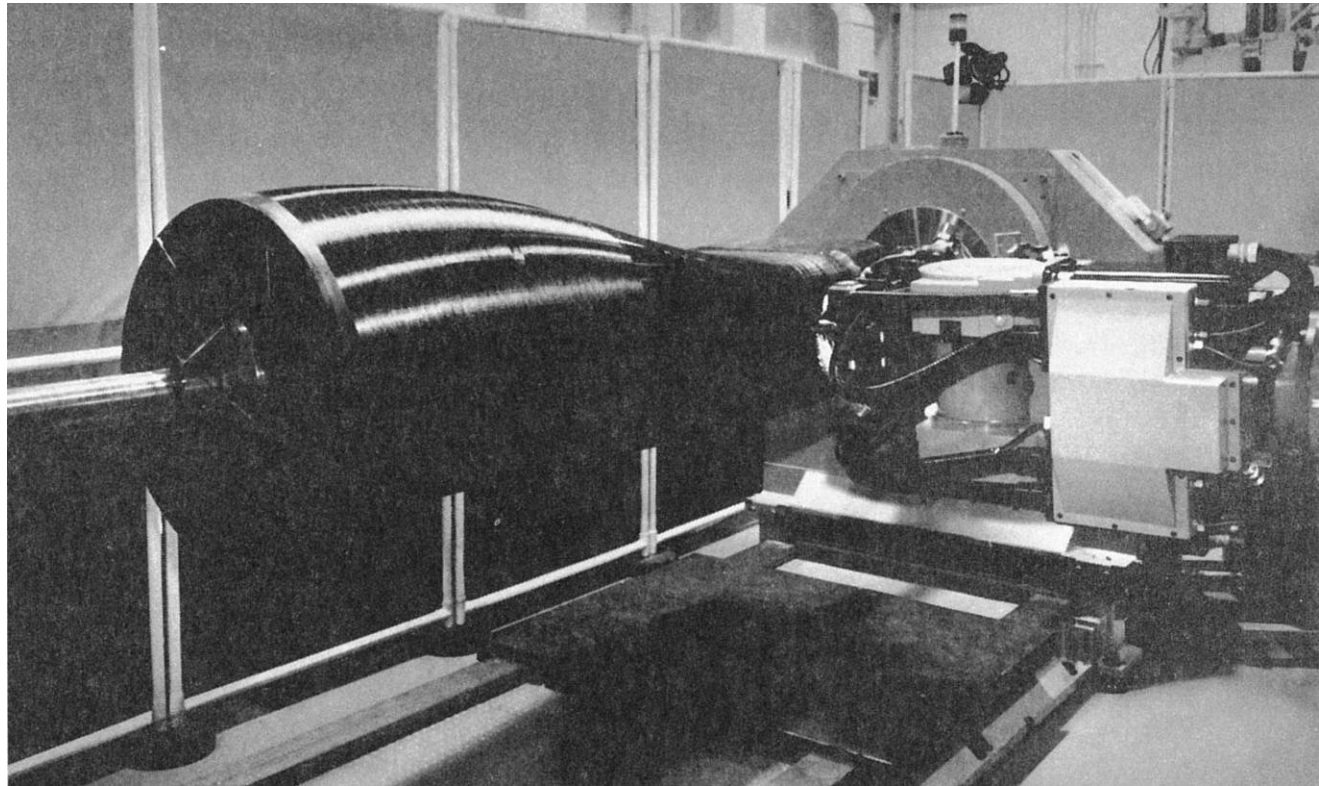


Manufacturing FRP Materials

Filament winding



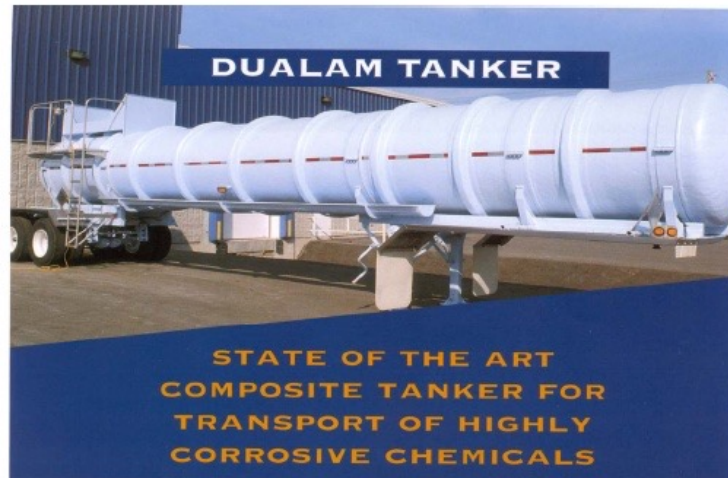
Filament Winding Machine



Filament winding machine (photo courtesy of Cincinnati Milacron).



Products made form filament winding process



Pultrusion Processes

- Similar to extrusion (hence the name similarity) but workpiece is pulled through die (so prefix "pul-" in place of "ex-")
- Like extrusion, pultrusion produces continuous straight sections of constant cross section
- Developed around 1950 for making fishing rods of glass fiber reinforced polymer (GFRP)
- A related process, called *pulforming*, is used to make parts that are curved and which may have variations in cross section throughout their lengths

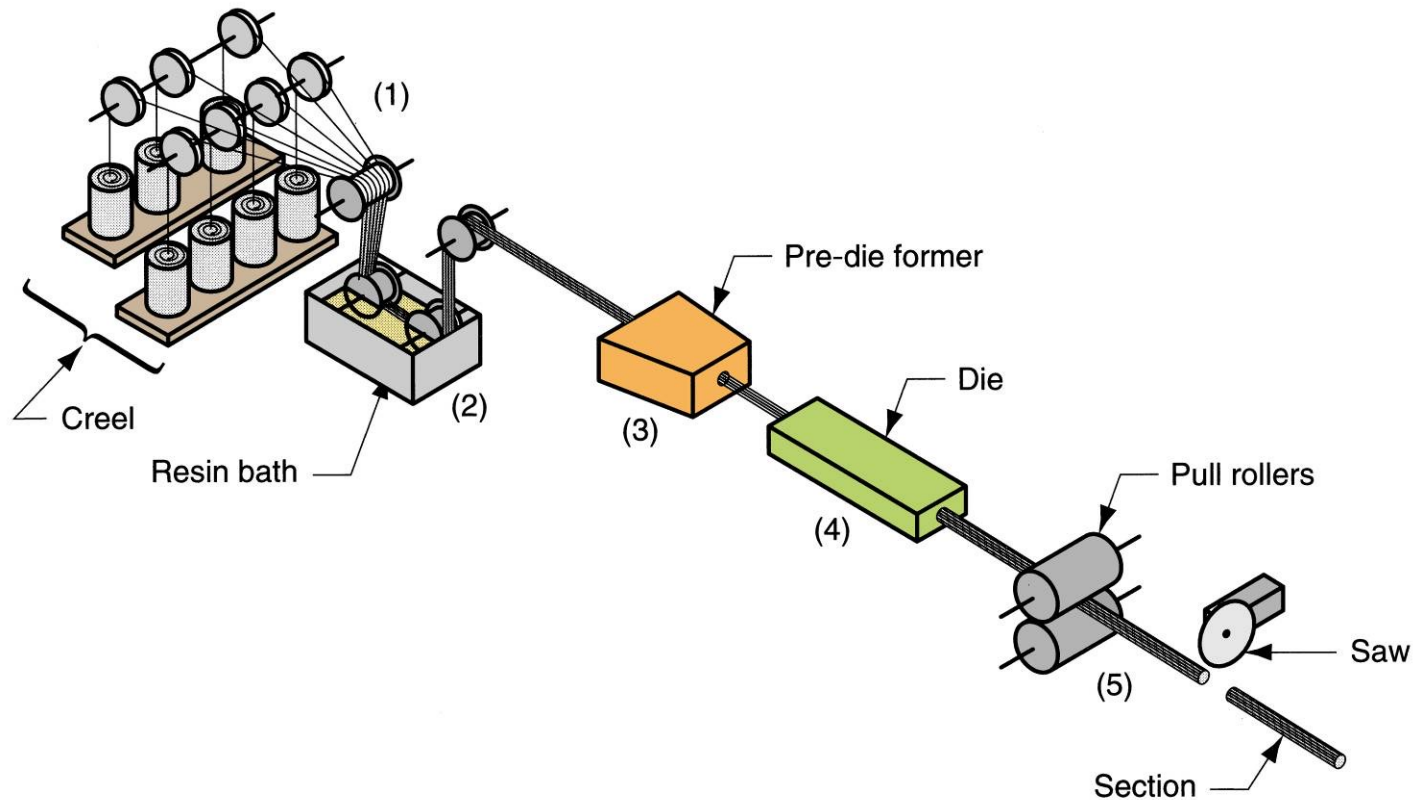


Pultrusion-process

- Continuous fiber rovings are dipped into a resin bath and pulled through a shaping die where the impregnated resin cures
- The sections produced are reinforced throughout their length by continuous fibers
- Like extrusion, the pieces have a constant cross section, whose profile is determined by the shape of the die opening
- The cured product is cut into long straight sections



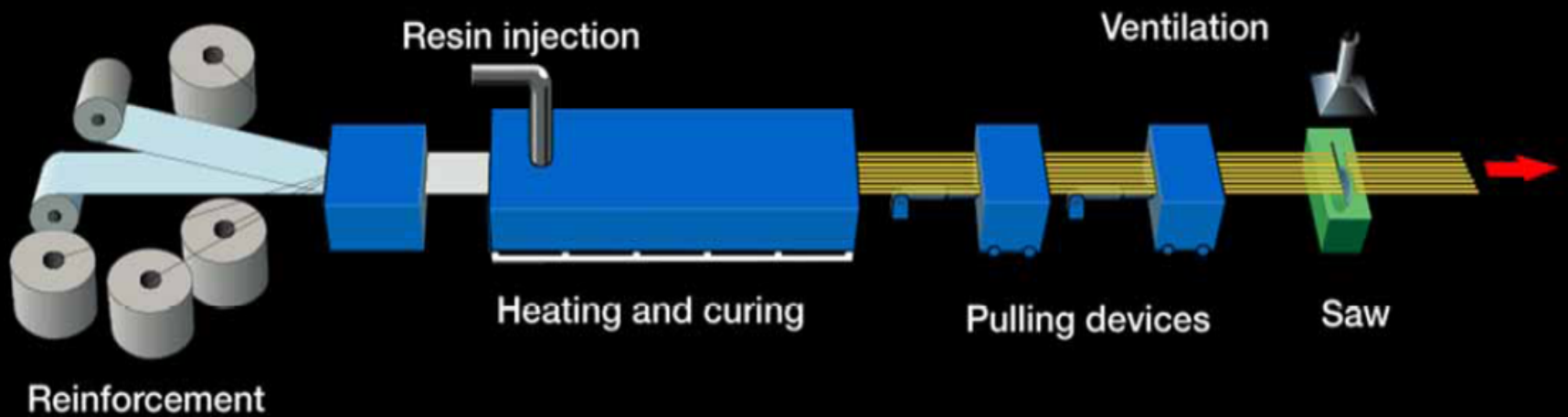
Pultrusion Process



Pultrusion process

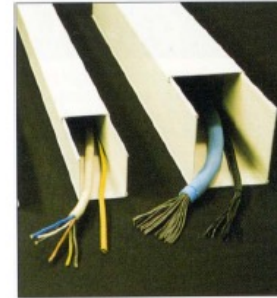
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The Pultrusion Process

Examples of pultrusion products.

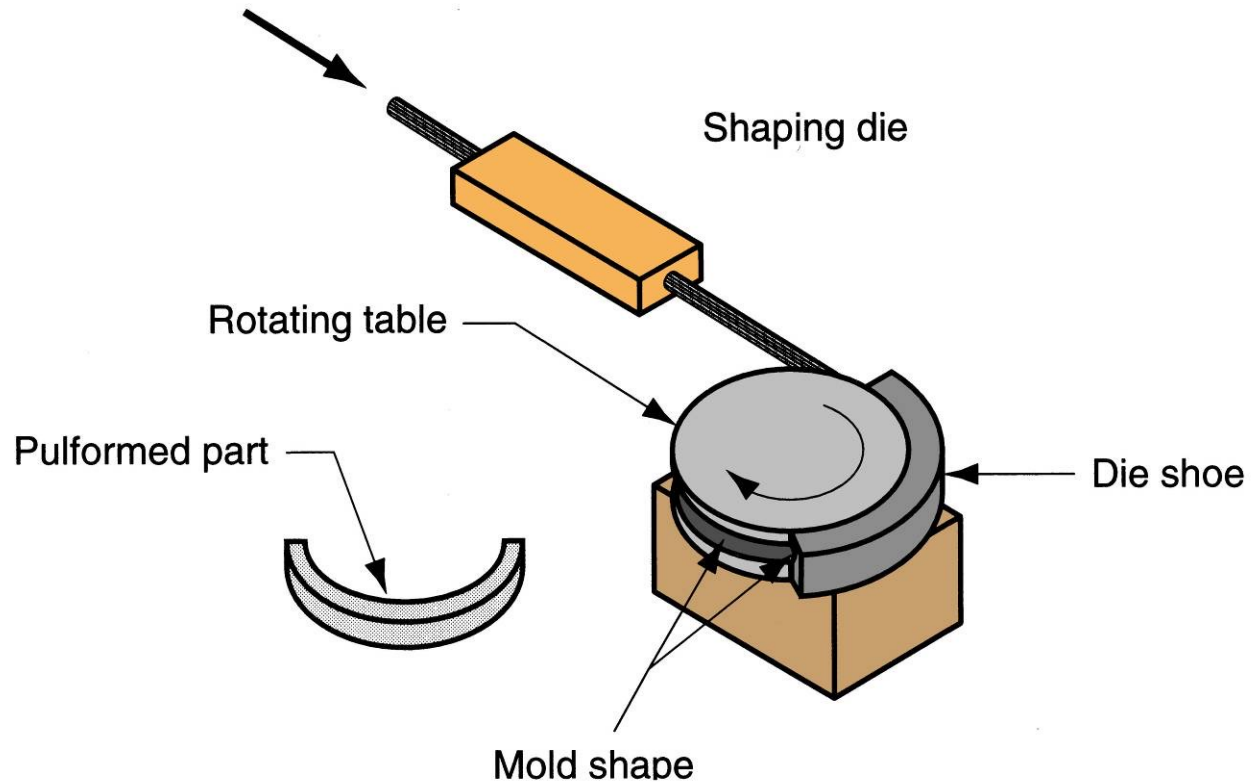


Pulforming

- Pultrusion with additional steps to form the length into a semicircular contour and alter the cross section at one or more locations along the length
- Pultrusion is limited to straight sections of constant cross section
- There is also a need for long parts with continuous fiber reinforcement that are curved rather than straight and whose cross sections may vary throughout length
 - Pulforming is suited to these less regular shapes



Pulforming Process



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



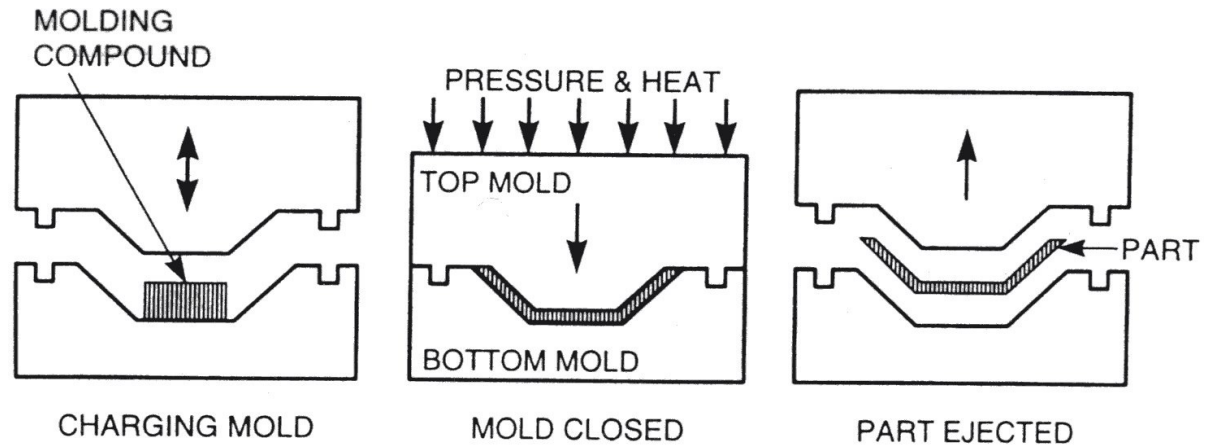
Prepregs

- Prepreg and prepreg layup
 - “prepreg” - partially cured mixture of fiber and resin
 - Unidirectional prepreg tape with paper backing wound on spools
 - Cut and stacked
 - Curing conditions
 - Typical temperature and pressure in autoclave is 120-200C, 100 psi

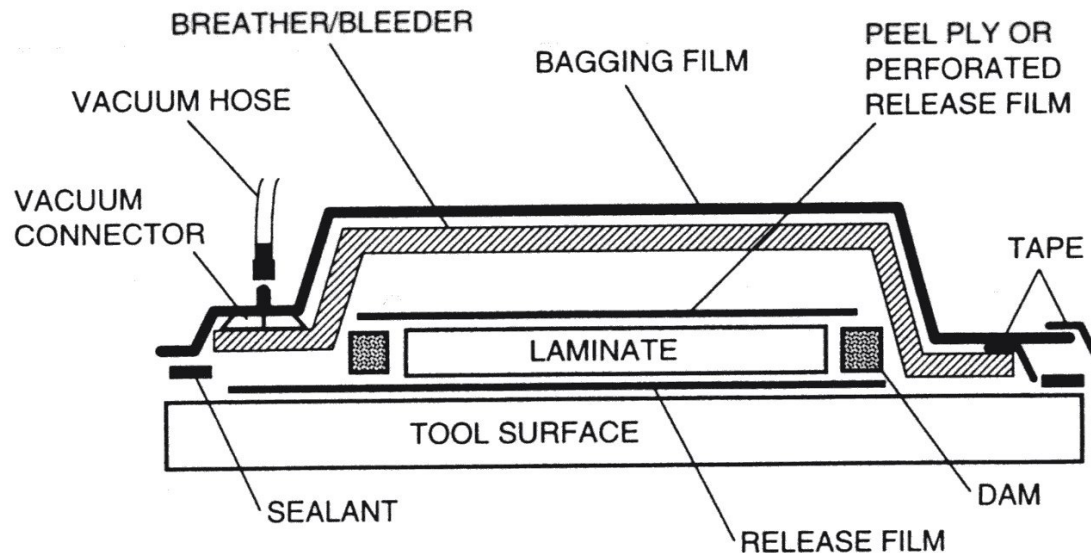


Manufacturing - Layups

compression
molding



vacuum bagging



Other PMC making Processes

- Centrifugal casting
- Tube rolling
- Continuous laminating
- Cutting of FRPs
- In addition, many traditional thermoplastic shaping processes are applicable to FRPs with short fibers based on TP polymers
 - Blow molding
 - Thermoforming
 - Extrusion



Cutting Methods

- Cutting of FRP laminated composites is required in both uncured and cured states
- Uncured materials (prepregs, preforms, SMCs, and other starting forms) must be cut to size for lay-up, molding, etc.
 - Typical cutting tools: knives, scissors, power shears, and steel-rule blanking dies
 - Nontraditional methods are also used, such as laser beam cutting and water jet cutting



Cutting Methods

- Cured FRPs are hard, tough, abrasive, and difficult-to-cut
 - Cutting of FRPs is required to trim excess material, cut holes and outlines, and so on
 - For glass FRPs, cemented carbide cutting tools and high speed steel saw blades can be used
 - For some advanced composites (e.g., boron-epoxy), diamond cutting tools cut best
 - Water jet cutting is also used, to reduce dust and noise problems with conventional sawing methods

