Chapter 5

Polymer Matrix Composites

A bicycle frame made of carbon fiber/epoxy
(lightness, good mechanical characteristics, sleek lines)

An offshore wind farm

Each rotor blade is 36.8 m long. w.ww.lmglasfiber.com .

GEnx engine
Carbon fiber/epoxy blades

Polymer matrix composites

- Two main classes:
  - Thermoset matrix (epoxy, vinyl ester, unsaturated polyester, etc.)
  - Thermoplastic matrix (nylons, polyolefins, etc.)

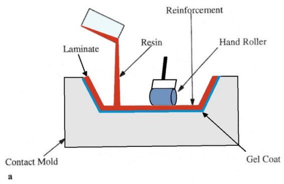
Processing of Thermoset Matrix Composites

1- Hand Layup and Spray Techniques

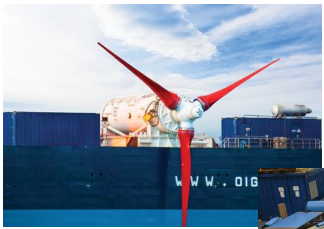
- The simplest polymer processing techniques
- Fibers is laid onto a mold by hand and the resin (+ catalysts) is sprayed or brushed on.

•The deposited layers are densified with rollers.

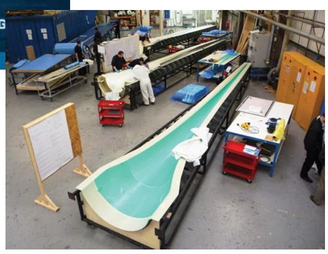
•The most common resins used: Unsaturated polyester



Hand layup

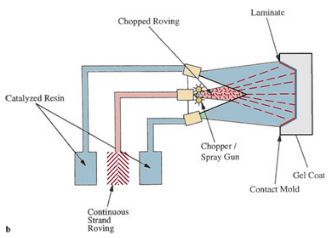


A 1-MW tidal turbine



http://www.compositesworld.com

- Resin and chopped fibers can be sprayed together onto the mold surface.



Spray-up

- Curing may be done at room temperature or at a moderately high temperature (200 °C or higher) in an oven.

2. Filament winding

- A resin-impregnated continuous tow or roving is wound on a mandrel in a precise geometric pattern.
- The winding of roving can be polar (hoop) or helical.

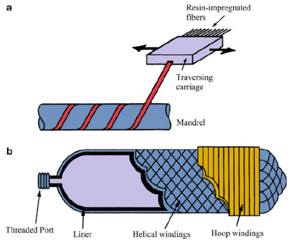
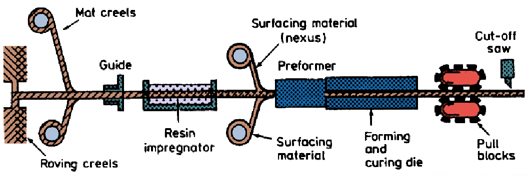


Fig. 5.2 (a) Schematic of filament winding process. (b) Schematic of a filament wound pressure vessel with a liner; helical and hoop winding are shown

- Successive layers are laid on at a constant or varying angle until the desired thickness is attained.
- Curing of the thermosetting resin is done at an elevated temperature and the mandrel is removed.
- Glass, carbon, and aramid fibers are routinely used with epoxy, polyester, and vinyl ester resins for producing filament wound shapes.

3. Pultrusion



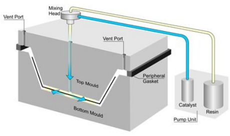
- Continuous PMC sections with fibers oriented mainly axially
- Mat or biaxial fabric may be added to provide some transverse strength.
- Continuous fiber tows pass through a resin bath containing a catalyst.

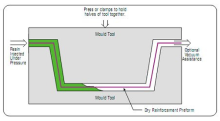
- The resin impregnated fibers pass through a series of wipers to remove any excess polymer, then a collimator, and then enter a heated die.
- The resin is cured in the die and the composite is pulled out.
- Can produce continuously at a rate of 10 to 200 cm/min.
- Pultruded profiles as wide as 1.25 m with more than 60% fiber volume fraction can be made routinely.

✓ Example:
  - A helicopter windshield post, 1.5 m long
  - Carbon fiber/vinyl ester

4. Resin transfer molding (RTM)

- A closed mold, low pressure technique
- The desired fiber preform (carbon, glass, or aramid) is placed inside a mold
- The fibrous preform is preheated.
- A liquid resin (epoxy, polyester, …) is injected into the mold by a pump and is allowed to cure.
- Low polymer viscosity (< 1 Pa.s) to wet the fibers easily
- The mold has built-in heating elements to accelerate the curing process.





Darcy's law: A phenomenological expression that describes the fluid flow through a porous medium

$$J = -\frac{k}{\eta}\nabla P$$

J = volume current density (i.e. volume/area × time) of the fluid

k = Permeability of a porous medium (a function of the properties of the porous medium, not those of the fluid)

η = fluid viscosity

∇P = pressure gradient that drives the fluid flow

Advantages of RTM:

- Large and complex shapes and curvatures
- High level of automation
- Quicker than manual operations
- High fiber volume fractions (65%) possible
- Closed mold process: less emissions of volatile organic compounds (VOC) compared to hand layup or spray-up techniques.

•Significant weight reduction in making automotive parts by RTM

✓For example, composite parts made by RTM resulted in 90 kg reduction in the weight of Dodge Viper automobile.

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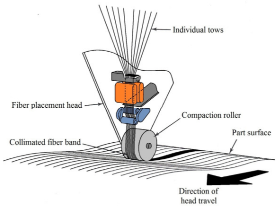
5. Automated Fiber Placement (AFP)

- The fiber tows, pre-impregnated with the resin, are fed into the fiber placement head where they are collimated into a single band and laminated onto the work surface.
- Typically, each tow is about 3 mm wide strand of continuous fibers.
- A strand may consist of 12,000 individual filaments impregnated with an epoxy resin.



Automatic fiber placement

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- A compaction roller or shoe consolidates the tape, pressing it onto the work surface.
  - Removes any trapped air and any minor gaps between individual tows

- Very popular with the coming of large-sized civilian aircraft.

- Used for automated fabrication of composite fuselage panels for the commercial aircrafts.

The VIPERs made by MAG Cincinnati will produce 92 % of the fuselage for the Airbus A350 XWB.

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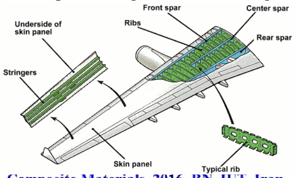
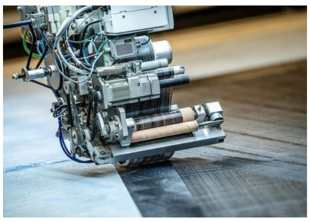
6. Automated tape placement (ATP) Automated tape Laying (ATL)

- Resin pre-impregnated high performance reinforcement fibers in the form of a *tape* are placed in specific directions using a CAD system.
- Has gained wide acceptance for part fabrication in the aerospace industry. Examples include aircraft parts such as wing stringers, spars, skins and elevators, tail skins and horizontal planes, engine cowls, fuselage skins and belly fairings.



- In ATP pre-impregnated tape is laid down continuously to form parts.

- **Prepreg** is generally in the form of a thin sheet or lamina of unidirectional fiber/polymer composite protected on both sides with easily removable separators.
- The prepreg generally has the resin in a partially cured state with a moderately self-adhesive tack.
- A spool of prepregd tape (e.g. C_f pre-impregnated with a thermosetting resin, commonly epoxy) is unwound.
- The film and the paper are peeled off. The tape is automatically cut to the correct shape.



- Often used for parts with highly complex contours or angles.
- Tape deposit speed of up to 50 m/min
- Commonly used with thermosets. But it can be adapted for thermoplastic materials.

The laminate is pressurized using a vacuum bag and then heat cured.

7. Autoclave based processes (Bag molding processes)

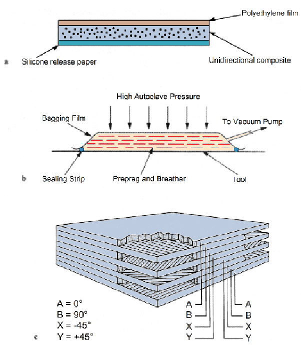
- For making large, very high quality product in aerospace field
- An autoclave is a closed vessel (round or cylindrical) in which processes (physical and/or chemical) occur under simultaneous application of high temperature and pressure.
- Heat and pressure are applied to appropriately stacked prepregs (pre-impregnated fibers).

Fig. 5.5:

(a) Schematic of a prepreg.

(b) Setup in an autoclave to make a laminated composite.

(c) Layup of plies with different fiber orientations.



- Bags containing prepregs in predetermined orientations are placed in an autoclave.
- The bags consist of thin and flexible membranes made of rubber that separate the layup from the gas used to compress.
- Densification and curing are achieved by pressure differential across the bag walls.
- One can use vacuum, in which case the bag contents are evacuated and atmospheric pressure consolidates the composite.
- The combined action of heat and pressure consolidates the lamina, removes the entrapped air, and helps cure the polymeric matrix.

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Autoclave for Boeing 787 wing

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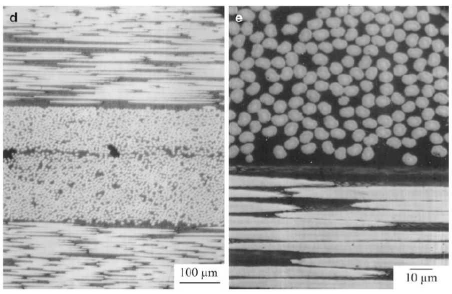

- Fig. 5.5:
- (d) Micrograph of carbon fiber/epoxy laminated composite made in an autoclave.
- (e) A higher magnification picture of (e).
- ✓ Note the different fiber orientation in different layers

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Processing of Thermoplastic Matrix Composites

Commodity Thermoplastics

- Polyethylene (PE)
- Polypropylene (PP)
- Polyvinyl chloride (PVC)
- Polystyrene (PS)

- These four represent about 85% by volume of world plastics. Main attraction: low cost!

Other thermoplastics

- Poly methyl methacrylate (PMMA)
- Nylons (Nylon 6 and Nylon 66)
- Polyesters (PET)
- Poly ether ether ketone (PEEK)
- Poly phenylene sulfide (PPS)

Thermoplastics

Advantages:

- Refrigeration is not necessary with a thermoplastic matrix.
- Parts can be made and joined by heating.
- Parts can be remolded, and any scrap can be recycled.
- Thermoplastics have better toughness and impact resistance than thermosets.

Disadvantages:

- The processing temperatures are generally higher than those with thermosets (275-350 °C).
- Thermoplastics are stiff and lack the tackiness of the partially cured epoxies.

1- Film stacking

- Stack laminae of thermoplastic matrix containing fibers with a very low resin content (15%) alternately with laminae of pure polymer matrix material.
- Laminae of fibers impregnated with insufficient matrix and polymer films of complimentary weight to give the desired fiber volume fraction in the end product.
- Consolidate under heat and pressure.
- Impregnation of the reinforcement preform according to Darcy's law

- A good quality laminate must be void-free.
  - There must be sufficient flow of the thermoplastic matrix between layers as well as within individual tows.
- Typically, a pressure of 6-12 MPa, a temperature between 275 and 350 ^{o}C, and dwell times of up to 30 minutes are appropriate for thermoplastics such as polysulfones and polyetheretherketone (PEEK).

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2. Thermoplastic Tape Laying

- Similar to the thermosetting tape laying machines.
- The hot head dispenses thermoplastic tape from a supply reel.
- The hot shoes heat the tape to molten state. The cold shoes cool the tape instantly to a solid state.

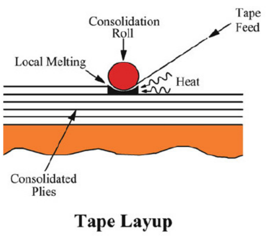

Fig. 5.7 Schematic of a thermoplastic tape laying machine (courtesy of Cincinnati Milacron)

3. Commingled Fibers

- The **matrix fiber** and the **reinforcement fiber** (e.g., carbon fiber and PEEK fiber) are commingled to produce a yarn that is a blend of the thermoplastic matrix and reinforcement yarn.
- The commingled yarn can be woven, knit, or filament wound.
- The yarn formed into the appropriate shape is then subjected to heat and pressure to melt the thermoplastic matrix component and obtain a composite.
- There are many commingled fibers available commercially for processing into a composite.

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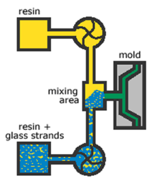
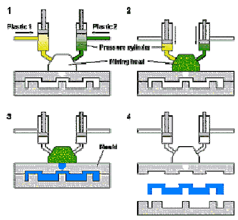
4. Reinforced Reaction Injection Molding (RRIM)

•Two liquid components containing short fibers (or fillers) are pumped at high speeds and pressured into a mixing head and then into a mold where the two components react to polymerize rapidly.





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5. Long Fiber Thermoplastic (LFT) Compression Molding (Injection molding)

- Conventional injection molding practice: Short fibers (<2-3 mm)
- Increasing the length of fibers to greater than 10 mm would result in more improved properties (Chap. 10).

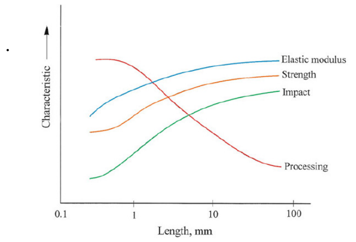

Fig. 5.8 Variation of some mechanical properties of a composite as a function of fiber length

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LFT processing

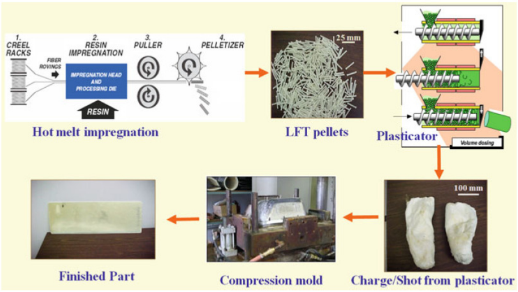

Fig. 5.9 Extrusion/compression molding process for making long fiber reinforced thermoplastic (LFT) composites. Hot melt impregnation of fibers is used to produce tapes, rods or long pellets of LFT. Pelletized LFT material is fed into an extruder or plasticator. Plasticized LFT charge is compression molded to different product forms

Long fiber thermoplastic (LFT) composites

- High V_f, continuous, unidirectionally aligned fibers in a TP matrix

  → Rod form (Dia. ~2.25 mm)
- Cut about 12.5 mm pellets from the rod

  → ~12.5 mm long fibers
- Injection mold these pellets containing fully wetted fibers

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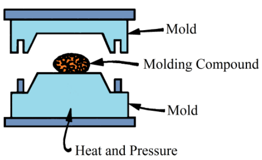
6. Sheet molding compound (SMC)

•A polyester (or vinyl ester) resin containing short glass fibers plus some fillers.
•The fillers generally consist of fine calcium carbonate particles, mica flakes and sometimes hollow glass microspheres (lower density, more expensive).



•Used in making auto body parts: bumper beams, radiator support panels, ...

•Polypropylene resin reinforced with calcium carbonate particles, mica flakes, or glass fibers are used in automotive parts, appliances, electrical components, …