Aalto-yliopisto
Kemian tekniikan korkeakoulu

Polymer blends and composites - processing i.e. manufacturing of products

14.10.2019

Sedigheh Borandeh

FUNDAMENTALS

OF

POLYMERS

Aalto-yliopisto
Kemian tekniikan korkeakoulu

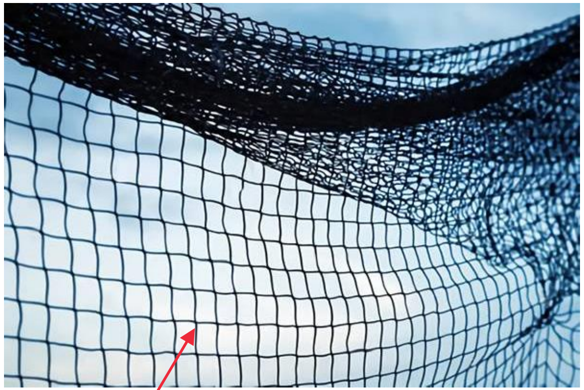
Polymer Matrix Composite (PMC)

Two basic categories of polymer matrices → **Thermoplastics**

→ **Thermosets**

Thermosets vs thermoplastics

Thermosets



Unaligned chains
(amorphous phase)

Thermoplastics

(Not always) Aligned chains
(crystalline phase)

(Always) Unaligned chains
(amorphous phase)

Different polymer systems → different properties + different processing conditions

Themal transitions in Polymers

- Most importants (there are more):
- Tm (Melting Temperature)
  - Only semicrystalline thermoplastics
  - Solid to liquid
  - Depends on the crystallinity (more than 1 Tm possible)
- Tg (Glass transition temperature)
  - From glassy to rubber
  - Relaxation of amorphous phase
  - Rubber (thermoset, Tg <0°C)
  - Loss of mechanical strength

Observations (FYI)

- Same "type" of polymer (e.g. Polyurethanes) can be thermoplastic, thermosets, rubbers, … but it is not going to be the same exact polymer.
- Same polymer can have different properties depending on many factors.
- Amorphous thermoplastics are NOT thermosets!
- Same polymer can have different types (polymorphs) of crystallinity (this is still quite academic).
- There are two amorphous phases (Mobile and rigid). The latter is very academic and not so much used in industry.

Observations (FYI)

- The properties of BOTH thermoplastics and thermosets, depends on processing temperature.

- Thermoplastics generally due to crystallinity, but thermosets also change properties with temperature (and sometimes require **postcuring**).

Thermosets vs thermoplastics

Thermosets (resins)

Thermoplastics

Sometimes → liquid monomers
and polymerization
Polymerization more complex than curing

Thermoset *vs.* thermoplastic polymers

- **Thermoplastics,** in basic terms, are melt-processable plastics (materials that are processed with heat). When enough heat is added to bring the temperature of the plastic above its melt point, the plastic liquefies (softens enough to be processed). When the heat source is removed and the temperature of the plastic drops below its melt point, the plastic solidifies (or freezes) back into a glass-like solid. This process can be repeated, with the plastic melting and solidifying as the temperature climbs above and drops below the melt temperature, respectively.

Thermoset *vs.* thermoplastic polymers

- **Thermosets,** are unmeltable, are materials that undergo curing and transform from a liquid form to a solid. In its uncured form, the material has very small and unlinked monomers. The addition of catalyst and/or heat or some other activating influence will initiate the chemical reaction. During this reaction the molecules cross-link and form significantly longer molecular chains, causing the material to solidify. This change is permanent and irreversible. Subsequently, exposure to high heat will cause the material to degrade, not melt.

Thermoplastics

- Thermoplastics have **high viscosity** at processing temperatures, which makes them more difficult to process.
- High viscosity and surface tension makes difficult wetting of fillers/**fibers.**
- Increasing temperature too much may lead to degradation of polymer/fillers.
- The high shear stresses are needed to make thermoplastic flow, which cause damage to the fibers resulting in a reduction of fiber length
- Thermoplastics do not require refrigerated storage.
- Have unlimited(*) shelf or pot life.
- Thermoplastics **are more resistant to cracking and impact damage** compared to thermosets; but show **lower high-temperature strength and chemical stability.**

Thermosets

- A thermoset matrix is formed by the irreversible chemical transformation of a resin system into an amorphous cross-linked polymer matrix.
- The polymer is called ***resin system*** during processing and ***matrix*** after the polymer has cured.
- Thermosetting resins have ***low viscosity and surface tension*** which allows for excellent impregnation of the fiber reinforcement and high processing speeds.
- Curing can vary from minutes to hours (depending on the choice of the catalyst and reactivity of the resin).
- The curing reactions are exothermic.
- Because of their three-dimensional crosslinked structure, they tend to have high dimensional stability, high-temperature resistance, and good resistance to solvents.

Most common properties required

- Mechanical properties
- Lightweight
- Thermal stability (Degradation, Tg, Tm)
- Chemical resistance
- Transparency and barrier properties (food packaging)
- Bio-based, recyclability > biodegradable

Polymer Matrix Composites

Figure 3-2.—Comparison of General Characteristics of Thermoset and Thermoplastic Matrices

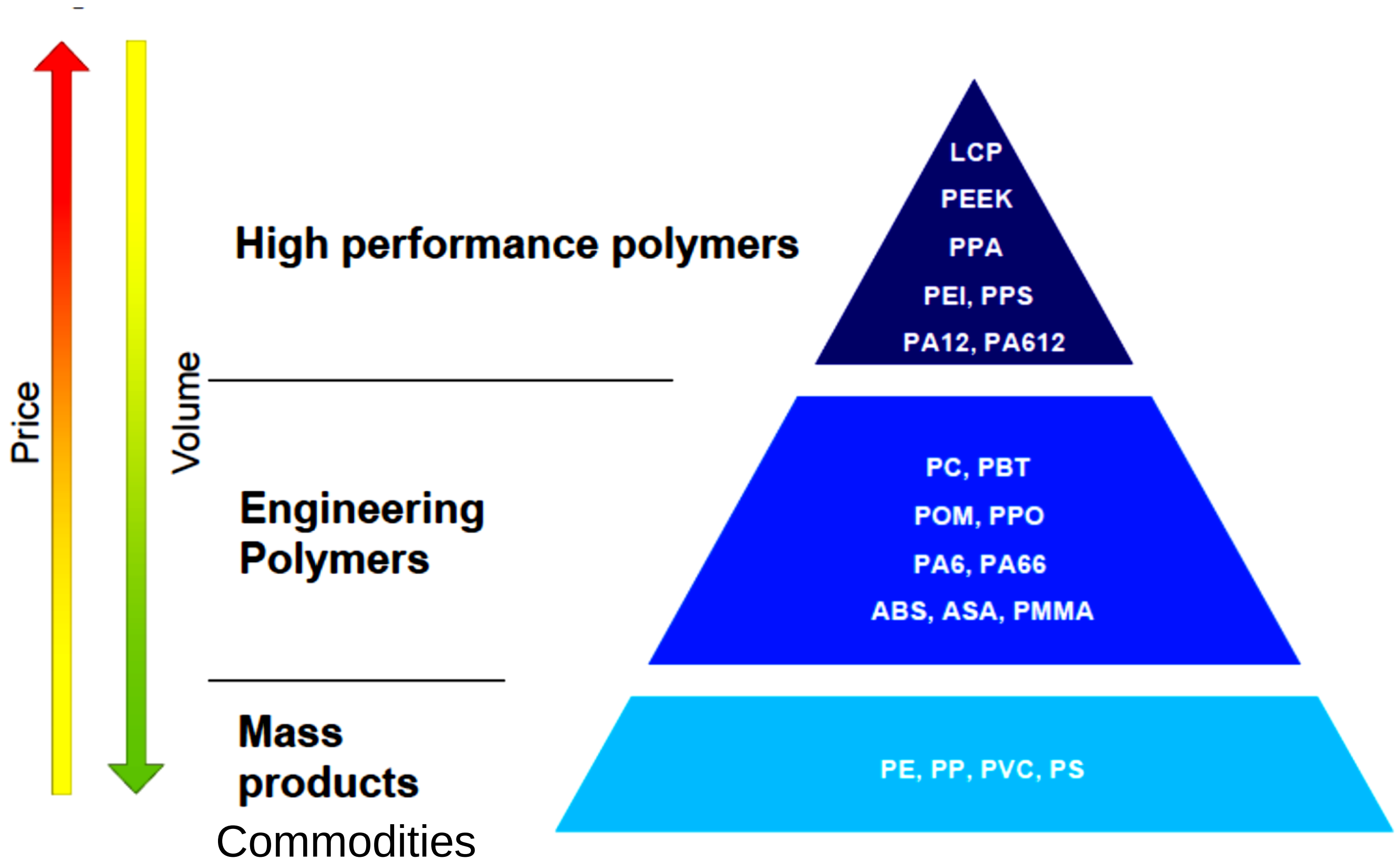
Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughened thermoset	↑	↓	↑	↑	↓
Lightly crosslinked thermoplastic					
Thermoplastic	High	Low	Low	Low	High

SOURCE: Darrel R. Tenney, NASA Langley Research Center.

MOST USED

THERMOPLASTICS

Thermoplastic Matrices



Examples of common thermoplastic polymers

PET - Water and soda bottles

Polypropylene - Packaging containers

Polycarbonate - Safety glass lenses

PBT - Children's toys

Polyethylene - Grocery bags

PVC - Piping

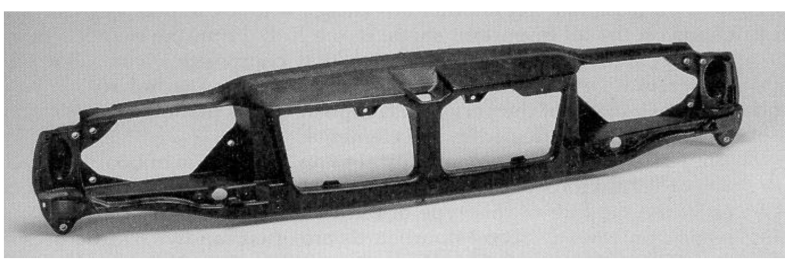
PEI - Airplane armrests

Nylon - Footwear

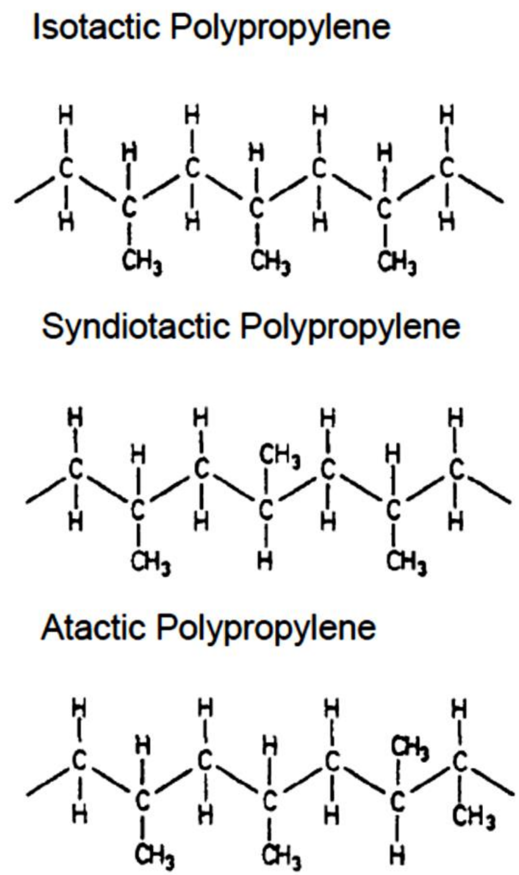
PLA – Food packaging

Polypropylene (PP)

- Low density and good mechanical properties for applications up to 50 ºC.
- PP is often used in combination with PE and/or thermoplastic elastomers, to increase the mechanical properties at low temperatures.
- Moderate surface quality
- The use of PP is increasing in Automotive construction as matrix system.



Tacticity



Polyethylene terephthalate (PET)

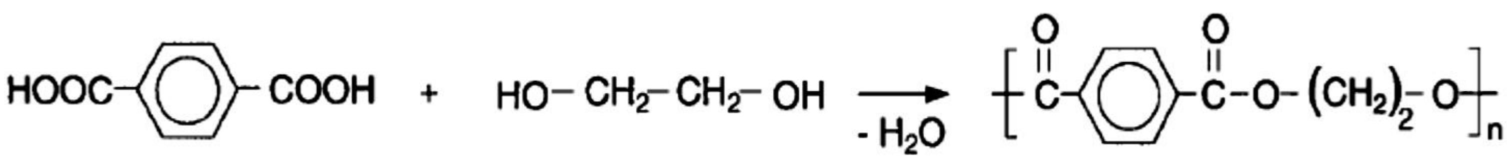
- Amorphous and/or semicrystalline
- Similar application spectrum as PA and PP

however:

- Comparably better mechanical and

thermal properties as PP

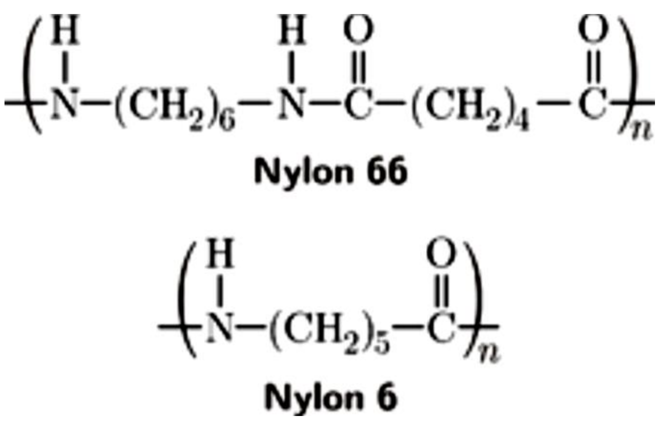
- PET is often reinforced with glass fibers.
- Commodity- and Engineering applications
- Not suitable for high-performance applications
- **Excellent barrier properties (food packaging).**
- Bio-based PET available.



Terephthalic acid **Ethylene glycol** **Polyethylene terephthalate**

Polyamide (PA)

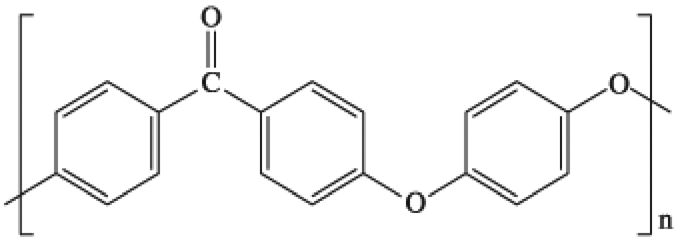
- Also known as nylon
- Semicrystalline
- Interesting for automotive applications
- High tendency to absorb water
- Often seen reinforced with glass or carbon fibers.



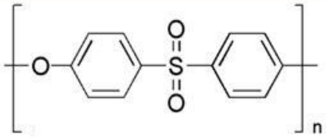
Car seat back
Faurecia

Polyether ether ketone (PEEK)

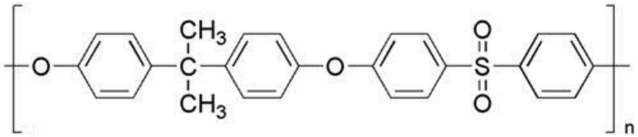
- Semicrystalline type
- Excellent mechanical and physical
- properties
- Exclusive for high-performance
- applications
- High processing temperatures
- Very expensive



Polysulfones



【 Polyethersulfone 】

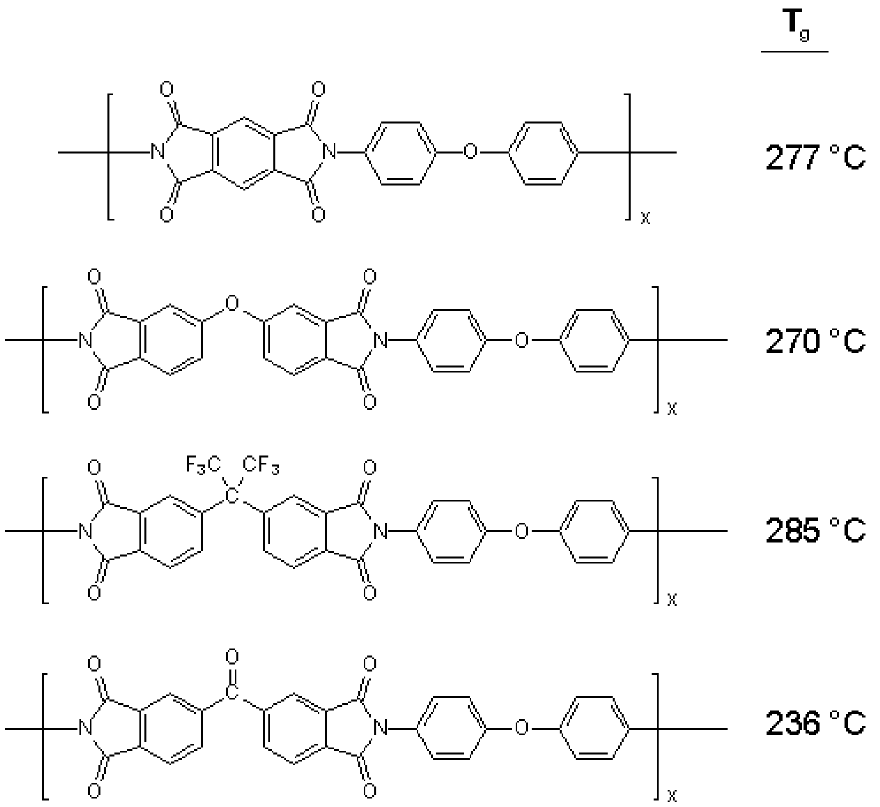


【 Polysulfone 】

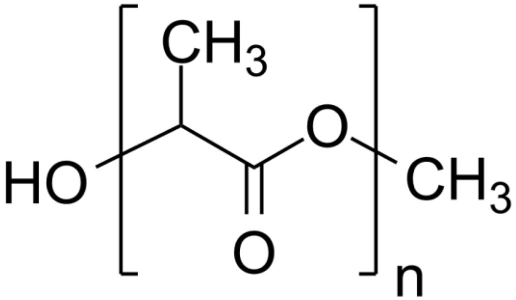
- Amorphous thermoplastic.
- **Excellent stability under hot and wet conditions**.
- Their high hydrolysis stability allows their use in medical applications requiring autoclave and steam sterilization.
- Due to the high cost of raw materials and processing, polysulfones are used in specialty applications.
- Not UV-stable

Polyimides

- Amorphous thermoplastics with high glass transition temperatures.
- Polyamide-imides have exceptional mechanical, thermal and chemical resistant properties. These properties put polyamide-imides at the top of the price and performance pyramid.
- PAI has low processability.



Polylactic acid (PLA)



- Most used bio-based plastic. Compostable. Close to commodity polymer.

- Good mechanical properties, transparency and processability

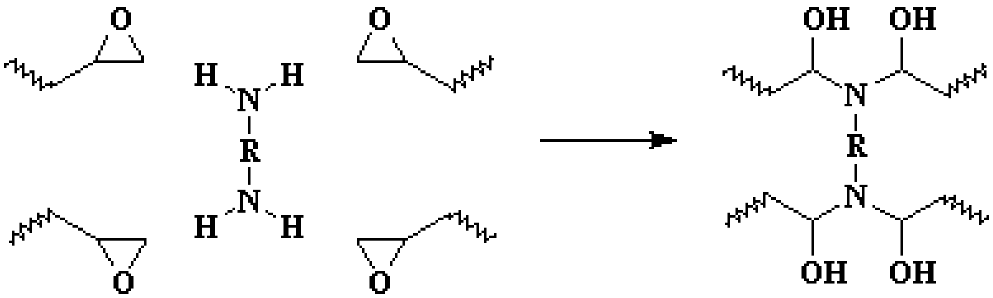
- Brittle, low thermomechanical properties, slow crystallization kinetics, high moisture sorption (create wrinkles in polymers)

- Food packaging (moderate barrier), 3D printing

MOST USED

THERMOSETS

Epoxy Resins



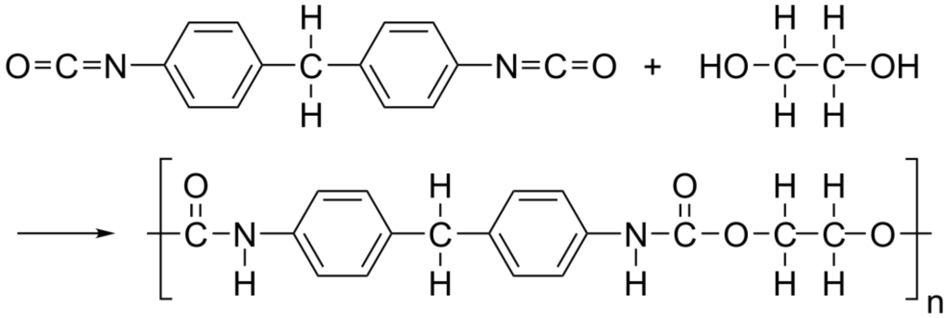
•Because of all those hydroxyl groups, epoxy resins can bond well to glass fibers.

•Epoxy resins are widely used because of their high mechanical properties and high corrosion resistances.

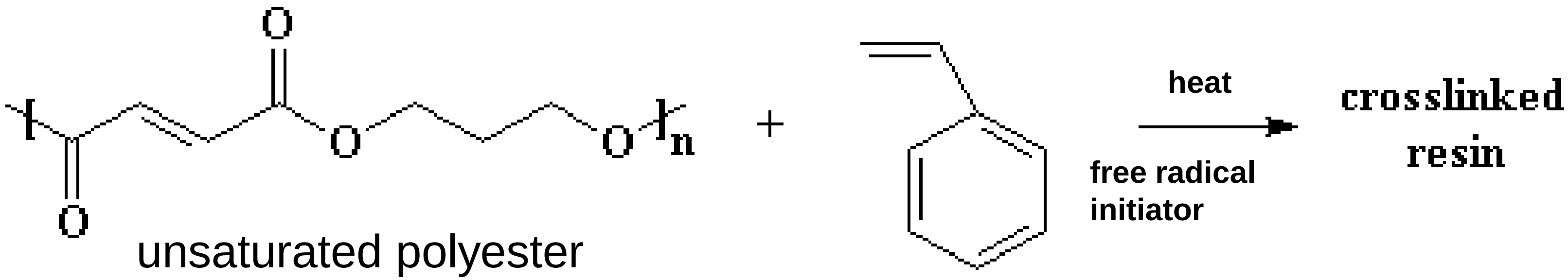
•Epoxy systems are used in applications like aerospace, defense, marine, sports equipment. They are also used as adhesives, body solders (lehim), sealant and casting compounds. Besides, they have a wide range of uses in the electrical business because of their excellent electrical insulation.

Polyuretanes (PU(R))

- Can form thermoplastic, thermosets and foams
- They can be biocompatible
- Generally: Isocyanates + polyols
- Sometimes quite hydroscopic (cyanates reacts violently with water)
- Bio-based PURs
- Common use:
  - Foams and adhesives



Polyester Resins



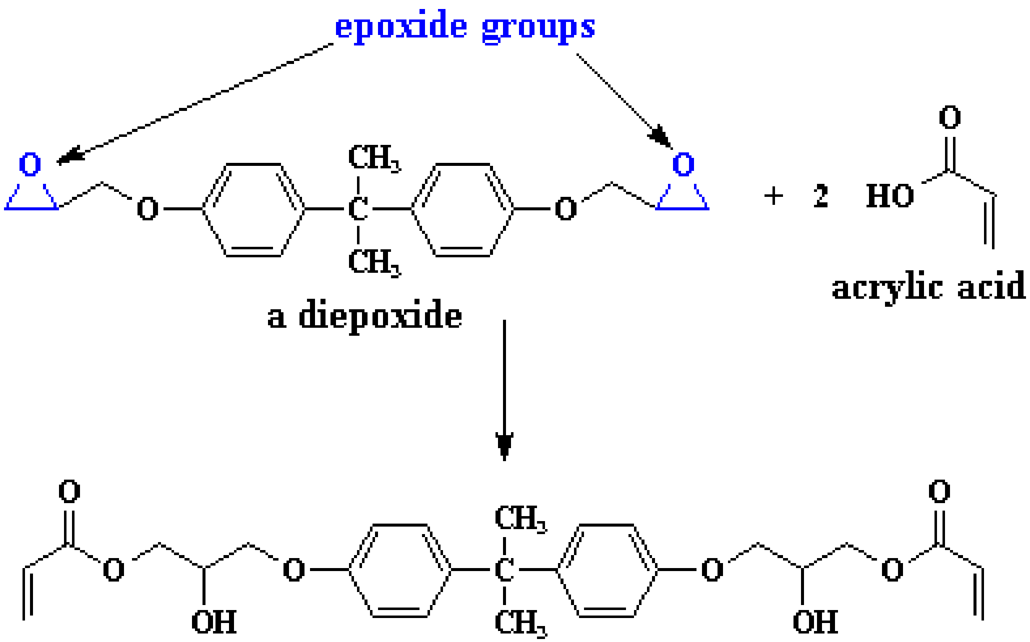
* Cross linking can be accomplished at room temperature using suitable activators.

*Polyester resins can be used in many outdoor applications. Superior durability, color retention and resistance to fiber erosion can be obtained when styrene-MMA monomer blends are used.

*MMA-polyesters have refractive index matched to that of glass fibers allowing to prepare transparent building panels.

***Polyester resins are considered low cost resins**.

Vinyl Ester Resins



Vinyl ester resins have some advantages over unsaturated polyesters:

•They don't absorb as much water,

•They don't shrink nearly as much when cured.

•They have very good chemical resistance.

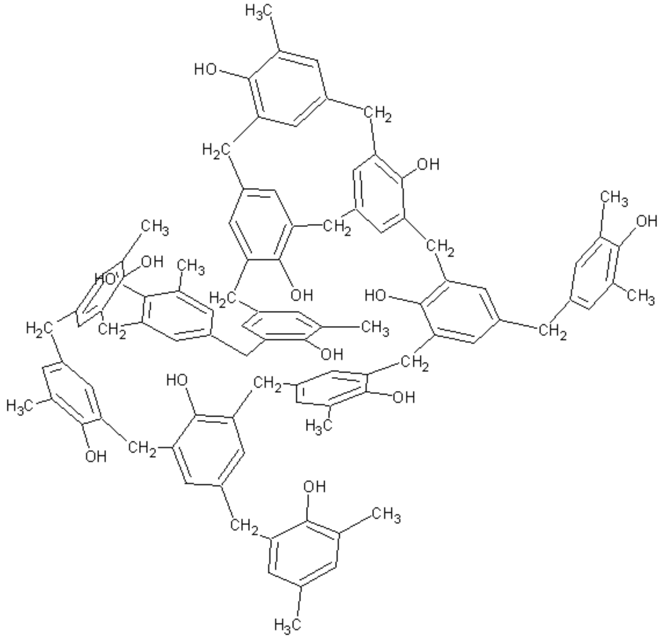
•Because of the hydroxyl groups, it bonds well to glass.

It is a common resin in the marine industry due to its increased corrosion resistance and ability to withstand water absorption.

* The cost of vinyl ester resins is between that of polyesters and epoxies.

Phenolic Resins

- Phenolic resins have low flammability and low smoke production compared with other low-cost resins.
- They have good dimensional stability under temperature fluctuations and good adhesive properties.



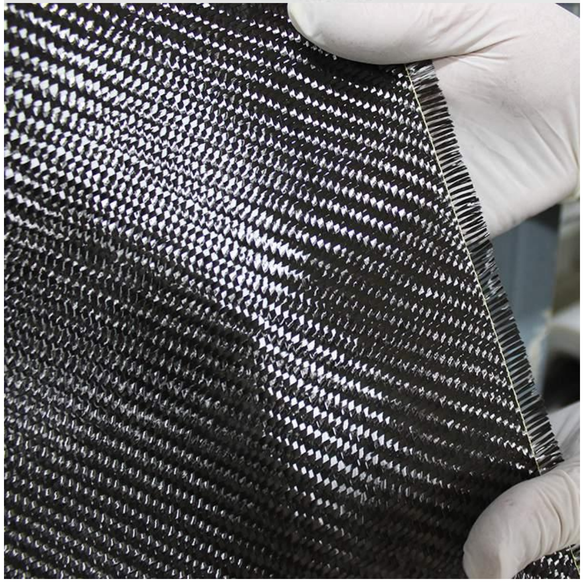
Used as molded disc brake cylinders, saucepan handles, electrical plugs and switches, parts for electrical irons and interior construction materials of aircraft and mass transit vehicles where smoke production must be extremely low.

FUNDAMENTALS OF

COMPOSITES

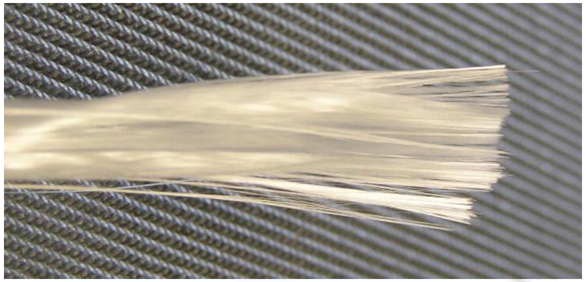
Most common fillers/reinforcements

- Carbon Fibers (CF)
  - 5-10 μm diameter. Tows 3k-50k fibers
  - Sold as tow/chopped fibers/Fabric/prepreg
  - Excellent mechanical properties
    - Especially **uniaxial** properties in "long fibers"
    - Fabric more isotropic
  - Lightweight
  - Generally "sized"
    - Sizing: coating fibers with a polymer to Increase compatibility
  - Conductive composites
  - Recyclability issue
  - Health hazard

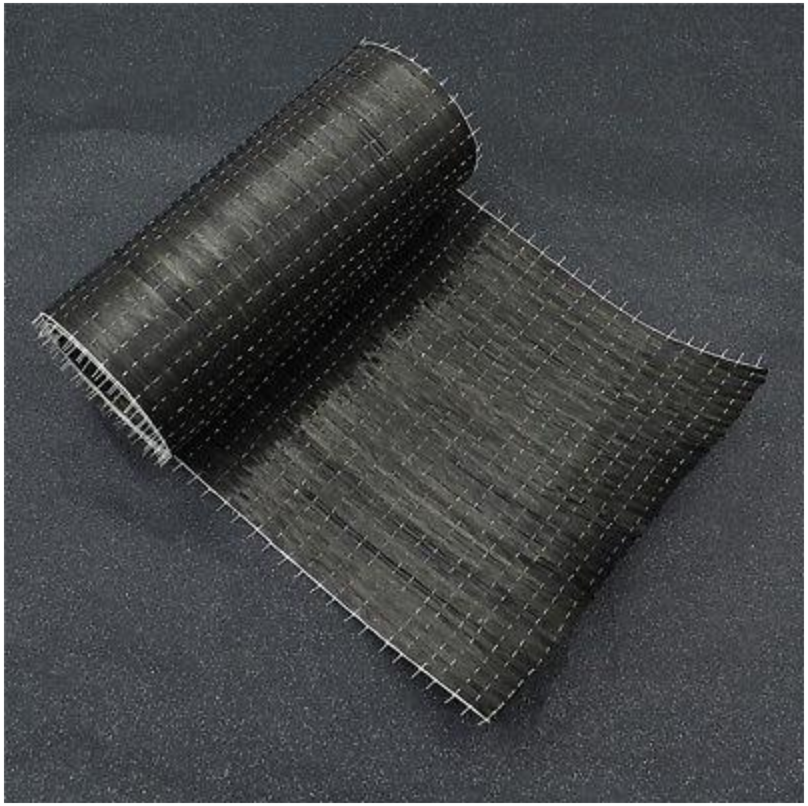


Most common fillers/reinforcements

- Glass fibers
  - Heavier and non-conductive
- Polymer fibers (kevlar fibers)
- Natural fibers
- Sawdust



Infiltration and wetting



Infiltration

Then the resin has to wet

the CF tow. (surface tension/viscosity).

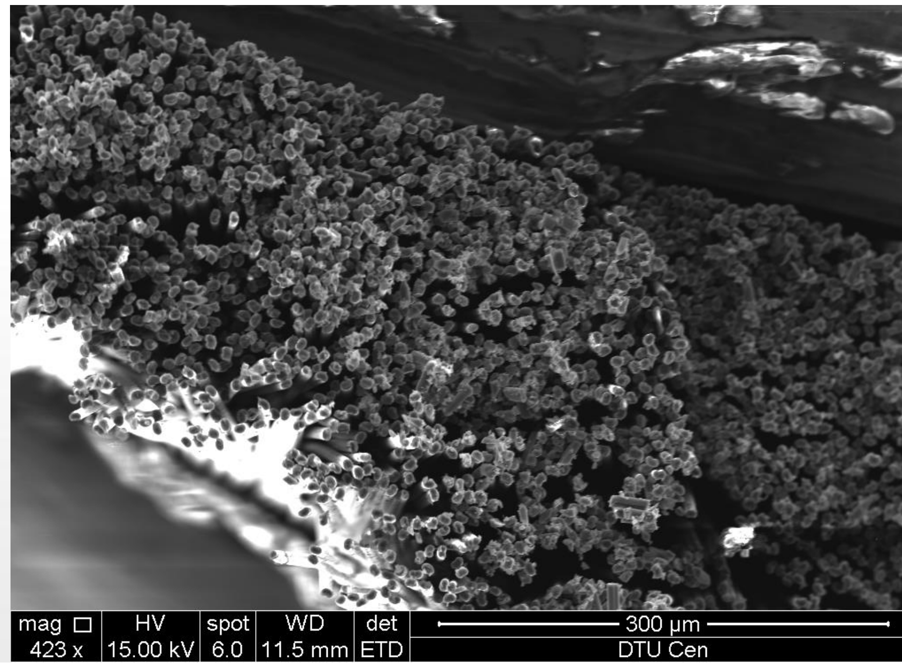
• (app) **1 m2/g**

1 mL of resin

should cover

0,5-1 m^2.

<u>**VACUUM**</u>

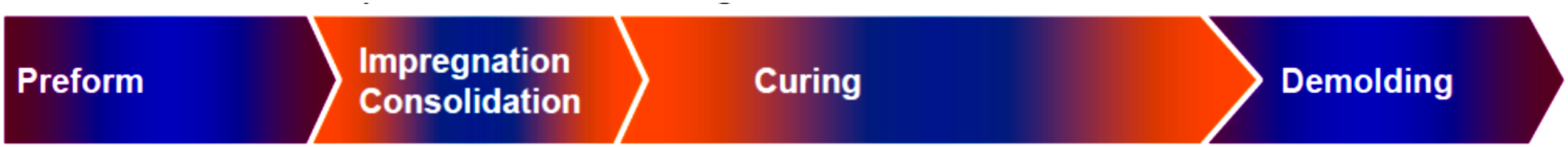


Comparison between Thermoplastic and Thermoset Composite Processing

- Thermoplastic Composite Processing

- Mats (GMT)
- Blended yarns
- Hybrid textiles
- Organo-sheets
- ...

- Thermoset Composite Processing



Processing Properties of Thermoplastics and Thermosets in Fiber-reinforced Composites

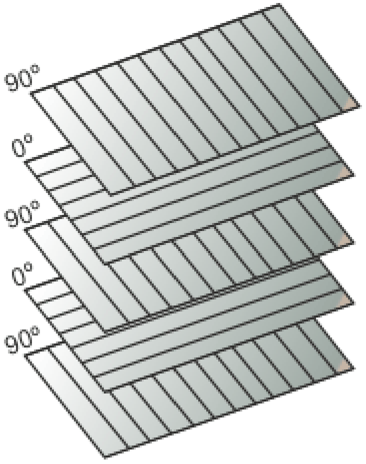
Feature	Thermoplastic matrix	Thermoset matrix
■ Fiber impregnation	■ difficult	■ state-of-the-art
■ Shelf life	■ Unlimited	■ Limited
■ Handling	■ Usually difficult	■ Usually easier
■ Industrial health	■ Easy	■ Critical
■ Machining effort	■ High	■ High
■ Processing time	■ Short to very short	■ Medium to long
■ Recycling	■ Possible	■ Under certain conditions

Polymer Matrix Composites

- The method of manufacturing composites is very important to the design and outcome of the product.
- Unique to the composites industry is the ability to create a product from many different manufacturing processes.
- There are a wide variety of processes available to the composites manufacturer to produce cost efficient products.
- Each of the fabrication processes has characteristics that define the type of products to be produced. This is advantageous because this expertise allows the manufacturer to provide the best solution for the customer.

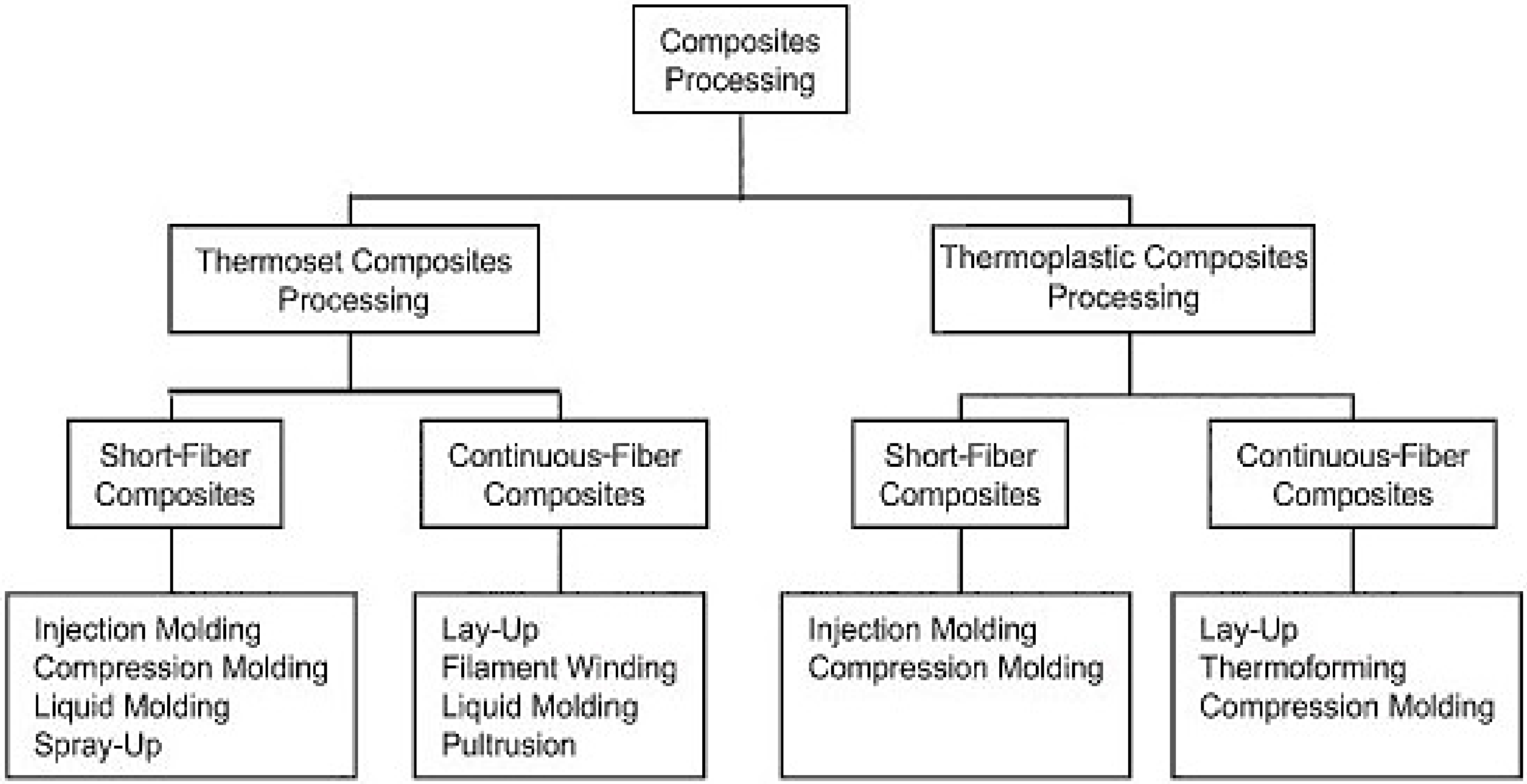
Short/milled fibers vs continuous/long fibers

- Short/milled fibers
  - Handling: A more viscous thermoset
  - Performance: Isotropical mechanical reinforcement
- Long fibers
  - Handling/manufacturing: Much more complex
  - Performance: Excellent uniaxial reinforcement, decreased in the perpendicular direction.
- Ply (long fibers)
  - Multilayer structure, uniaxially oriented fibers with different orientation
  - Crucial to determine the optimal orientation of layers
- Fabric



Fibers orientation

Major FRP fabrication processes



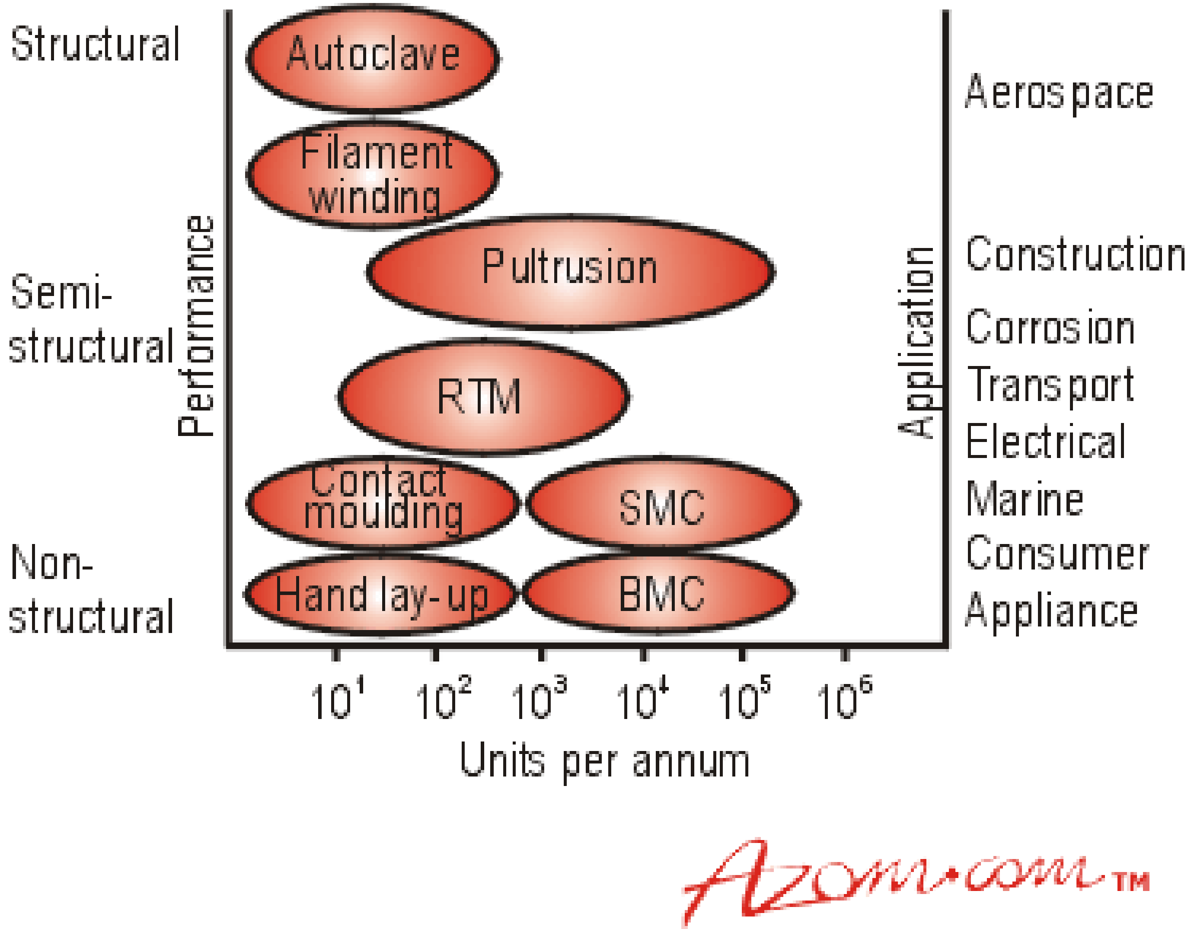
Production processes for thermoplastics

- Injection/compresion moulding
- Film stacking (multilayer – important adhesion)
- Diaphragm forming
- Thermoplastic tape laying

Production processes for thermosetting resins

- **Open mould processes**
  - Hand laminating
  - Spray up
  - Filament winding
  - Pultrusion

- **Closed mould processes**
  - Vacuum bag
  - Autoclave
  - Resin transfer moulding (RTM)
  - Vacuum-assisted resin injection

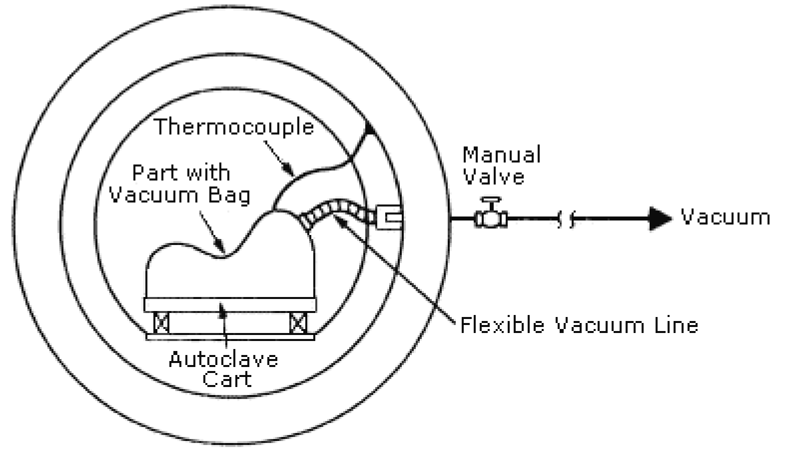

Structural
Semi-structural
Non-structural
Performance
Autoclave
Filament winding
Pultrusion
RTM
Contact moulding
SMC
Hand lay-up
BMC
Application
Aerospace
Construction
Corrosion
Transport
Electrical
Marine
Consumer
Appliance
10¹ 10² 10³ 10⁴ 10⁵ 10⁶
Units per annum
Azom.com TM

PROCCESING OF

THERMOSET

COMPOSITES

Autoclave



- This is a vacuum bag assembly placed within a pressure vessel. The laminate is subjected to vacuum, positive external pressure and heat simultaneously, resulting in very good consolidation, curing and high volume fractions.
- Postcuring

Wet/Hand Lay-Up

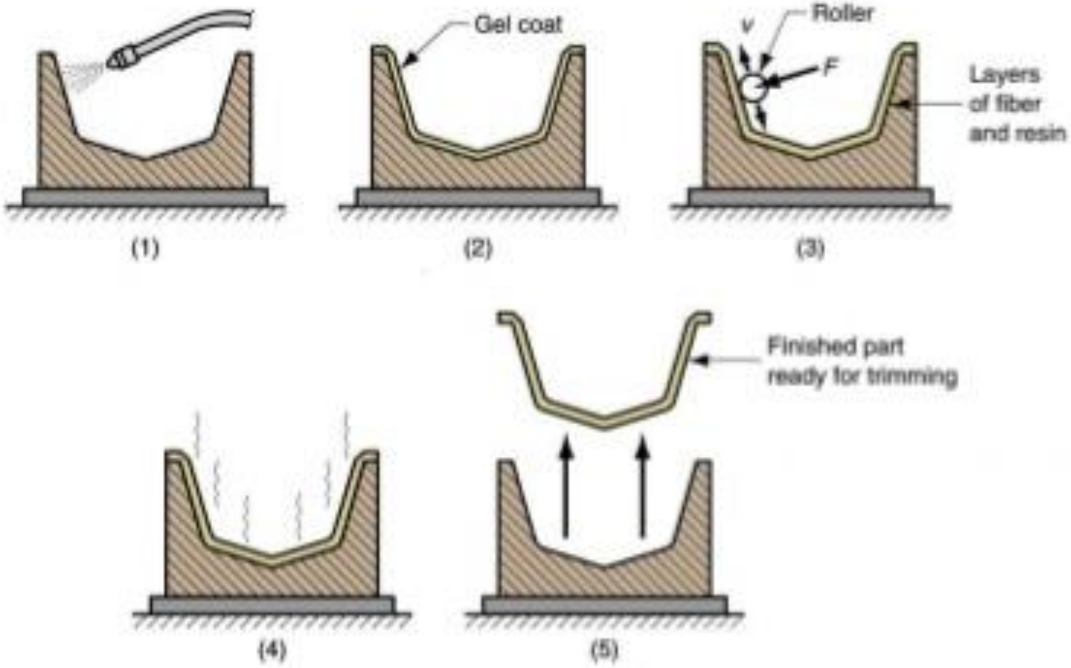
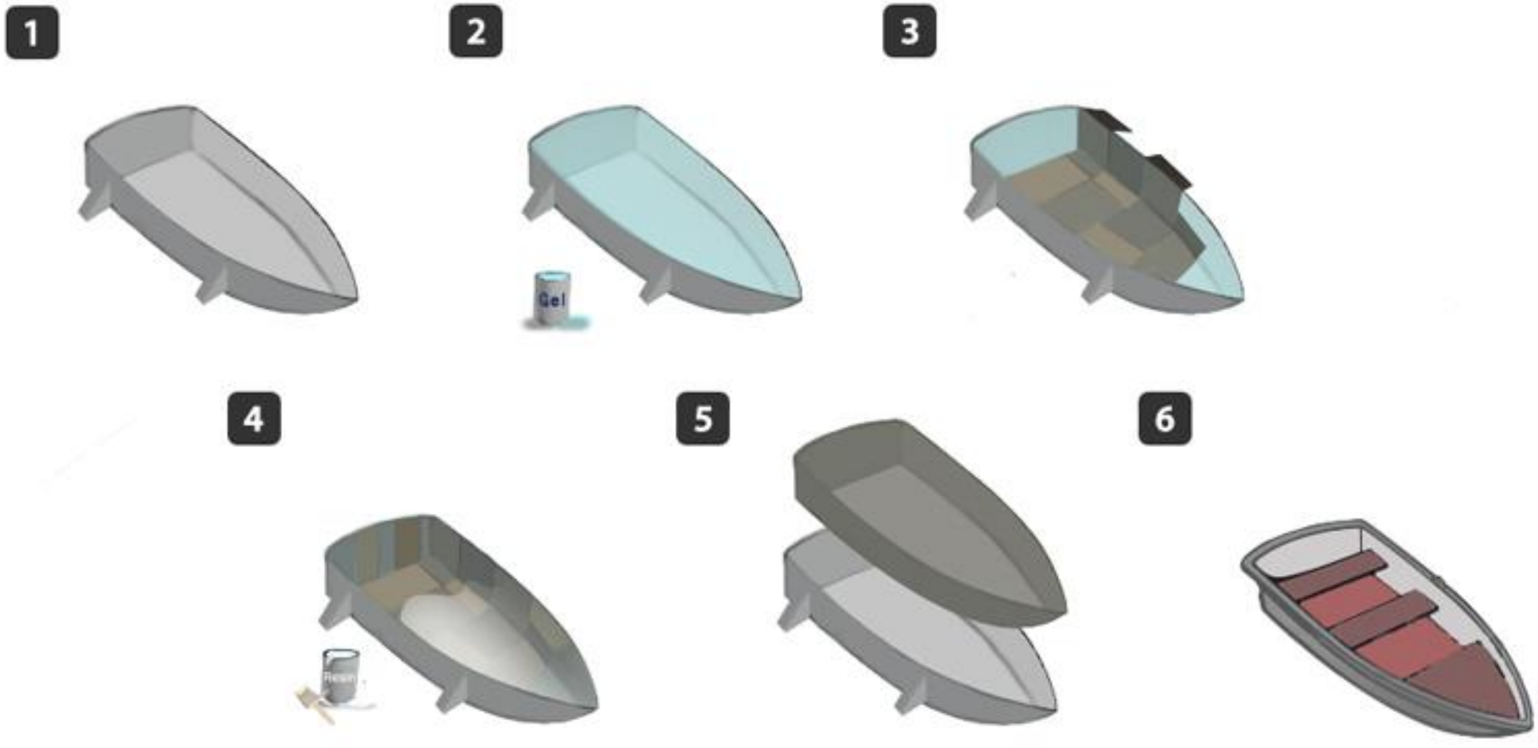


Figure 15.4 Hand lay-up : (1) mold is treated with mold release agent; (2) thin gel coat (resin) is applied, to the outside surface of molding; (3) when gel coat has partially set, layers of resin and fiber are applied, the fiber is in the form of mat or cloth; each layer is rolled to impregnate the fiber with resin and remove air; (4) part is cured; (5) fully hardened part is removed from mold.

Wet/Hand Lay-Up

- Hand layup is an open mold method for shaping to give a form to a structure.
- Since the layers are in direct contact with atmosphere, it is called an open mold process. Sometimes vacuum is required to remove bubbles and ensure good resin infiltration.
- It involves manual laying of fibers with resins on a mold by hands or hand tools.
- Any type of fiber, especially glass fiber is used.
- Thermoset resins almost used, which are in liquid form at room temperature, e.g. epoxy, polyester and etc.
- The mold has shape of product and the product has the better surface finish over the side that is in contact with the mold.

Wet/Hand Lay-Up



Wet/Hand Lay-Up

- Oldest and most commonly used manufacturing method
- Usually used to produce polyester or epoxy resin parts such as boat hulls, tanks and vessels
- The method is quite simple, the resin and reinforcement is placed against the surface of an open (one sided) mold and allowed to cure
- Often a gel coat is applied to the mold prior to produce a better surface quality and protect the composite from the elements
- A gel coat is a resin usually 0.4 to 0.7 mm thick, commonly seen on the outer surface of smaller boats
- DIY-friendly technique. (Remember to be safe!)

Advantages

- The large scale use of hand lay-up process is attributed to the simplicity of the process.
- No expensive equipment is required and only simple inexpensive tools like brushers and rollers are needed.
- Practically there is no restriction on the size of the product.
- It is possible to mold all shapes and incorporate inserts of any shape. Depending on the end user's taste, colors and decorative finishes can be incorporated in the product.
- This is the most suitable method for lining of tanks, ducts and boats and repairing of concrete structures.

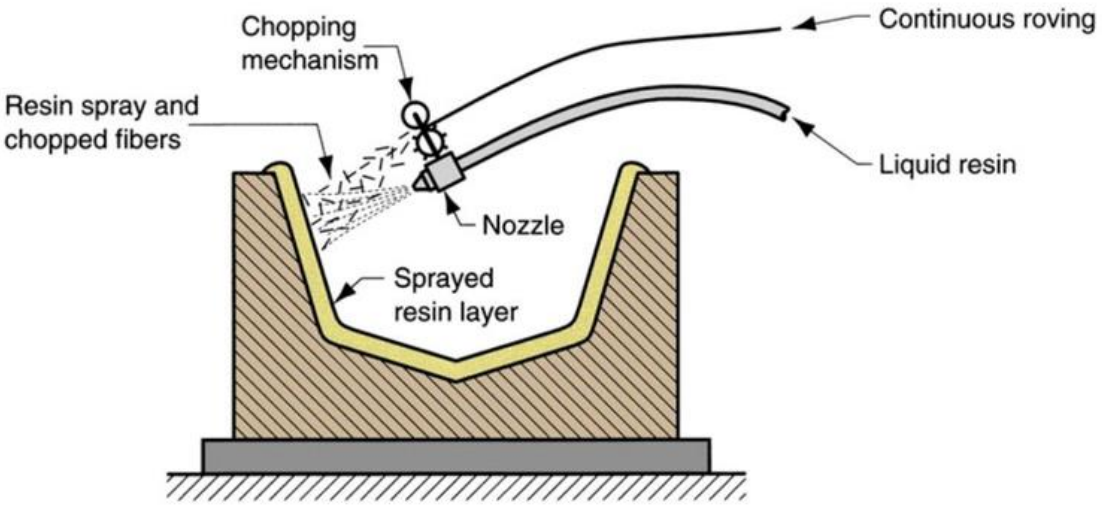
Limitations

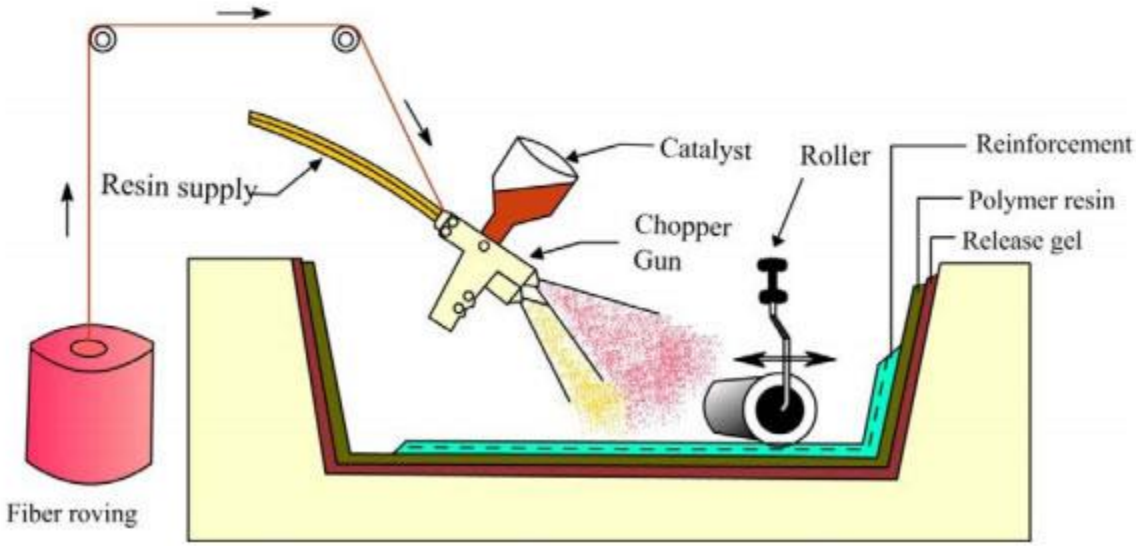
- The process is labor intensive, and the quality of the product depends largely on the **skill of the person doing the fabrication**.
- This process is not suitable if good surface finish is required on both sides of the product.
- This process cannot compete with compression molding for the mass production of small items.
- Thickness control is not accurate and it is difficult to obtain uniform fiber to resin ratio.

Some interesting videos

- https://www.youtube.com/watch?v=6j2ErRs6LCM
- https://www.youtube.com/watch?v=LdEjcNqyUMw&t=1s

Spray Lay-up Process





Videos

- https://www.youtube.com/watch?v=Tk0Bn4XwdWA
- https://www.youtube.com/watch?v=hZ5r9FxZ-90


Spray-up Molding

- Spray-up molding is much less labor intensive than the hand lay-up method by utilizing a spray gun and a fiber cutter.
- However, only short fiber reinforced composites can be made. A continuous fiber is fed into the cutter and chopped.
- The chopped fiber is sprayed upon a mold with the stream of resin mist and catalyst delivered through separate nozzles.
- The sprayed mixture of fiber and resin soon cures on the mold at room temperature and the product is produced.
- Because of the spraying operation, large and complex-shaped objects can be easily made.

Spray-up Molding

Advantages:

- Continuous process
- Any materials can be used as mold
- Error can be corrected by re-spraying

Disadvantages:

- Slow
- No control of fiber orientation
- Only one side finished
- Environmental unfriendly

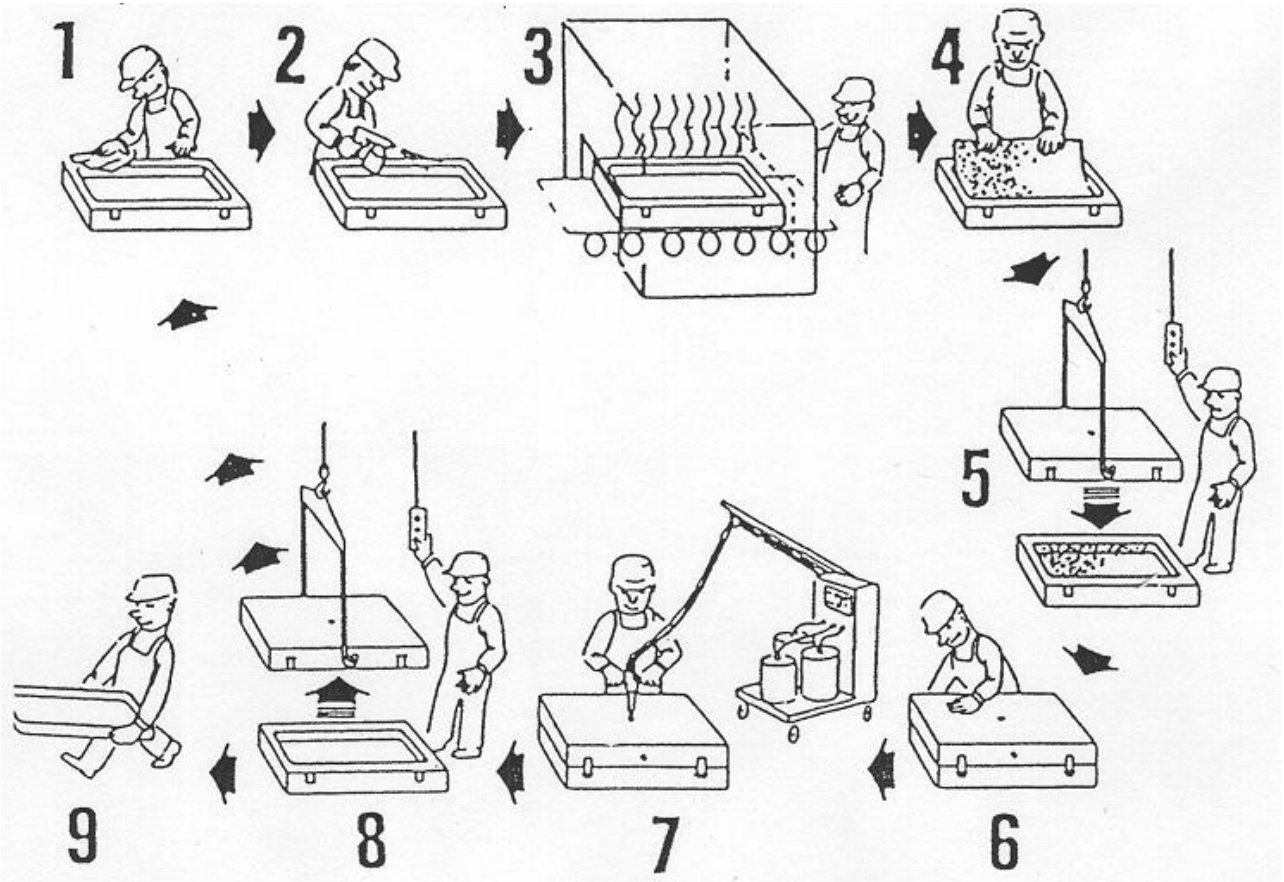
Evaluation of the method

- Unhealthy dust of hardener/resin
- Large products possible
- No tight tolerances in thickness allowed
- Possibility to make several product simultaneously
- Possibility to make it automatic
- Comparison with hand lamination
  + High productivity
  - Weaker tensile properties

Resin Transfer Moulding

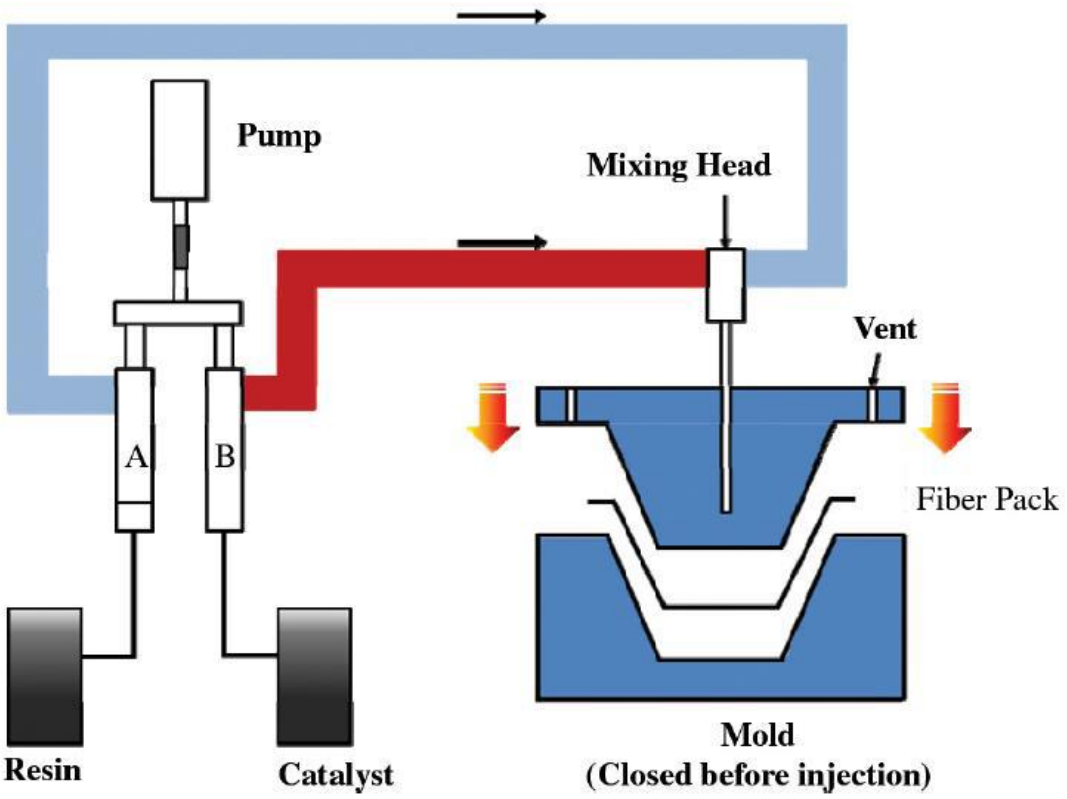
- Similar to wet/hand lay-up.
- Resin is injected to the reinforcement, trapped inside a mold, instead of manually.
- High temperature is applied.

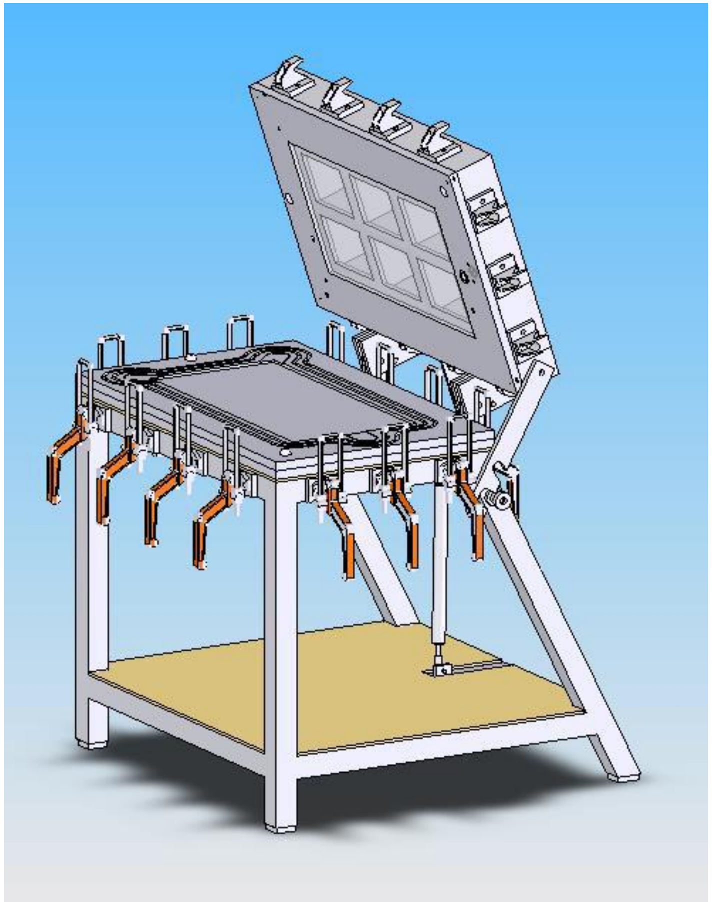
RTM Process steps



1. Cleaning and waxing
2. Gel-coat (if needed)
3. Hardening of gel-coat
4. Application of reinf.
5. Closing the mold
6. Locking of the mold
7. Resin injection
8. Opening of the mold
9. Specimen removal, finishing (cutting of edges, rinsing, checking, fixing)

Resin Transfer Moulding





Resin Transfer Molding (RTM)

- RTM is a closed mold semi-mechanical manufacturing method, generally used to produce fiber-reinforced thermoset polymer products.
- Unlike hand lay-up and spray up processes, RTM process gives better control on product thickness and good surface finish on both sides.
- In this process, the fiber is packed to the required geometrical arrangement in the cavity of a closed mold, and a liquid resin of low viscosity is injected under pressure into the cavity.
- The resin wets the fiber completely and then cures.
- The RTM process gives faster production cycles than hand lay-up process, since fast curing polyester or epoxy resins are generally used.

Resin Transfer Moulding (RTM)

- A wide range of resin systems can be used, including polyester, vinylester, epoxy, phenolic and methylmethaacrylate, combined with pigments and fillers including alumina trihydrate and calcium carbonates.
- Filler may be added to the resin during the RTM process.
- The main purpose of adding filler is to lower the cost of the part.
- Mixing the filler with the resin increases the viscosity of the resin and slows the production rate.

Advantages

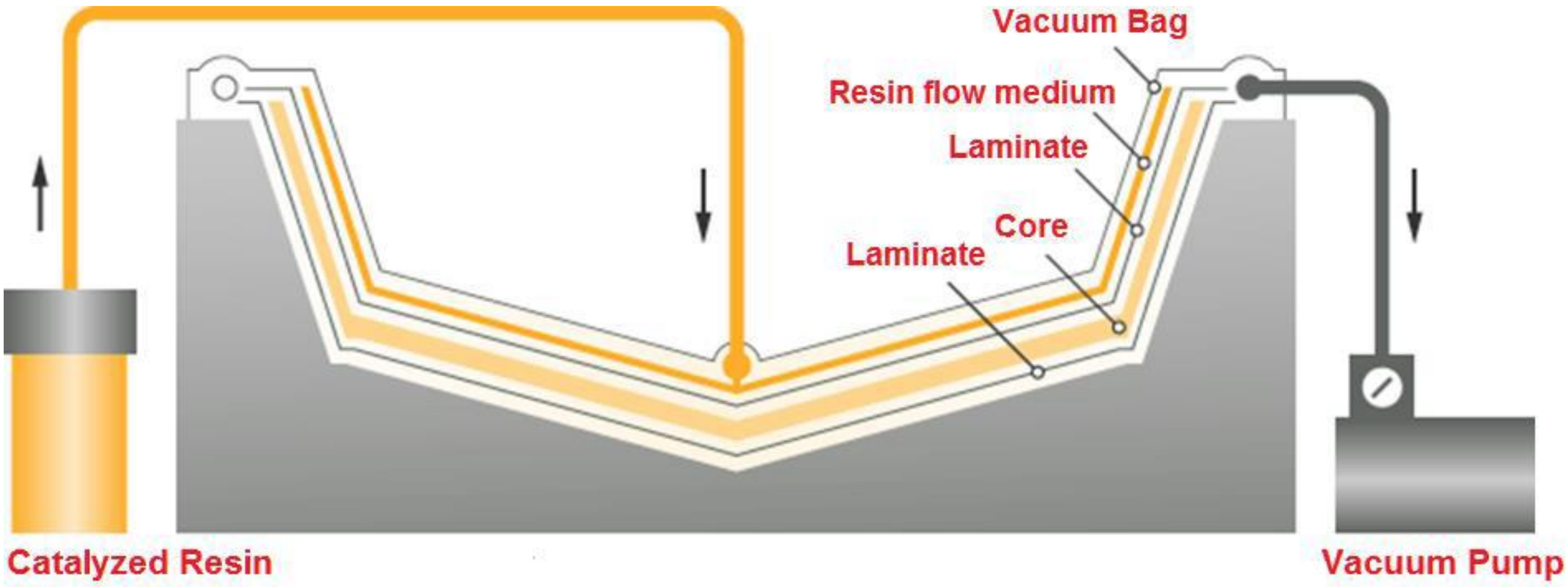
- Initial investment cost is low because of reduced tooling costs and operating expenses as compared to compression molding and injection molding.
- Molding can be manufactured close to dimensional tolerances.
- RTM processing can make complex parts at intermediate volume rates.
- RTM provides for the manufacture of parts that have a good surface finish on both sides.
- **Higher fiber volume fraction**, up to 65% can be achieved. Better mechanical properties.
- Inserts can be easily incorporated into moldings and thus allows good joining and assembly features.

Disadvantages

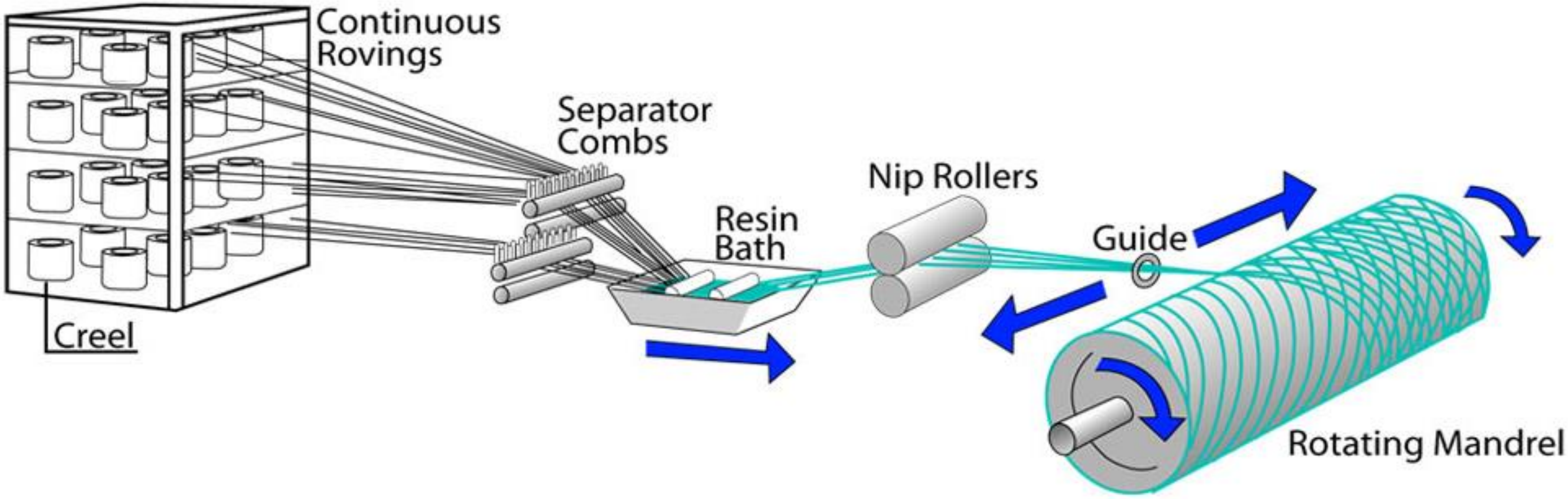
- The manufacture of complex parts requires a good amount of trial and error experimentation.
- Tooling and equipment costs for the RTM process are higher than hand lay-up and spray-up processes.
- The tooling design is complex.
- Reinforcement loading may be difficult with complex parts.

Vacuum Assisted Resin Transfer Moulding

Vacuum Assisted Resin Transfer Moulding (VARTM) is an adopted version of RTM process, in which the application of assists the better impregnation of fiber packing.

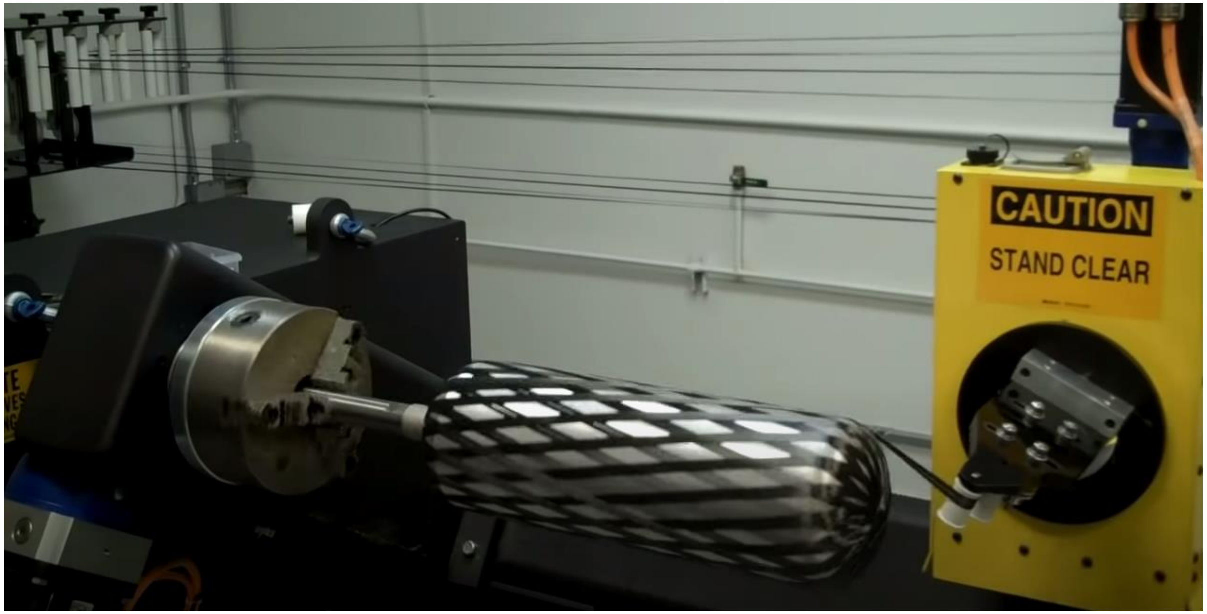


Filament Winding



Filament Winding

- https://www.youtube.com/watch?v=3K8FPyfA0vc
- https://www.youtube.com/watch?v=1A3vaJaNDLY



Filament Winding

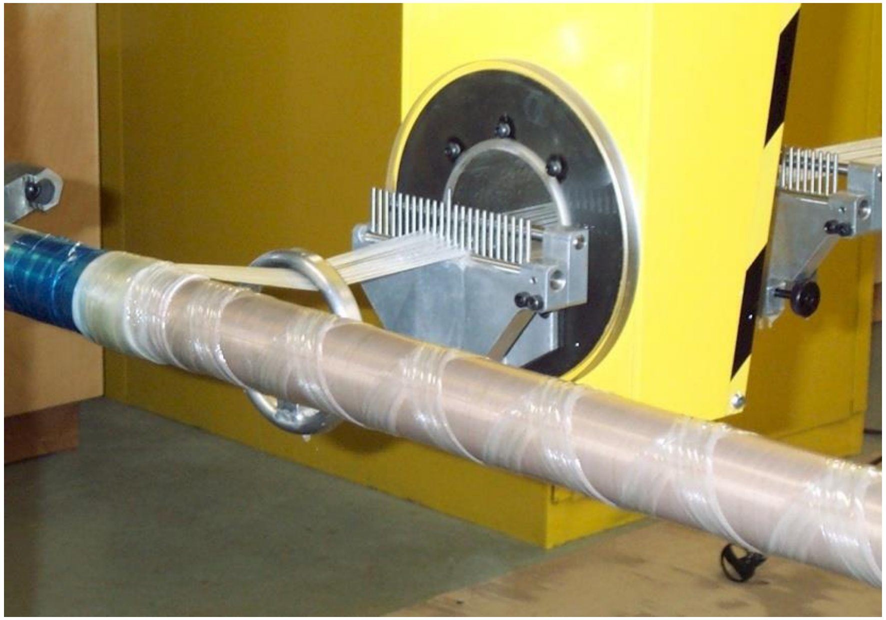
- Filament winding is one of the most important of the composite processes in terms of the number of users and the total number of parts made.
- Filament winding is a process in which resin-impregnated fibers are wound over a rotating mandrel at the desired angle.
- **Continuous fiber reinforcements** are precisely positioned in a pre-determined pattern on a rotating mandrel.

Filament Winding

- Filament winding process can be used to produce any product with positively curved surface.
- Cylindrical, spherical, conical, and geodesic shapes are within winding capabilities.
- Filament winding is used in the production of pressure vessels, gas bottles, pipes, rocket motors etc.

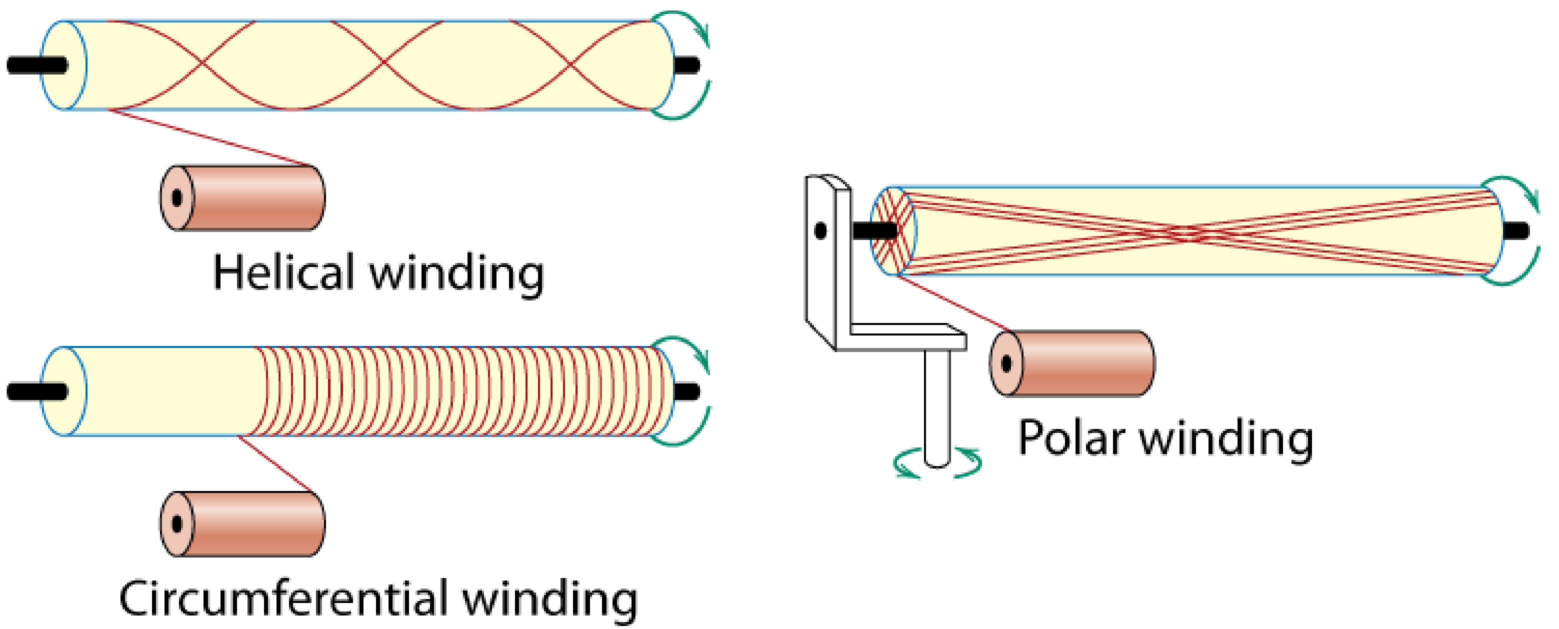
Filament Winding

Impregnated fibers are rolled up on a rotary mandrel, then cured in an oven



Filament Winding

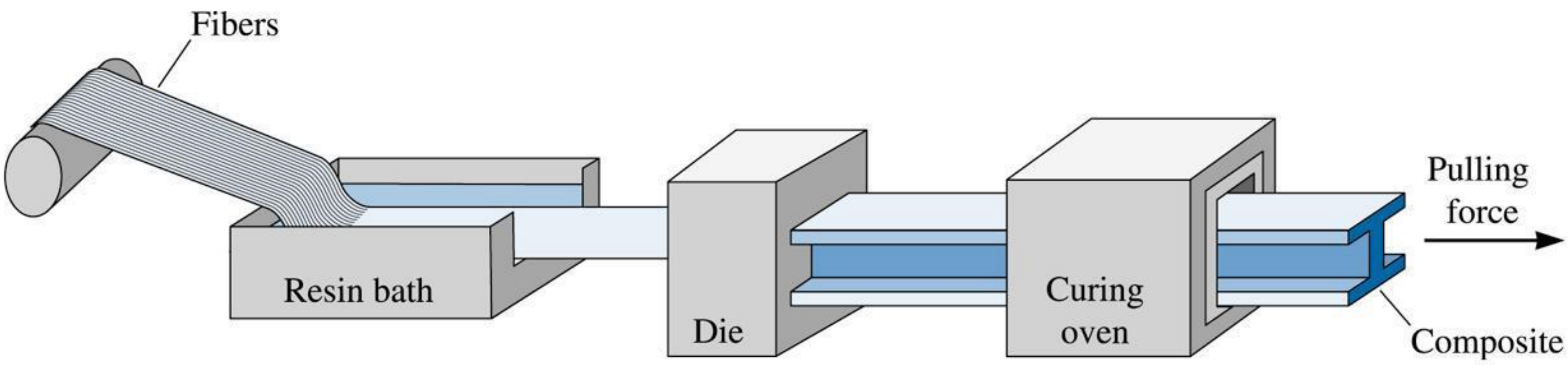
- Continuous filaments wound onto mandrel
- Important for mechanical properties (uniaxial)



Filament Winding

- **Pros:** fast lay-up speed, very accurate and repeatable product, possibility to use continuous fiber, parts can have huge size
- **Cons:** expensive equipment, high cost for mandrel, poor surface finish, shape of the products limited curing by heat is not easy to apply, spinning speed is limited due to resin penetration and splashing

Pultrusion

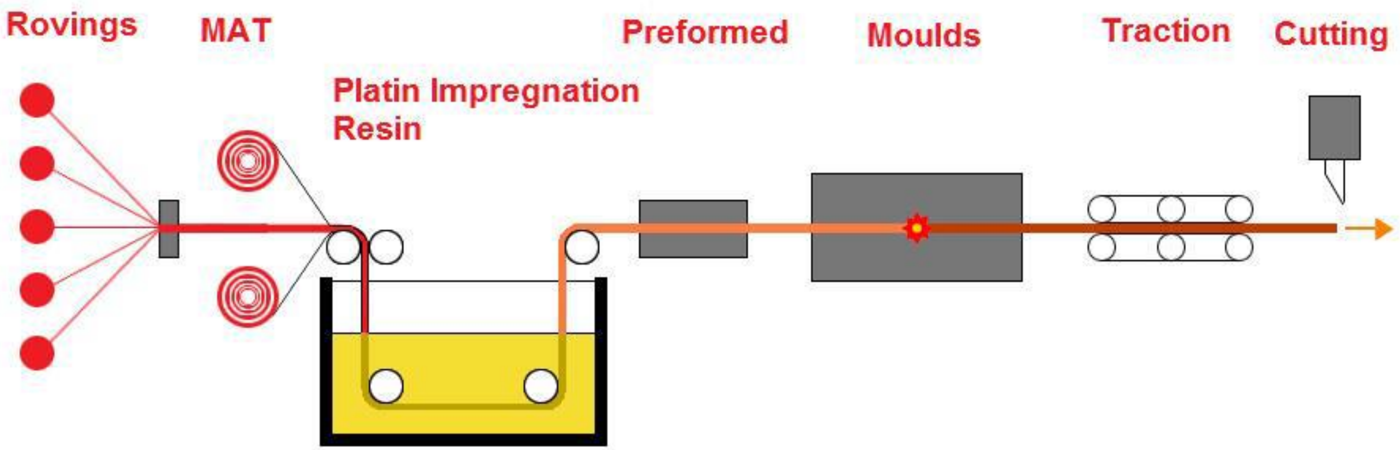


Producing composite shapes by pultrusion

Pultrusion

- The pultrusion process is a low-cost, high volume manufacturing process in which resin-impregnated fibers are pulled through a die to make the part.
- The process is similar to the metal extrusion, with the different being that instead of material being through the die in a pultrusion process.
- Pultrusion creates parts of constant cross-section and continues length.

- In the pultrusion process, continuous rovings and/or mats are pulled through a resin bath and then into performing fixtures, where the section is partially shaped and excess resin and entrapped air are removed.
- The impregnated fibers then pass through heated dies, where the section is cured.



Pultrusion

- Standard extruded shapes can easily be produced such as pipes, channels, I-beams, etc.

Pultrusion

Advantages:

- Automated processes.
- High speed.
- Versatile cross-sectional shape.
- Continuous reinforcement.

Disadvantages:

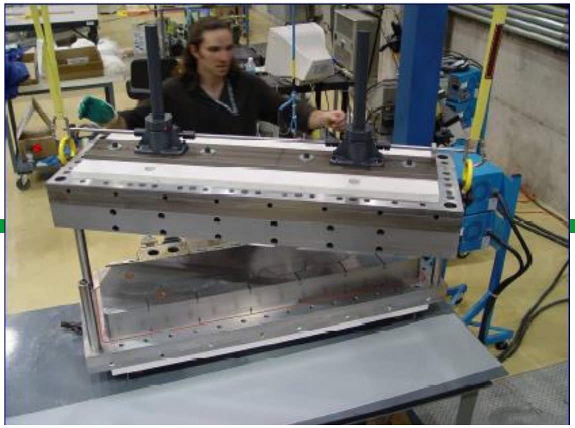
- Die can be easily messed up.
- Expensive die.
- Mainly thermoset matrix.

Applications

- Wing panel
- Truck panel
- Aerospace parts
- Boat hulls
- Wind turbine blades
- Helmet
- Bathroom fixtures
- Car body





AFP: Automatic Fiber Placement, 3D Printing of composites

- Still in its infancy. Industrial standards change quick.
- Application: 3D printing of planes and windmills.
- 3D printing of prepeg filaments
  - Via pultrusion made **uniaxially oriented <u>partially</u> cured** filaments.
  - The Tg of the filaments 20°C.
  - Below 20°C are not sticky so they

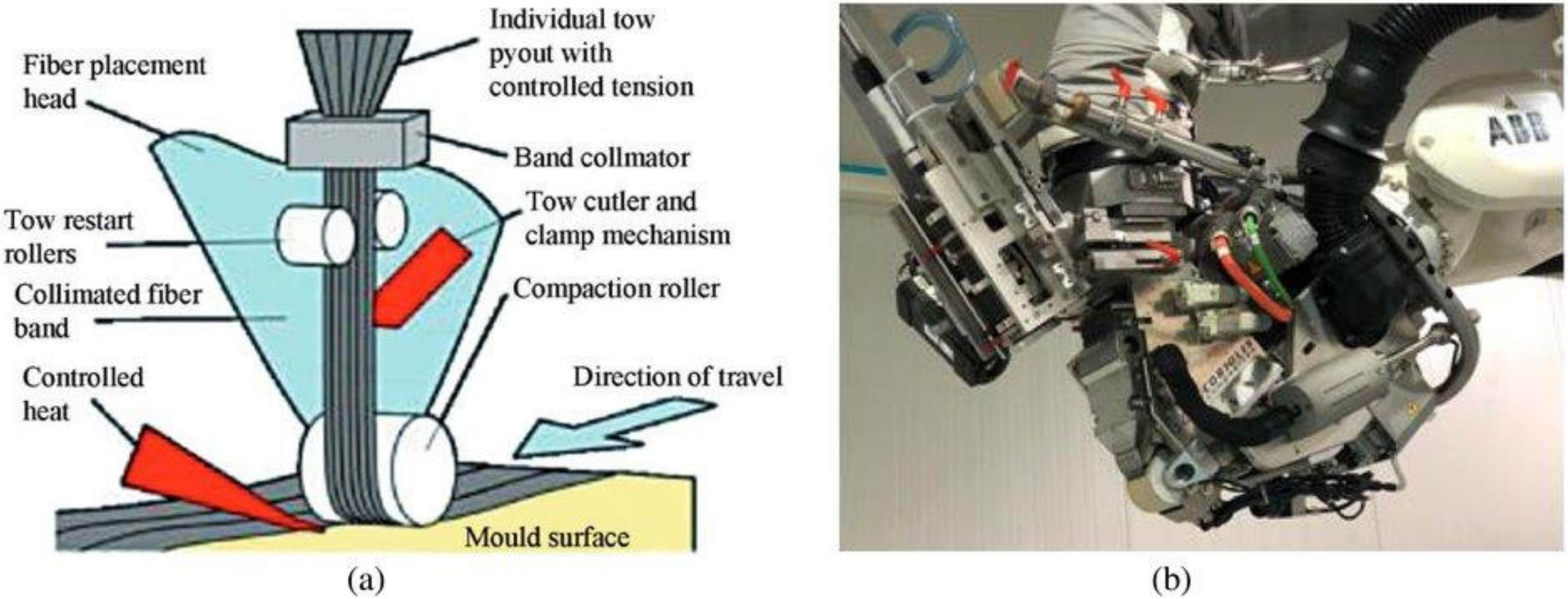
  can be winded (cold stored)

  - Heated by IR lamp after deposition
    - Become stiky
    - Reaction re-starts again

AFP: Automatic Fiber Placement, 3D Printing of composites

- https://www.youtube.com/watch?v=BZzfcJMYdLM
- https://www.youtube.com/watch?v=ulv50nbap5k
- https://www.youtube.com/watch?v=xK4gMDduHgA&t=50s

AFP: Automatic Fiber Placement, 3D Printing of composites



AFP: Automatic Fiber Placement, 3D Printing of composites

- Advantages
  - Automatized technique, does not depend on the operator.
  - Less human resources needed.
  - Can work 24 hours.
  - Less health-safety issues.
  - Theoretical high productivity
  - *In situ quality control (sensors)*
  - *AI compatible*

AFP: Automatic Fiber Placement, 3D Printing of composites

- Disadvantages/challenges/opportunities (as the day of today)
  - Practical Low productivity
    - After depositing a layer, it has to be carefully checked.
    - If a layer has an issue → limited time to fix it.
  - Gaps between layers
    - Reduced mechanical strength
  - Expensive raw materials
  - High initial investment
  - Issues to make complex parts

Markforged: 3D printing of continuos fiber composites

- https://www.youtube.com/watch?v=d2AZ_kfNwZI&app=desktop&ab_channel=QuestIntegration

- Matrix: Nylon reinforced with milled CF
- Fiber: Prepeg of CF

Summary of 'open-mould' processes

Process	*Process parameters*	*Materials*	*Advantages*	*Disadvantages*
Hand laminating	V_f: 0.13-0.5. Size range: 0.25-2,000m^2 Process pressure: ambient. Process temperature: ambient.	Reinforcement: Most types can be used. Resins: Polyester, epoxy, vinylester, phenolic.	Low capital outlay. Secondary bonding. No size limit. Flexibility.	Operator dependent. Labour intensive. Low production rate. Poor weight and thickness control. Only one moulded face.
Spray-up	V_f: 0.13-0.21. Size range: 2-100m^2 Processing pressure: ambient. Processing temperature: ambient.	Reinforcement: chopped roving only. Resins: Polyester, vinylester.	Low material cost. High production rate. Low tooling cost. Large parts.	Very operator dependent. Very poor thickness control. Only one moulded face. Random reinforcement only.
Filament-winding	V_f: 0.55-0.7. Size range: 0.1-1,000 m^2 Processing pressure: ambient. Processing temperature: ambient.	Reinforcement: continuous rovings only. Resins: polyesters, epoxy, vinyl ester.	Excellent mechanical properties. High production rate. Good control of fibre orientation. Good thickness control. Good fibre content control. Good internal finish..	Limited range of shapes. Limited number of practical winding patterns.

Summary of ‘closed mould’ processes I

Process	*Process parameters*	*Materials*	*Advantages*	*Disadvantages*
Vacuum bag	V_f: 0.15-0.6. Size range: 0.5-20m^2 Processing pressure: 1 bar. Processing temp: Ambient.	Reinforcement: Most types. Resins: Most types. Fillers: Not recommended.	Low capital outlay. Low cost of tooling. Large components. Well suited to making sandwich panels.	Labour-intensive. Low production rate. Only one accurate surface.
Autoclave	V_f: 0.35-0.7. Size range: 0.25-5.0m^2 Processing pressure: Up to 10 bar. Processing temp: 140^{0}C.	Reinforcement: Unidirectional and woven prepregs. Resins: Epoxy. Fillers: No.	Very high quality. High fibre content. Low void content. Controlled cure.	Labour intensive. Slow. High capital investment.
Cold press moulding	V_f: 0.15-0.25. Size range: 0.25-5.0m^2 Processing pressure: 2-5 bar. Processing temp: 20-50^{0}C.	Reinforcement: Continuous strand mat/woven cloth. Resins: Polyester. Fillers: Up to 20% by volume.	Good surface on both sides. Good production rate. Accurate dimensions.	Limited by press size. Low fibre content.

Summary of 'closed mould' processes II

Process	*Process parameters*	*Materials*	*Advantages*	*Disadvantages*
Hot press moulding	V_f: 0.12-0.4. Size range: 0.1-2.5m^2 Processing pressure: 50-150 bar. Processing temp: 130-150^{0}C.	Reinforcement: Usually pre-impregnated sheet moulding compound (SMC) or dough moulding compound (DMC). Resins: Polyester, epoxy, vinylester. Fillers: Up to 40%.	Very high production rate. Fine detail, close tolerance. Low cost. Long tool life.	Mechanical properties modest with SMC and DMC. Material flow causes property variability. High tooling cost.
Resin transfer moulding	V_f: 0.1-0.15. Size range: 0.25-5 m^2 Processing pressure: Max. 2 bar. Processing temperature: 20-50^{0}C.	Reinforcement: Continuous strand mat or chopped strand preform. Resins: Polyester, polyurethane, low viscosity epoxy. Fillers: Not recommended.	Good surface on both sides. Accurate dimensions. Wide range of part geometry. Reasonable production rate Sandwich construction possible.	Massive tooling. Low fibre content.
Vacuum-assisted resin injection	V_f: 0.15-0.35. Size range: 1.0-30 m^2 Processing pressure: Max. 2 bar. Processing temp: 15-30^{0}C.	Reinforcement: Continuous strand mat, woven cloths. Resins: Polyester, polyurethane. Fillers: Not recommended.	High fibre content. Large size. Low weight, low cost tooling. Full range of reinforcement.	One-shot process; modifications and repairs difficult. Production development usually needed on each mould.

PROCCESING OF

THERMOPLASTIC

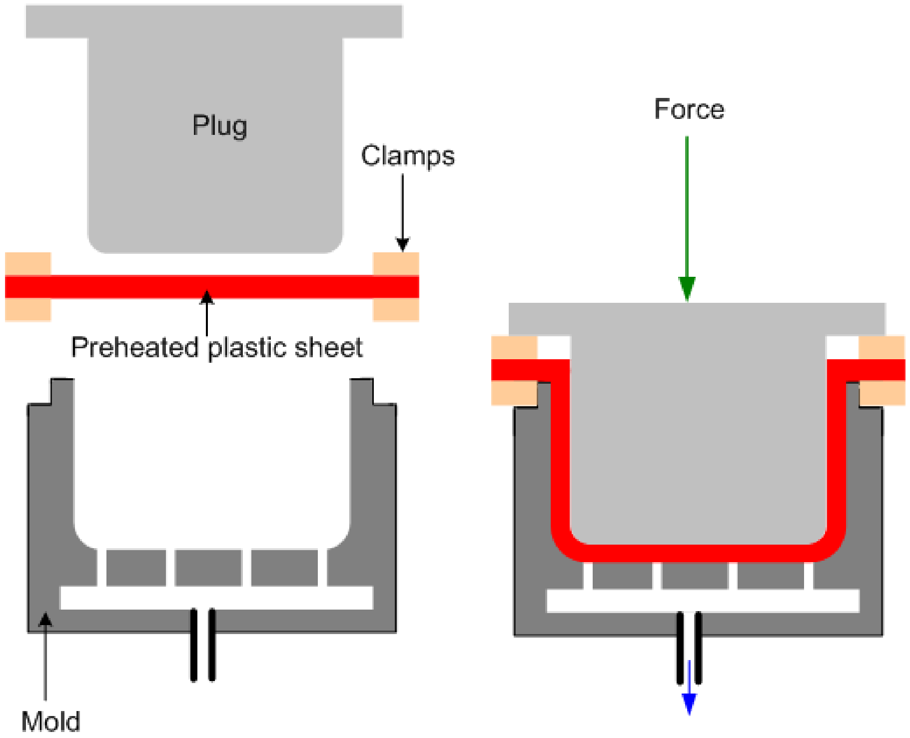
COMPOSITES

Aalto-yliopisto
Kemian tekniikan
korkeakoulu

Thermoforming

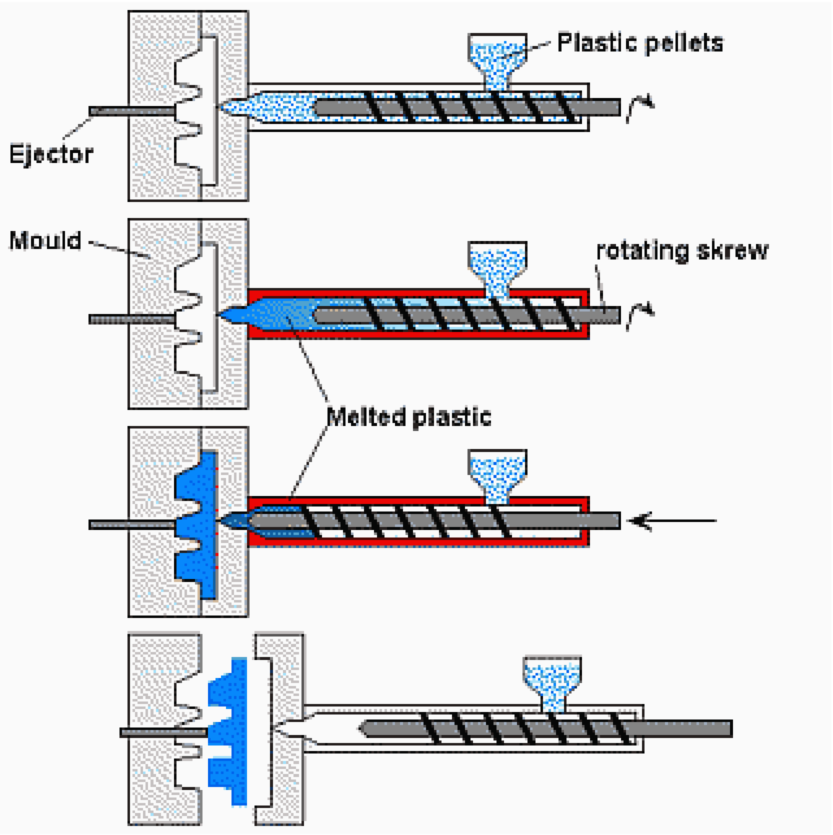
- One of the main advantages of thermoplastic composites is their ability to be rapidly transformed into structural shapes by thermoforming process.
- This process uses heat and pressure to transform a flat sheet into a structural shape.
- The blank is heated close to the melting temperature of the thermoplastic matrix and then quickly transferred to a press containing dies of the desired shape.
- Flat thermoplastic sheet or film is heated and deformed into desired shape using a mold.
- Heating usually accomplished by radiant electric heaters located on one or both sides of starting plastic sheet or film.
- Widely used in packaging of products and to fabricate large items such as bathtubs, contoured skylights, and internal door liners for refrigerators

- The process involves shaping a preheated thermoplastic sheet by means of a direct mechanical force.
- A core plug (positive mold) forces the soft sheet to fill the space between the plug and the negative mold.



Injection moulding

- Molten polymer/fibre blend is forced into a closed mould
- The mould is “split” so that then the polymer/blend has cooled and solidified, the mould can be opened and the injection moulded part can be removed

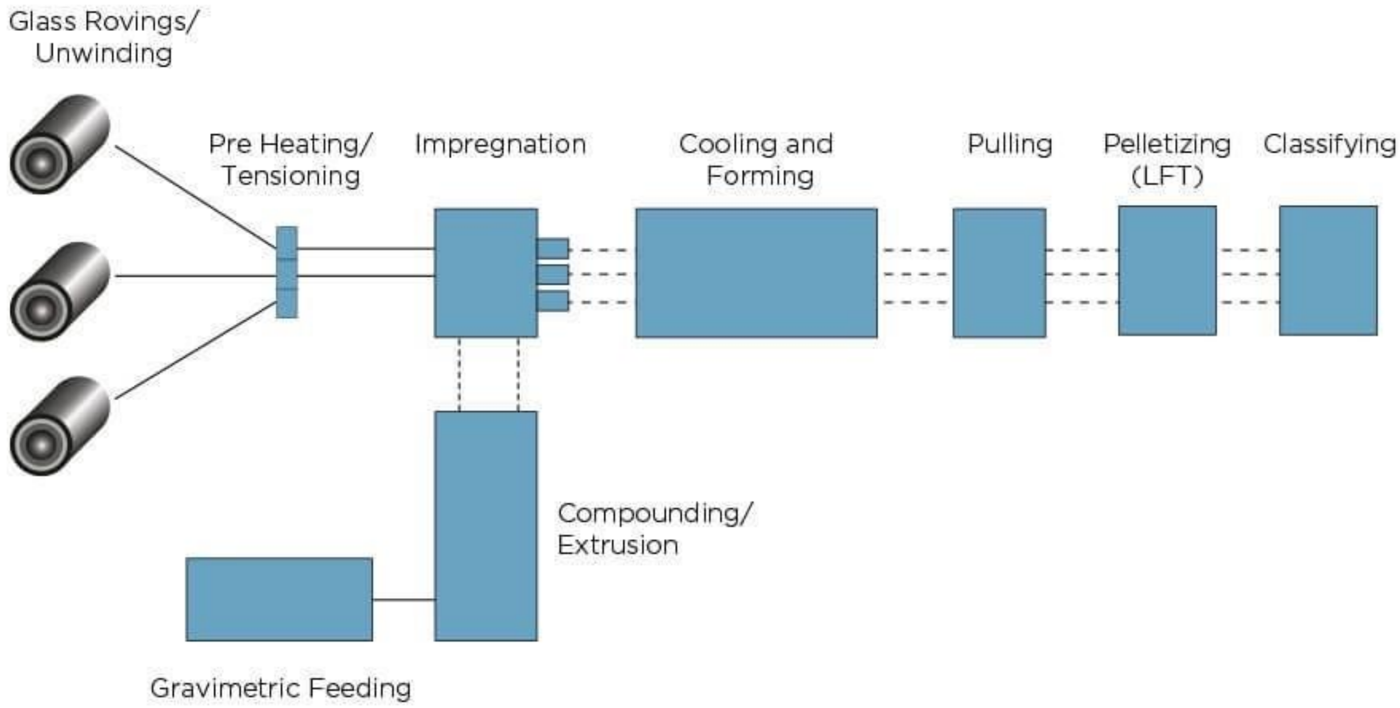


(Source http://designinsite.dk/htmsider/pb2012.htm)

Properties of the composite

- … are affected by
  - Raw materials
  - Processing of the product
  - Conditions where the product used

Thermoplastic pultrusion



Thermoplastic pultrusion

- The process setup the thermoplastic pultruted part is the same as the thermoset in the counterpart.
- Parts are made by pulling the composite from a heated die.
- Compaction starts as the material reaches the tapered section the die and continues until it leaves the die.
- The composite solidifies as it passes through the cooled portion the die.
- The part is then cut to a specified length using a cutter.