MME 3013 COMPOSITE MATERIALS

Polymer Matrix Composites Manufacturing Processes

Polymer Matrix Composites

- The method of manufacturing composites is very important to the design and outcome of the product
- With traditional materials one starts out with a blank piece of material ie: rod, ingot, sheet, etc and works it to produce the desired part.
- However, this is not the case with polymer-matrix composites.
- With these composites the material and the component are being produced at the same time, therefore we aim for the product to be a net or near net shape with little to no post processing.

Polymer Matrix Composites

- 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.

Polymer Matrix Composites

Thermosetting resins include polyesters, vinylesters, epoxies, bismaleimides, and polyamides.

Thermosetting polyesters are commonly used in fiber-reinforced plastics, and epoxies make up most of the current market for advanced composites resins.
Initially, the viscosity of these resins is low; however, thermoset resins undergo chemical reactions that crosslink the polymer chains and thus connect the entire matrix together in a three-dimensional network. This process is called curing.

Thermosets, because of their three-dimensional crosslinked structure, tend to have high dimensional stability, high-temperature resistance, and good resistance to solvents. Recently, considerable progress has been made in improving the toughness and maximum operating temperatures of thermosets.

Polymer Matrix Composites

Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyetherimide, polyamide imide, polyphenylene sulfide, polyether-etherketone (PEEK), and liquid crystal polymers. They consist of long, discrete molecules that melt to a viscous liquid at the processing temperature, typically 500” to 700” F (260° to 3710 C), and, after forming, are cooled to an amorphous, semicrystalline, or crystalline solid.

The degree of crystallinity has a strong effect on the final matrix properties. Unlike the curing process of thermosetting resins, the processing of thermoplastics is reversible, and, by simply reheating to the process temperature, the resin can be formed into another shape if desired.

Thermoplastics, although generally inferior to thermosets in high-temperature strength and chemical stability, are more resistant to cracking and impact damage.

However, it should be noted that recently developed high-performance thermoplastics, such as PEEK, which have a semicrystalline microstructure, exhibit excellent high temperature strength and solvent resistance.

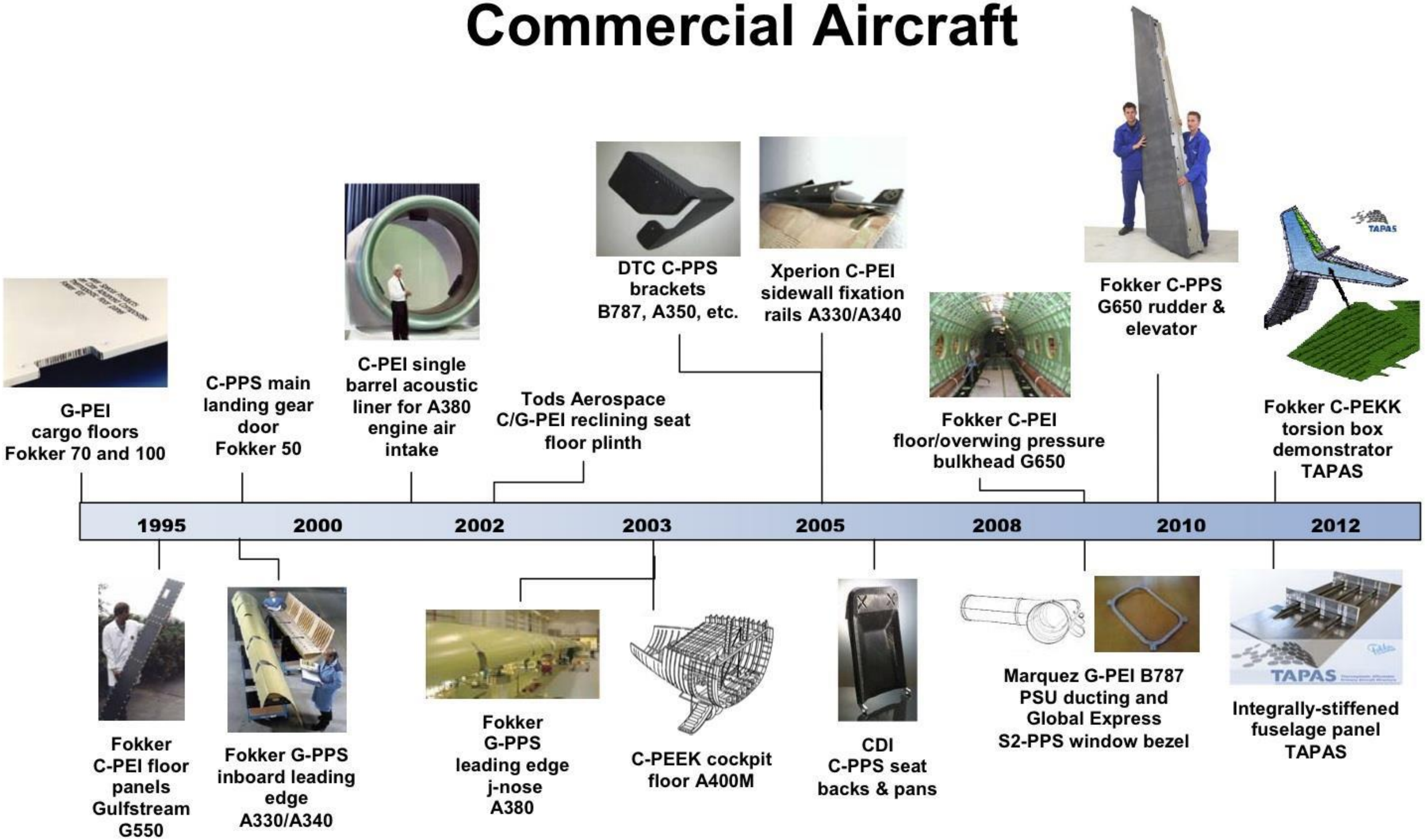
Polymer Matrix Composites

Thermoplastic resins

Thermoplastics offer great promise for the future from a manufacturing point of view, because it is easier and faster to heat and cool a material than it is to cure it. This makes thermoplastic matrices attractive to high-volume industries such as the automotive industry.

Currently, thermoplastics are used primarily with discontinuous fiber reinforcements such as chopped glass or carbon/graphite. However, there is great potential for high-performance thermoplastics reinforced with continuous fibers. For example, thermoplastics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft.

Thermoplastic Composites in Commercial Aircraft



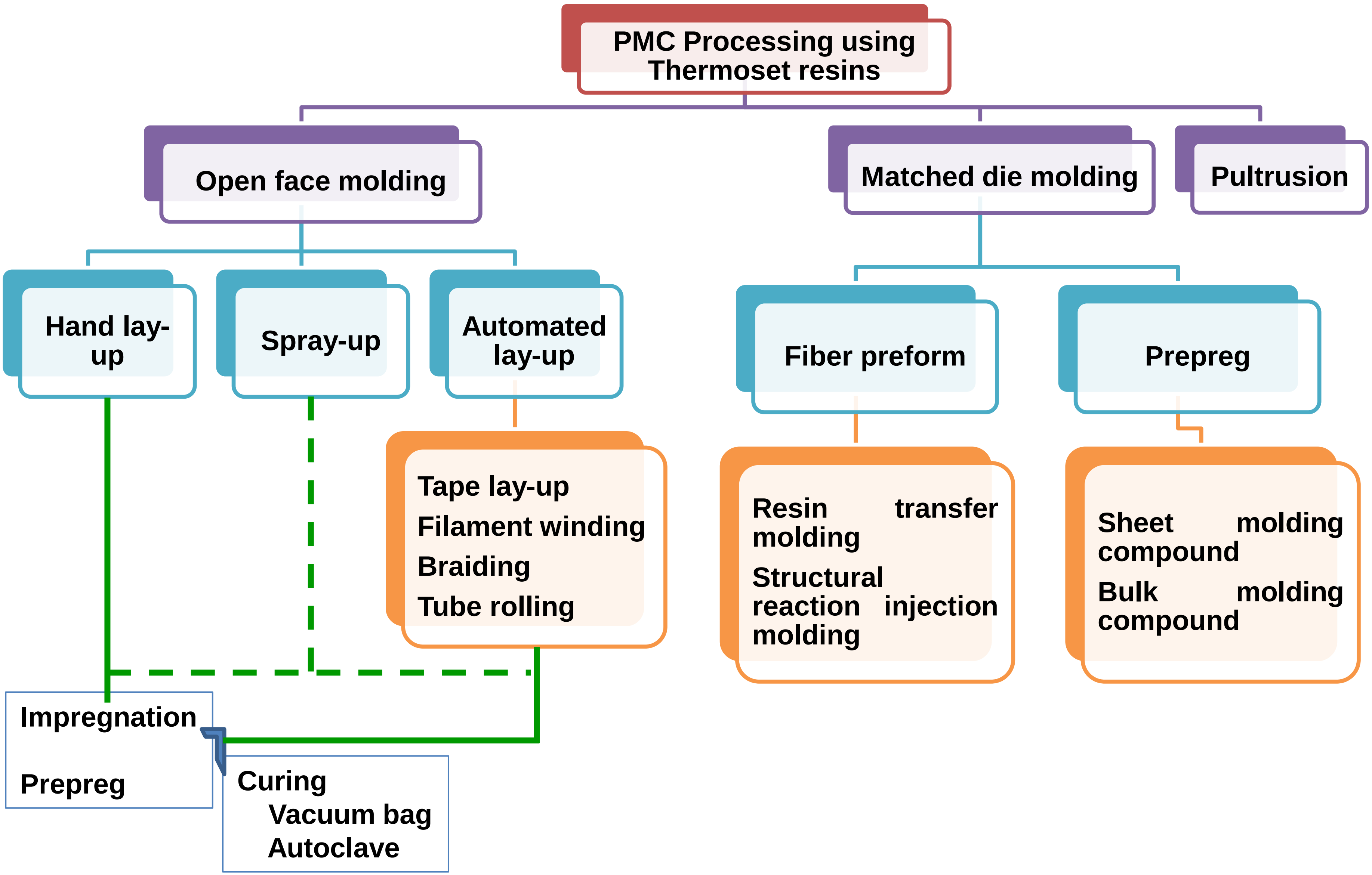
Polymer Matrix Composites

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

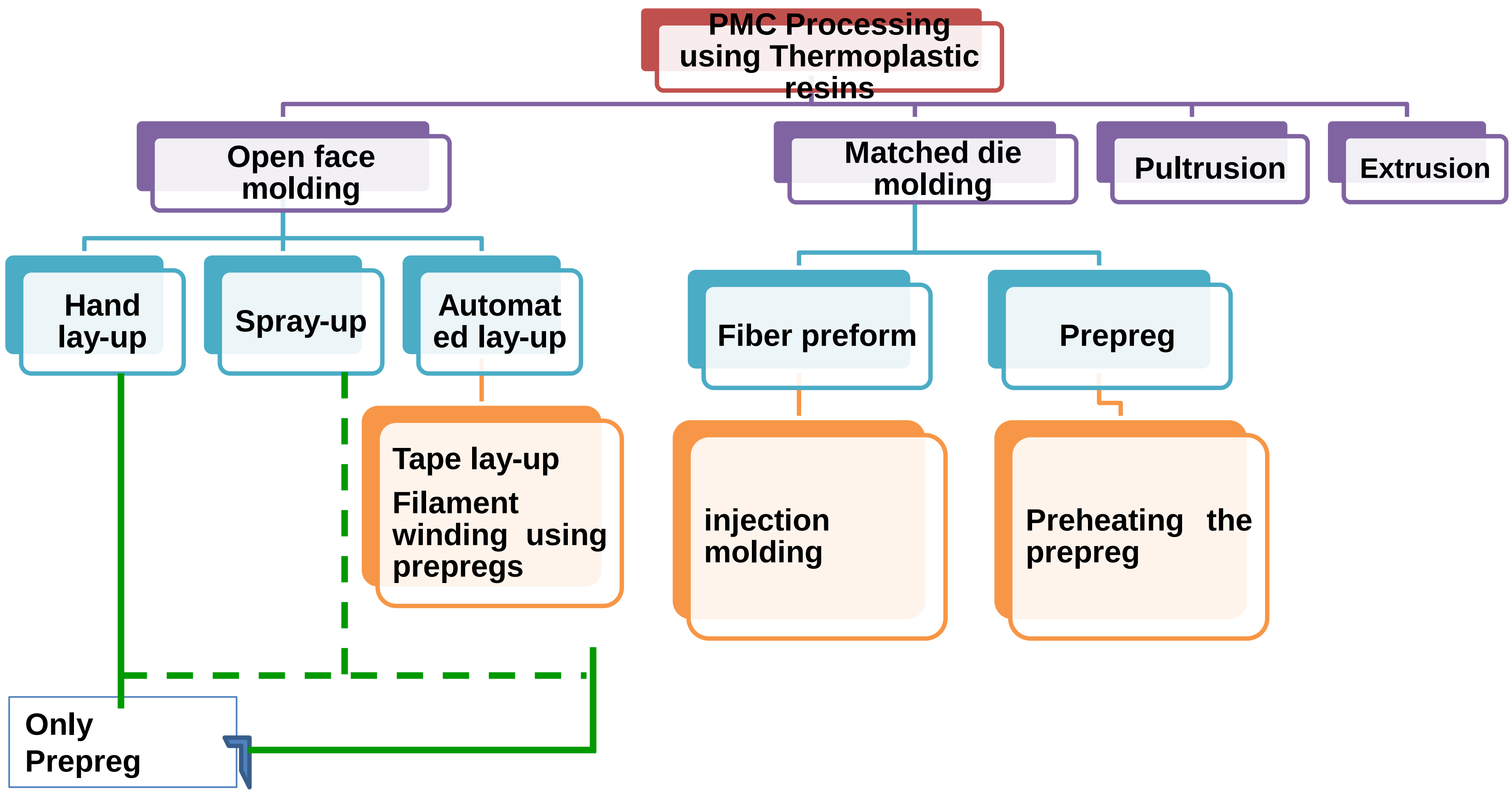
Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughened thermoset	↑	↓	↑	↑	↓
Lightly crosslinked thermoplastic	↑	↓	↑	↑	↓
Thermoplastic	High	Low	Low	Low	High

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

Polymer Matrix Composites



Polymer Matrix Composites



Polymer Matrix Composites

Table 3-1 .—Production Techniques for Polymer Composites

Technique	Characteristics	Examples
Sheet molding	Fast, flexible, 1-2” fiber	SMC automotive body panels
Injection molding	Fast, high volume very short fibers, thermoplastics	Gears, fan blades
Resin transfer molding	Fast, complex parts, good control of fiber orientation	Automotive structural panels
Prepreg tape lay-up	Slow, laborious, reliable, expensive (speed improved by automation)	Aerospace structures
Pultrusion	Continuous, constant cross-section parts	I-beams, columns
Filament winding	Moderate speed, complex geometries, hollow parts	Aircraft fuselage, pipes, drive shafts
Thermal forming (future)	Reinforced thermoplastic matrices; fast, easy repair, joining	All of above

SOURCE: Office of Technology Assessment, 1988.

Polymer Matrix Composites

Hand Lay-Up

Hand lay-up molding is the method of laying down fabrics made of reinforcement and painting with the matrix resin layer by layer until the desired thickness is obtained. This is the most time and labor consuming, composite processing method but majority of aerospace composite products are made by this method in combination with the autoclave method. Due to the hand assembly involved in the lay-up procedure, one can align long fibers with controlled orientational quality. Another advantage of this method is the ability to accommodate irregular-shaped products. Such advantages are utilized in low performance composites including fiber-glass boat and bath tub manufacturing.

Hand lay-up is the oldest and simplest method used for producing reinforced plastic laminates. Capital investment for the hand lay-up processes is relatively low. The most expensive piece of equipment typically is a spray gun for resin and gel coat application. Some fabricators pour or brush the resin into the molds so that a spray gun is not required for this step. There is virtually no limit to the size of the part that can be made. The molds can be made of wood, sheet metal, plaster, and FRP composites.

Polymer Matrix Composites

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, pick-up truck canopies
- The method is quite simple, the resin and reinforcement is placed against the surface of an open (one sided) mold and allowed to cure or in the case of spray-up the resin/reinforcement is sprayed onto the mold with a spray gun
- 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

Polymer Matrix Composites

Hand Lay-Up

- The pros of this process include: low initial start up cost, easy to change mold/design, on-site production possible (ie portable process)
- The cons include: labor intensive, the quality of parts depends on operator's skill and therefore inconsistent, only one good side to the part



Polymer Matrix Composites

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.

Polymer Matrix Composites

Spray-up Molding

Fibers are chopped, coated with resin and sprayed onto the mold

Polymer Matrix Composites

Spray-up Molding

Advantages:

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

Disadvantages:

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

Polymer Matrix Composites

Prepreg

Prepreg can be used in a few different ways

- It can be placed against a mold similar to the hand lay-up method
- Once placed in the mold the material must be compressed and cured according to a specific pressure/temperature cycle
- This is often done by means of a vacuum bag where a thin plastic cover is secured overtop of the composite and the air is vacuumed out
- This process can reduce manufacturing time and produce a stronger part (if a knitted preform is used)
- Another process used is ‘automated tape lay-up’
- This process uses a large automated roller similar to a packing tape roller
- The roller applies the tape with pressure which eliminates the need for a vacuum bag
- Automated tape lay-up is used to produce large parts, generally in aerospace applications and is also capable of 3-d parts

Polymer Matrix Composites

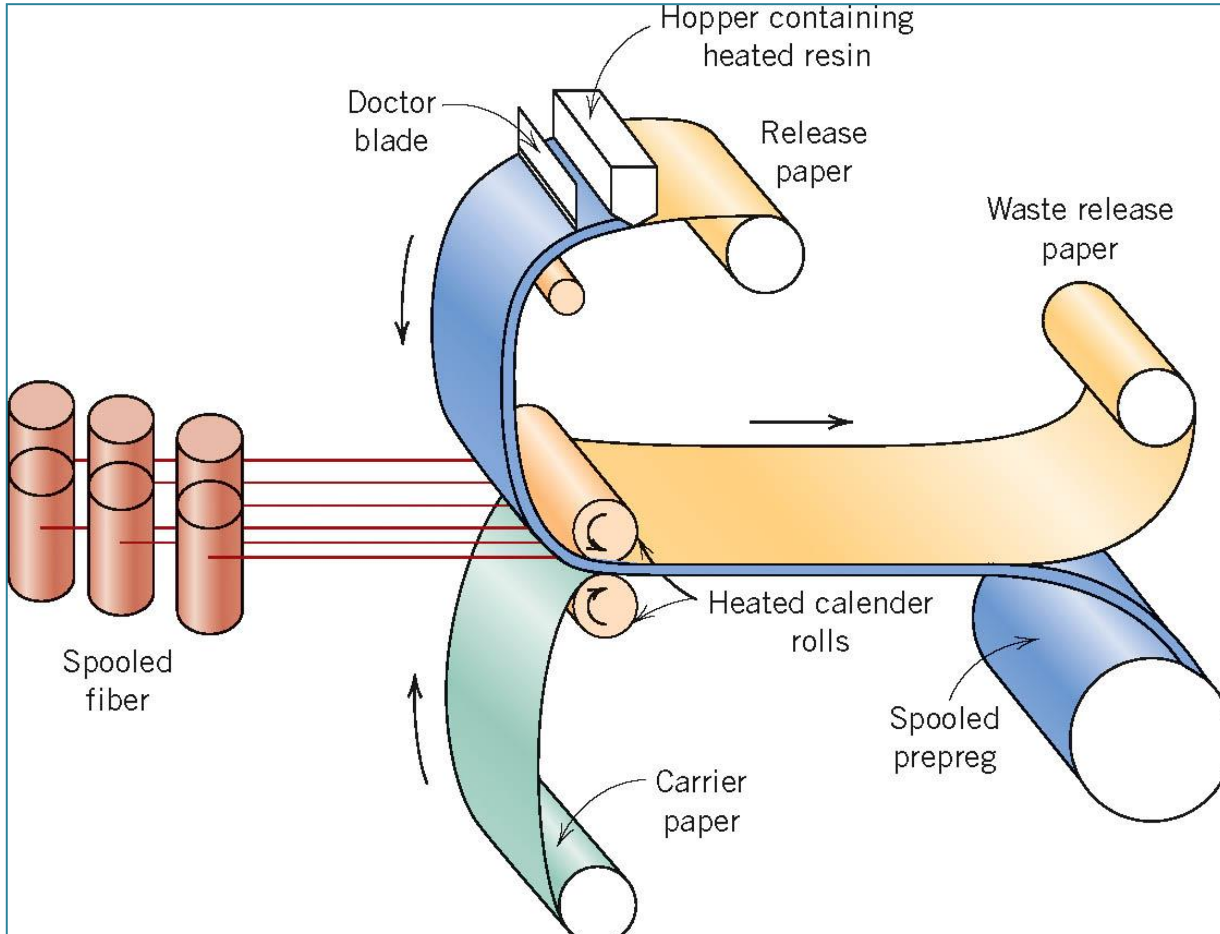
Prepreg

- A pregreg (short for preimpregnated) is a composite that comes with the resin already added to the reinforcement
- This means that the only concern when working with prepreg is shaping the part
- Since the resin is already mixed (resin and catalyst) there is a limited shelf life
- For the same reason prepreg must be cured in an oven or autoclave

Polymer Matrix Composites

Prepreg

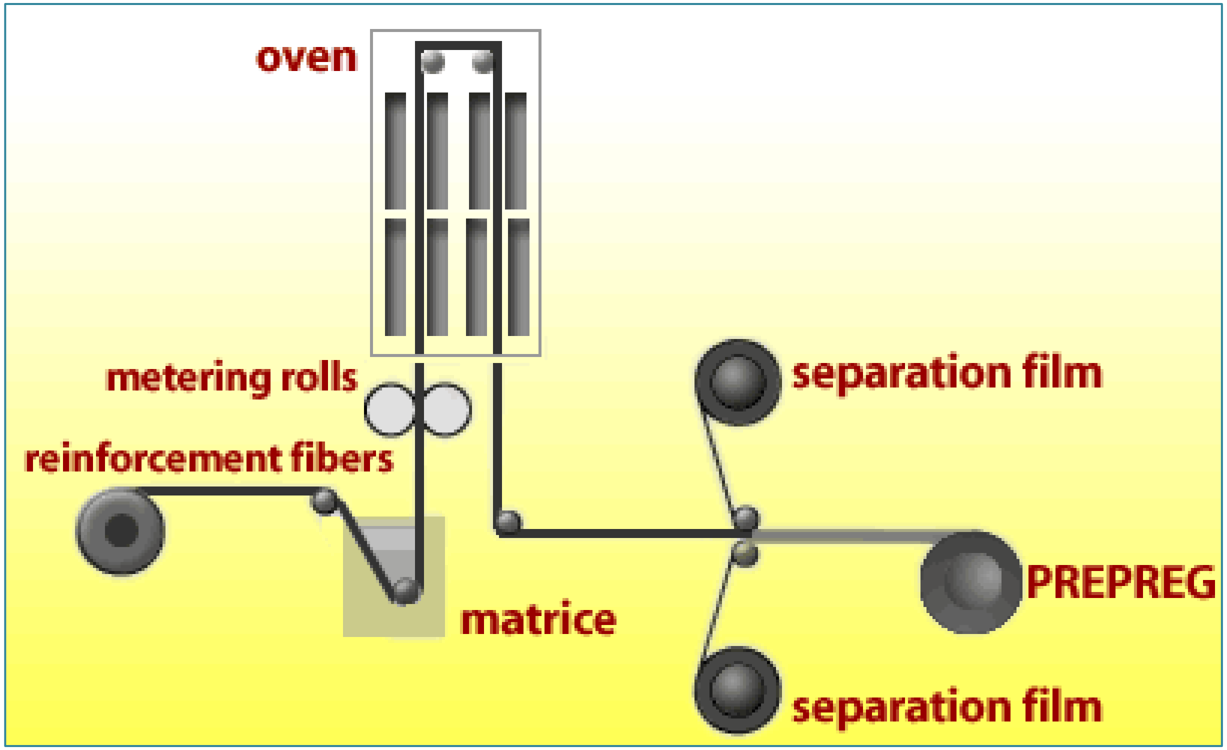
- Prepreg is the composite industry's term for continuous fiber reinforcement pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite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



Polymer Matrix Composites

- 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 assure thorough impregnation of the fibers.

Prepreg



Polymer Matrix Composites

Prepreg

- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin
- 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%

Polymer Matrix Composites

Prepreg

Advantages:

- orientation of fibers can be changed
- consistent
- high productivity

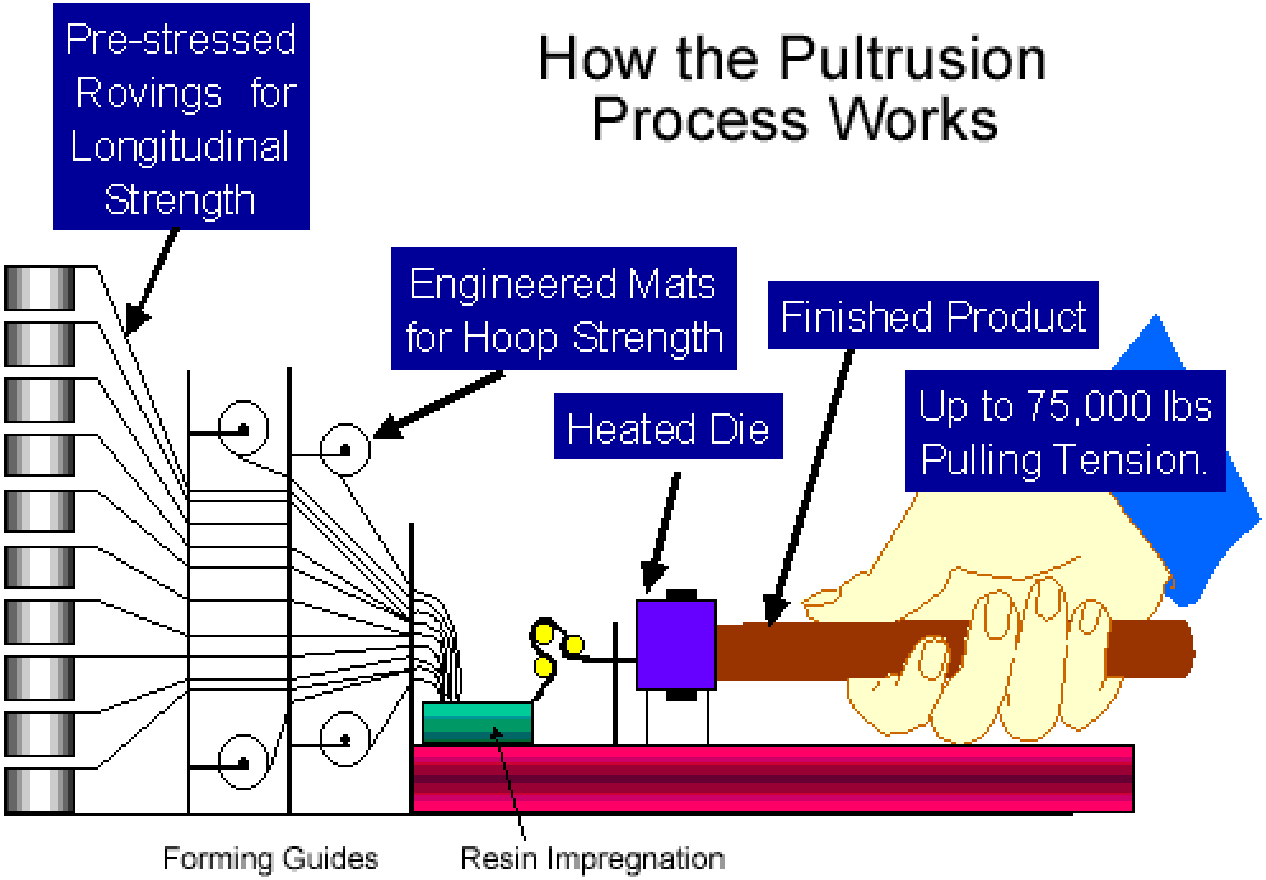
Disadvantages:

- continuous process needs work
- limited shelf life
- delamination

Processing of PMCs

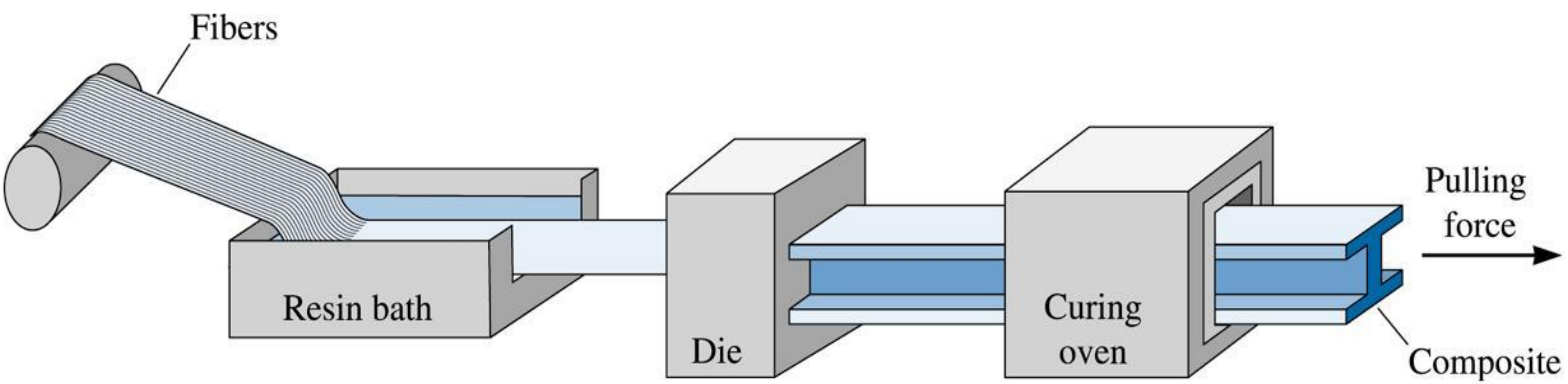
Pultrusion

- Similar to extrusion of metal parts
- Pultrusion involves pulling resin-impregnated glass strands through a die
- Standard extruded shapes can easily be produced such as pipes, channels, I-beams, etc.



Processing of PMCs

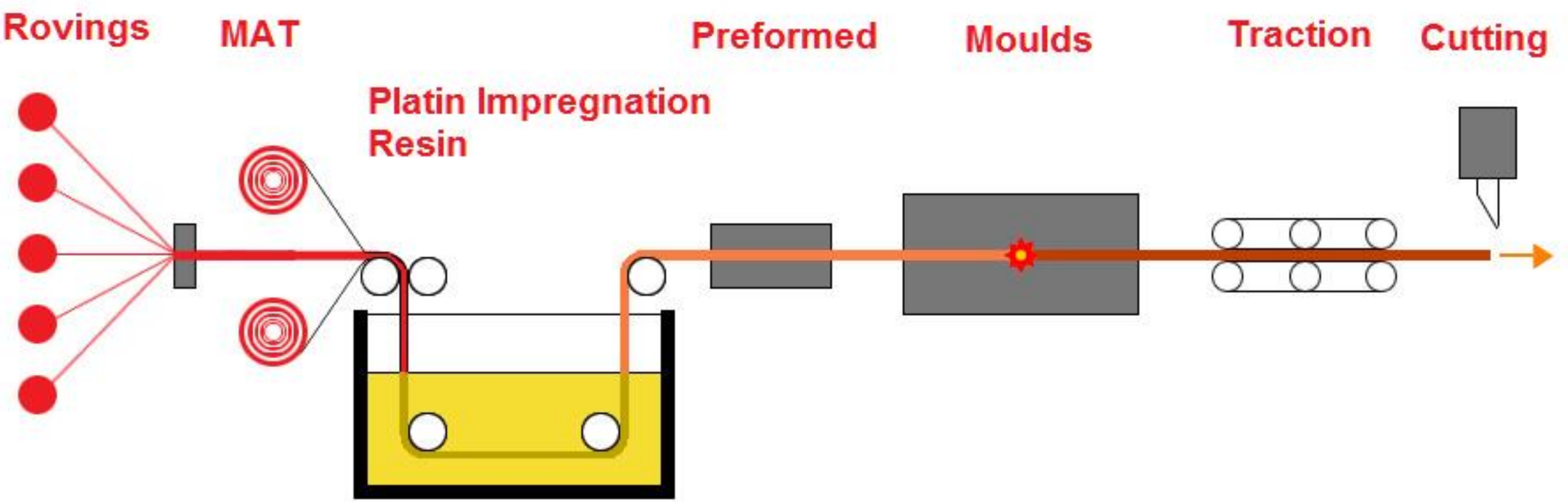
Pultrusion



Producing composite shapes by pultrusion.

Processing of PMCs

Pultrusion



Processing of PMCs

Pultrusion

Advantages:

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

Disadvantages:

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

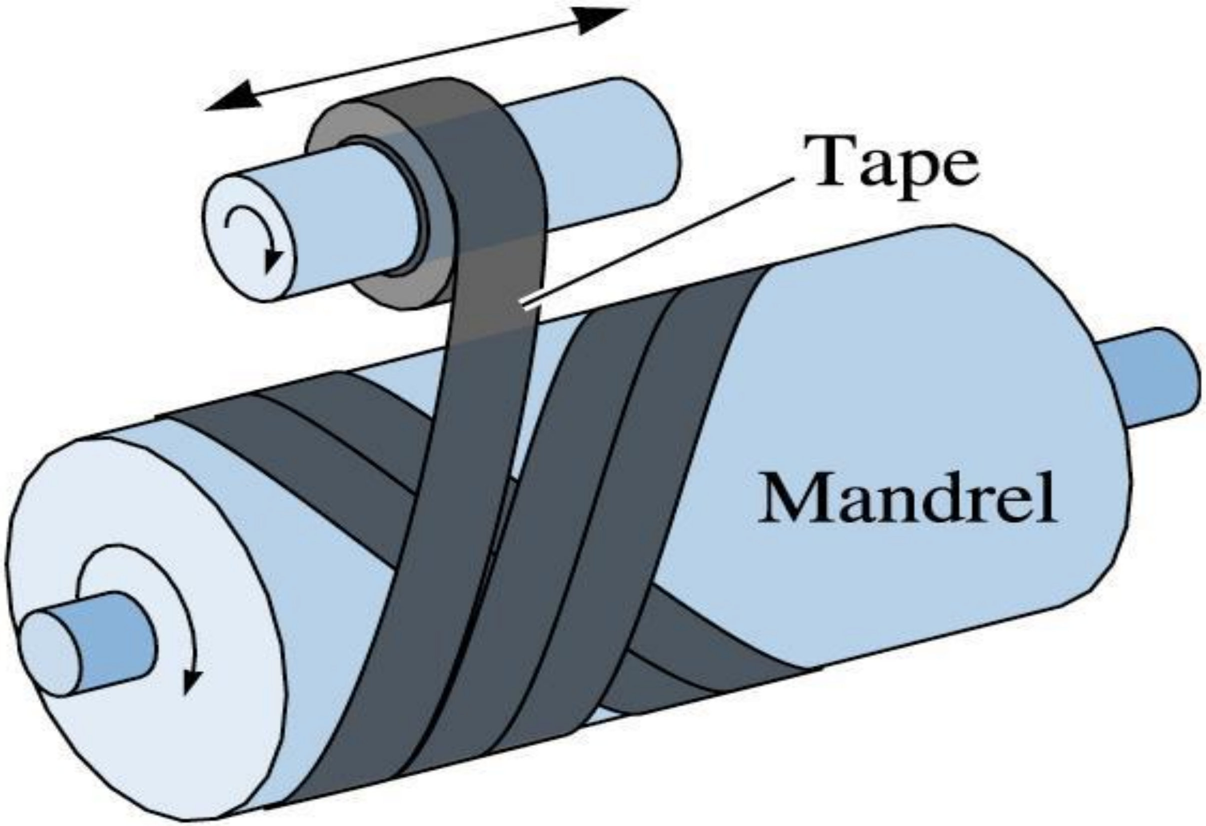
Processing of PMCs

Filament Winding

- A continuous reinforcement, either previously impregnated or impregnated during winding is wound around a rotating mandrel to form a composite part
- 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 (only cylindrical possible), curing by heat is not easy to apply, spinning speed is limited due to resin penetration and splashing, traveler speed and yarn breakage.
- Examples: oxygen bottles for firemen, rocket motors, tennis rackets, shafts

Processing of PMCs

Filament Winding

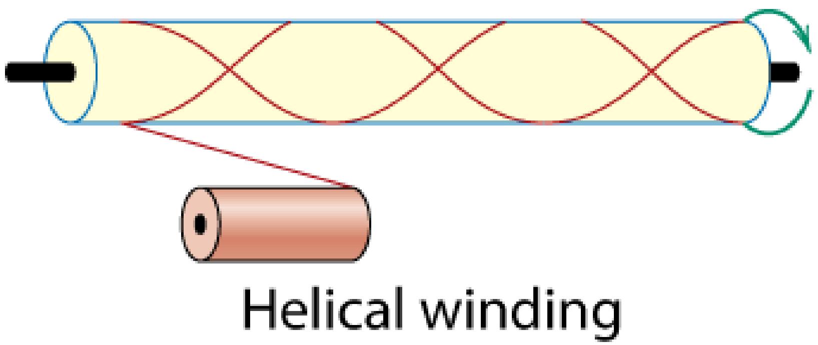


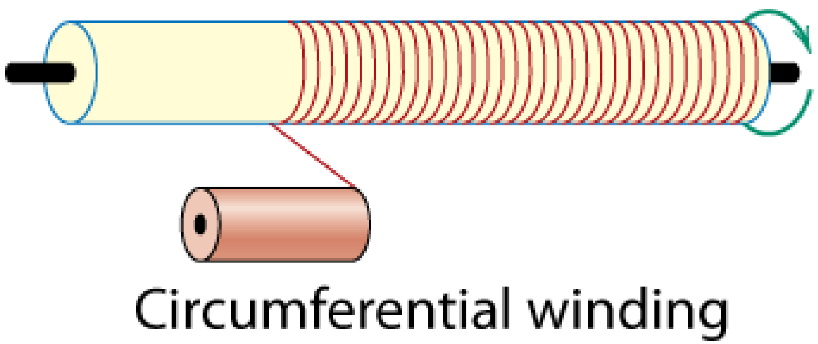
Producing composite shapes by filament winding.

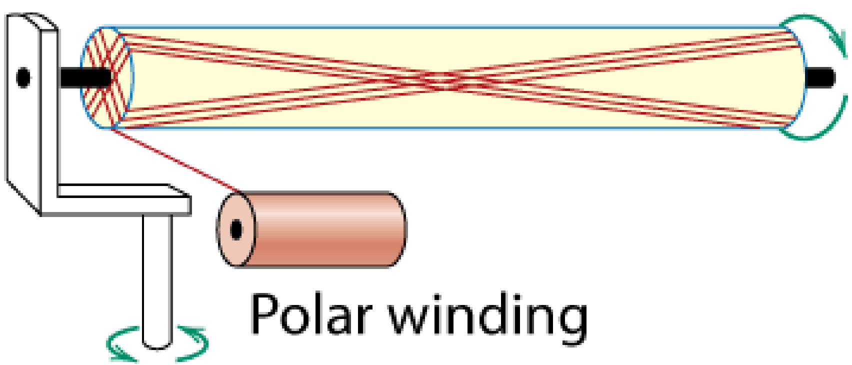
Processing of PMCs

Filament Winding

- Ex: pressure tanks
- Continuous filaments wound onto mandrel







from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.

Processing of PMCs

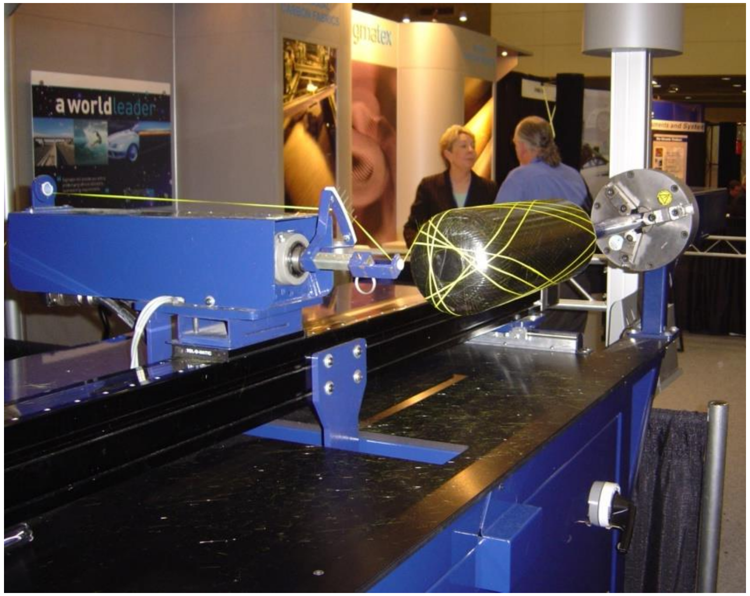
Filament Winding

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

Processing of PMCs

Filament Winding

- Filament winding and fiber placement
  - Fiber placement has greater accuracy
  - Fiber placement can wind on less symmetrical and even partially concave mandrels
- Tubes, tanks, wind turbine blades and rockets

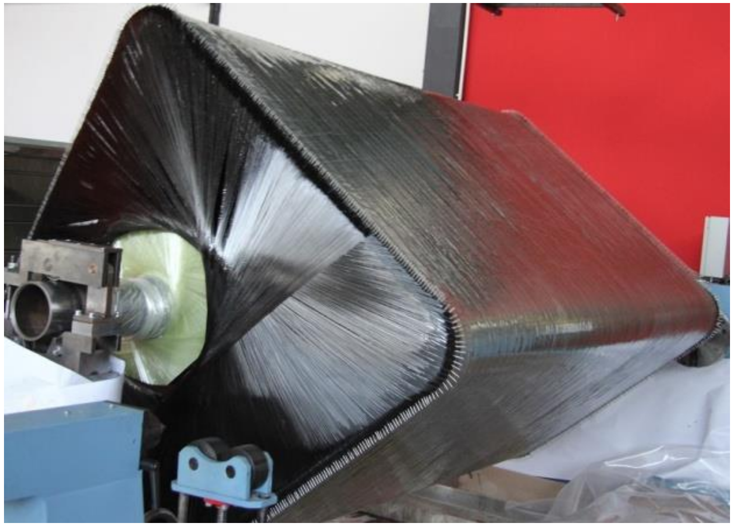


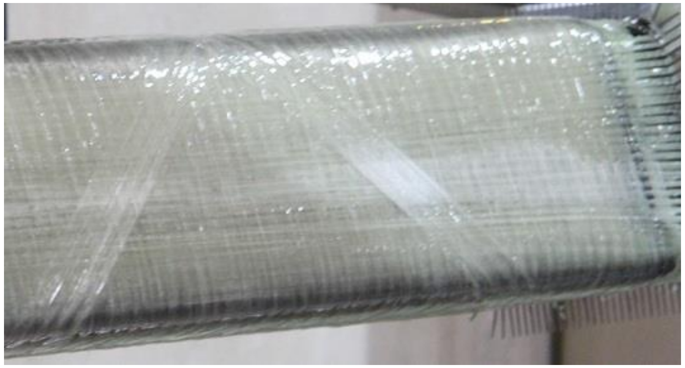
Processing of PMCs

Filament Winding

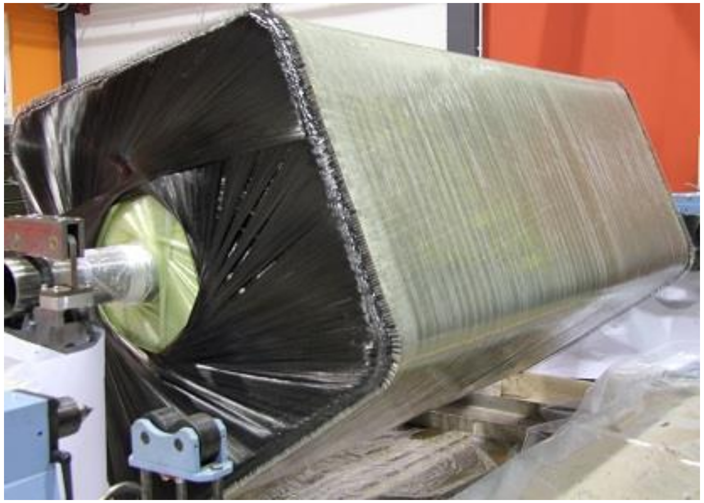
Winding process is defined with basic parameters for winding, like angle type, number of cycles, cycle length, layers length, number of tows, etc.

Winding with carbon fiber





Winding with glass fiber



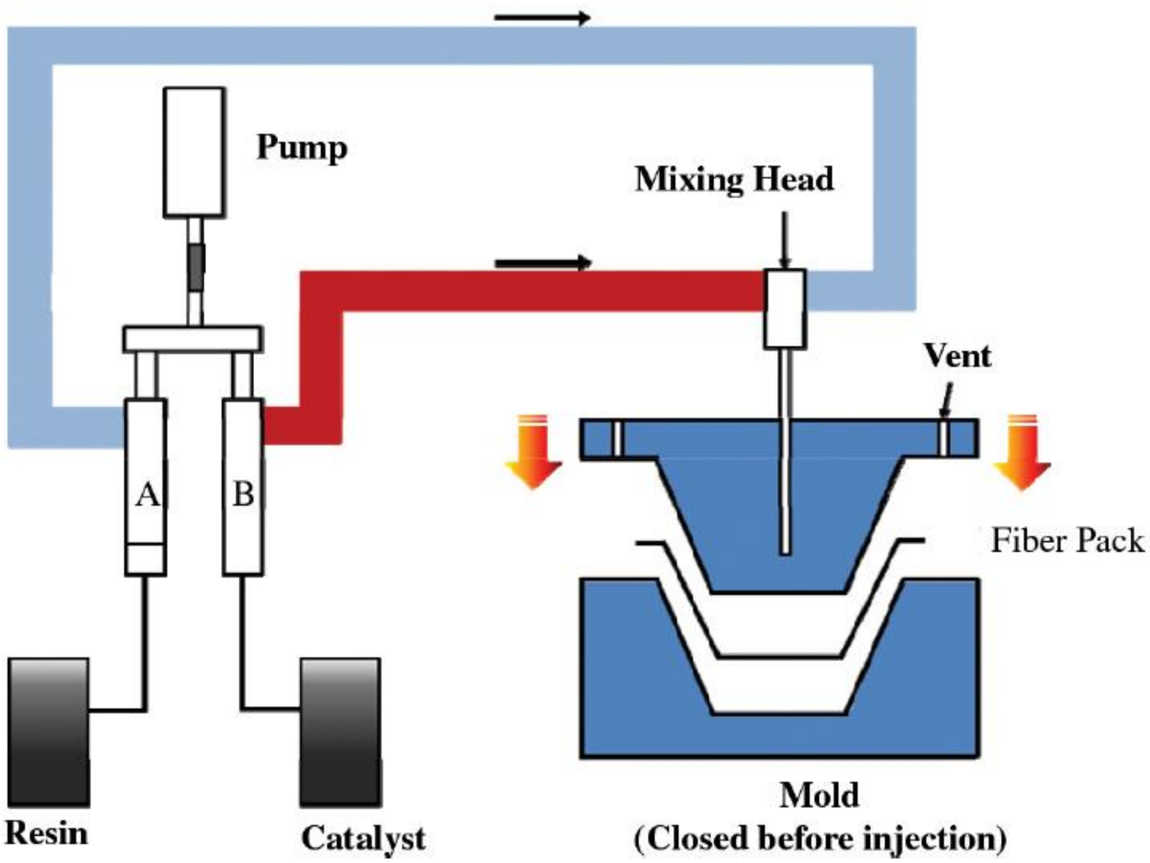
Processing of PMCs

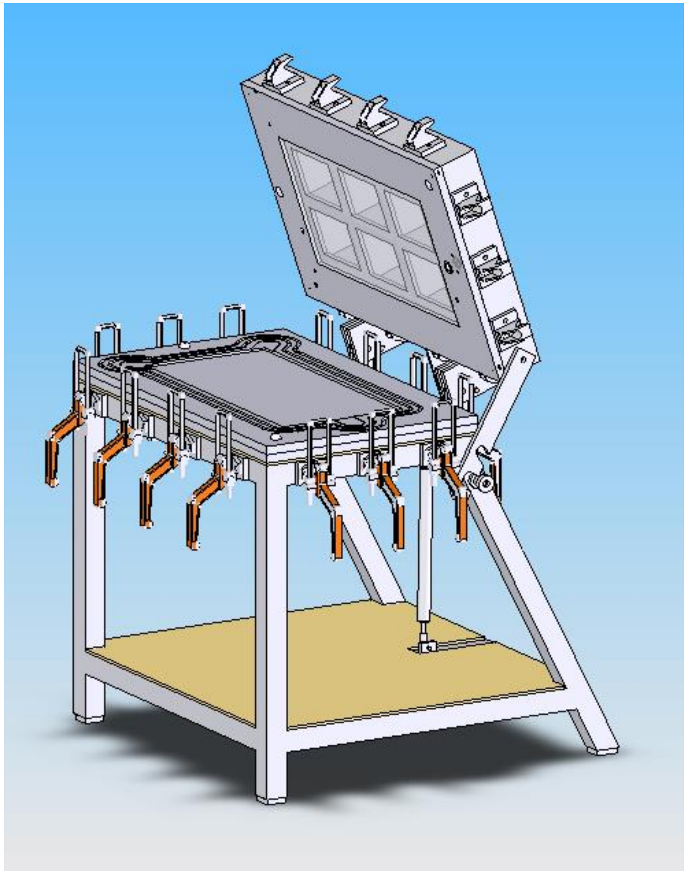
Resin Transfer Molding

- Resin transfer molding is a manufacturing method that is quite similar to injection molding where plastic is injected into a closed mold.
- In the RTM process the preform (precut piece(s) of reinforcement) is placed in the mold, the mold is closed and the thermoset plastic matrix is injected into the mold, once the matrix is cured the part is ejected.

Processing of PMCs

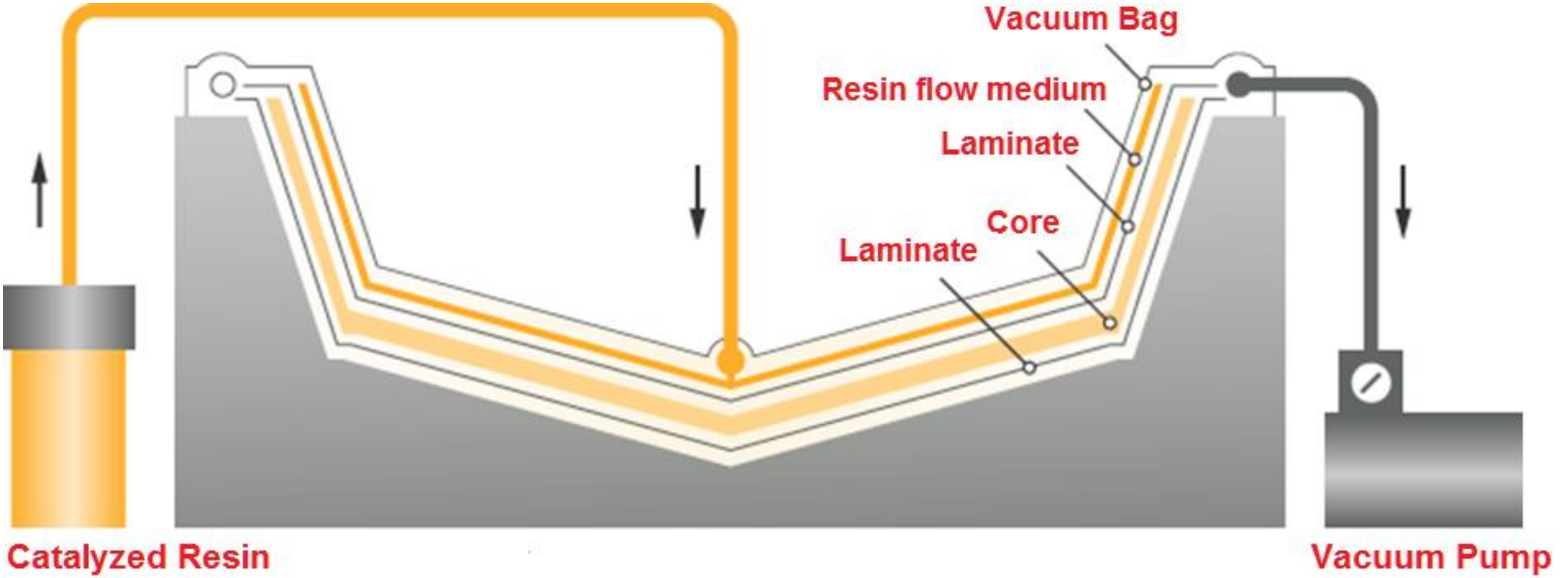
Resin Transfer Molding





Processing of PMCs

Vacuum Assisted Resin Transfer Molding



http://www.futuremediacreations.com/technoire/vartm.htm

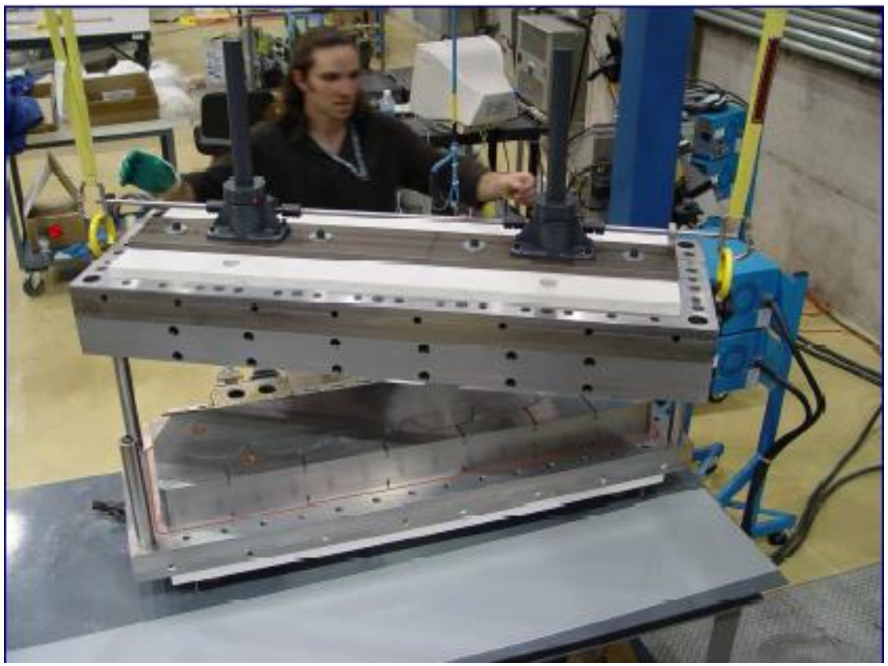
Processing of PMCs

Resin Transfer Molding (RTM)

Pros	Cons
1. As a closed mold process, emissions are lower than open mold processes such as spray up or hand lay up. 2. The mold surface can produce a high quality finish (like those on an automobile). 3. This process can produce parts faster as much as 5-20 times faster than open molding techniques. 4. Resin transfer molding produces tighter dimensional tolerances to within 0.005 inch. 5. Complex mold shapes can be achieved. Cabling and other fittings can be incorporated into the mold designs.	1. High production volumes required to offset high tooling costs compared to the open molding techniques. 2. Reinforcement materials are limited due to the flow and resin saturation of the fibers. 3. Size of the part is limited by the mold.

Processing of PMCs

Resin Transfer Molding

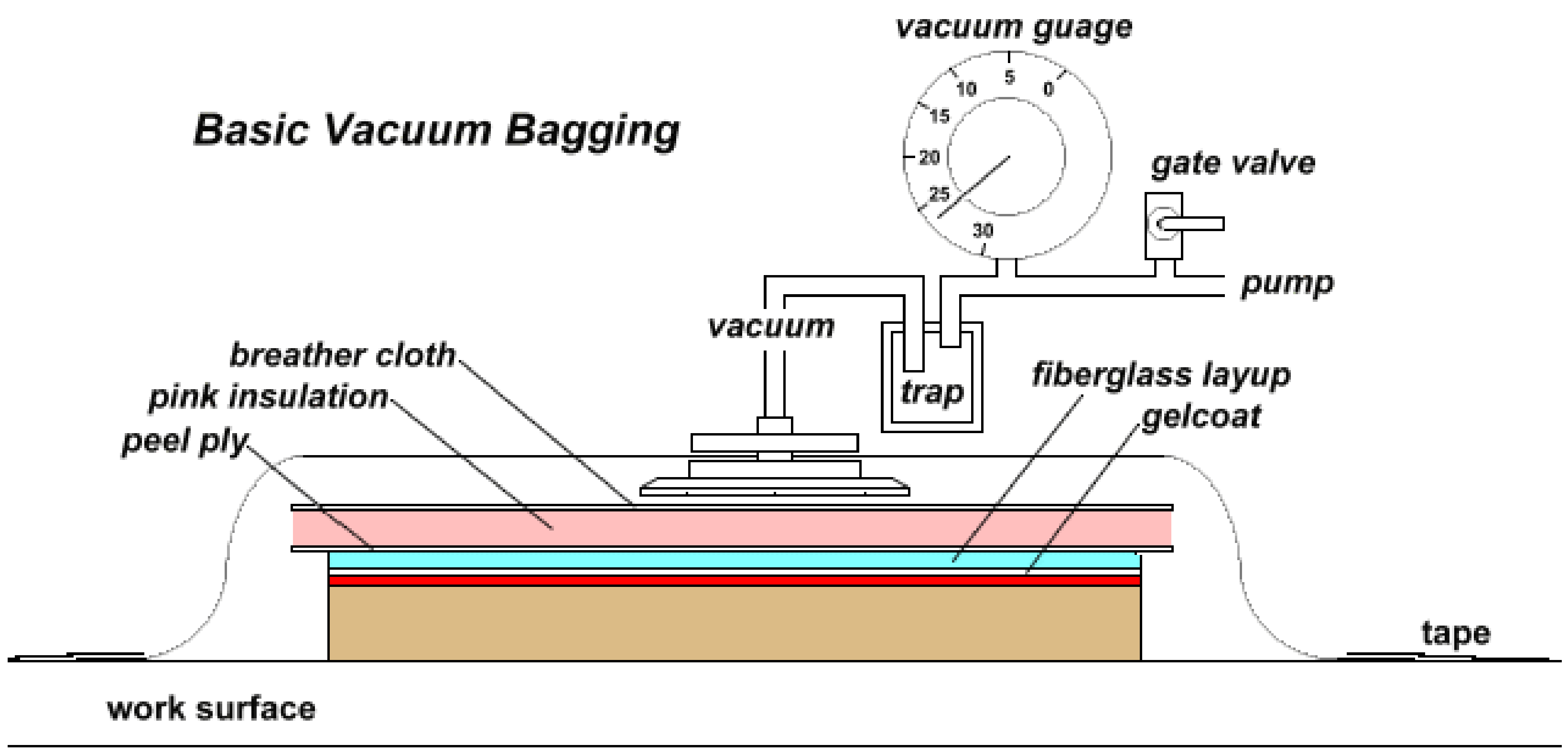


Researcher from Aerospace Manufacturing Technology Center in Montreal molding members for a helicopter

Processing of PMCs

Vacuum Bagging

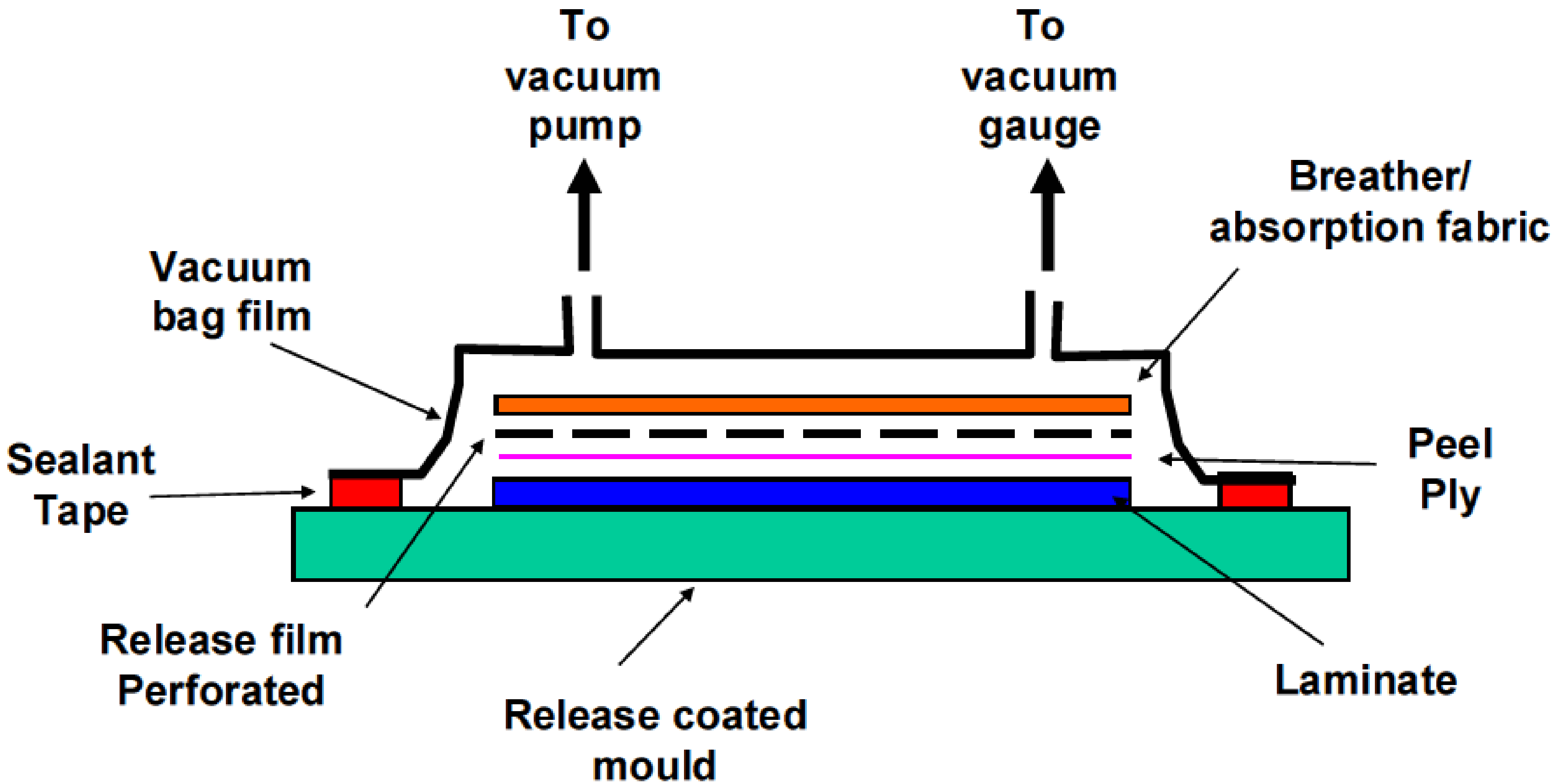
- Provides increased part consolidation
- Reduces matched die mold costs



Processing of PMCs

Vacuum Bagging

Applications:
Large, one-off cruising boats, racecar components, core-bonding in production boats



Processing of PMCs

Vacuum Bagging

Advantages:

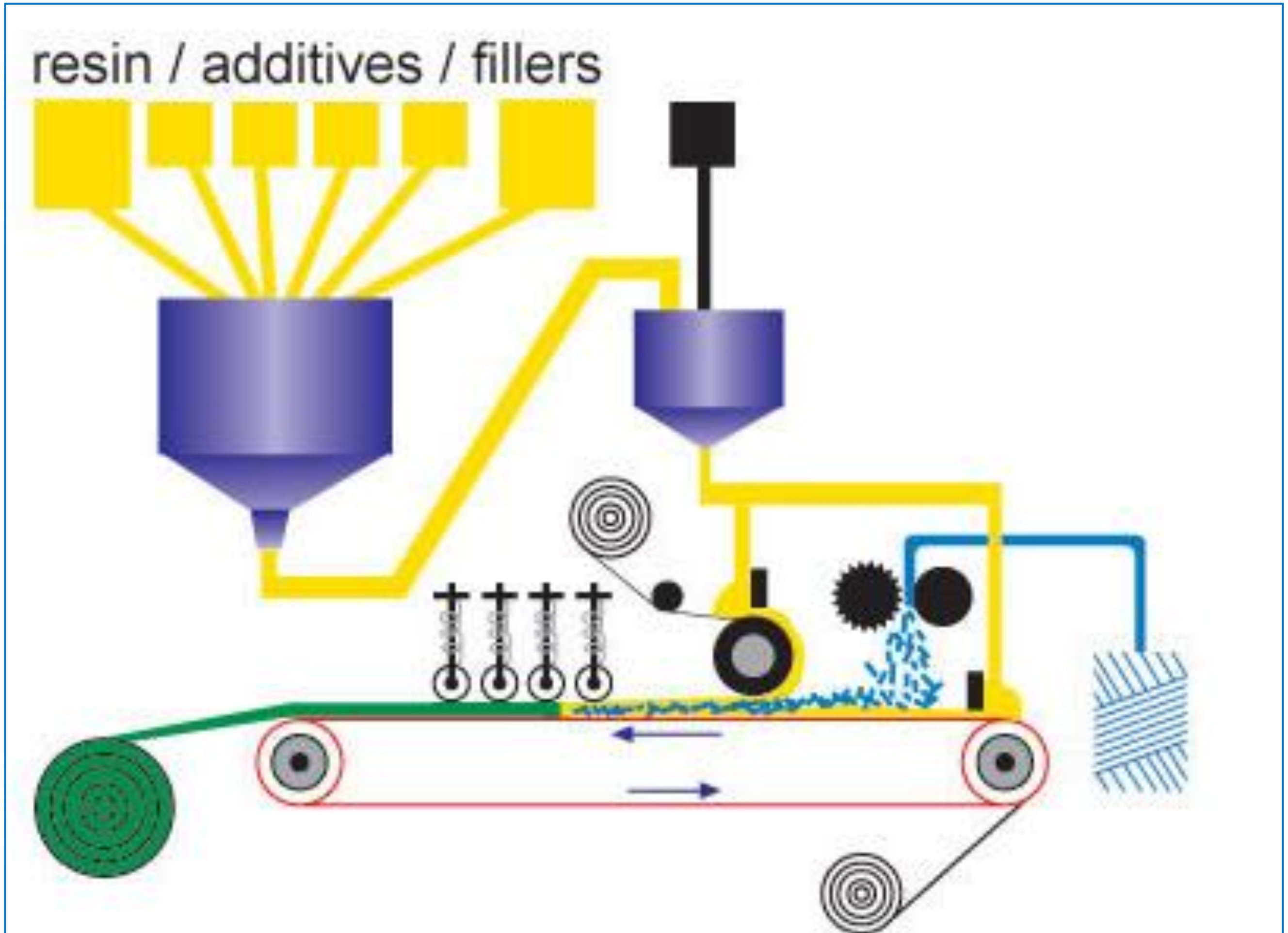
- simple design
- any fiber/matrix combination
- ok with cheap mold material
- better quality for the cost

Disadvantages:

- cannot be heated up too much
- breather clothe has to be replaced frequently
- low pressure (760 mm Hg the most)
- slowest speed
- inconsistency

Processing of PMCs

Sheet Molding



Processing of PMCs

Sheet Molding

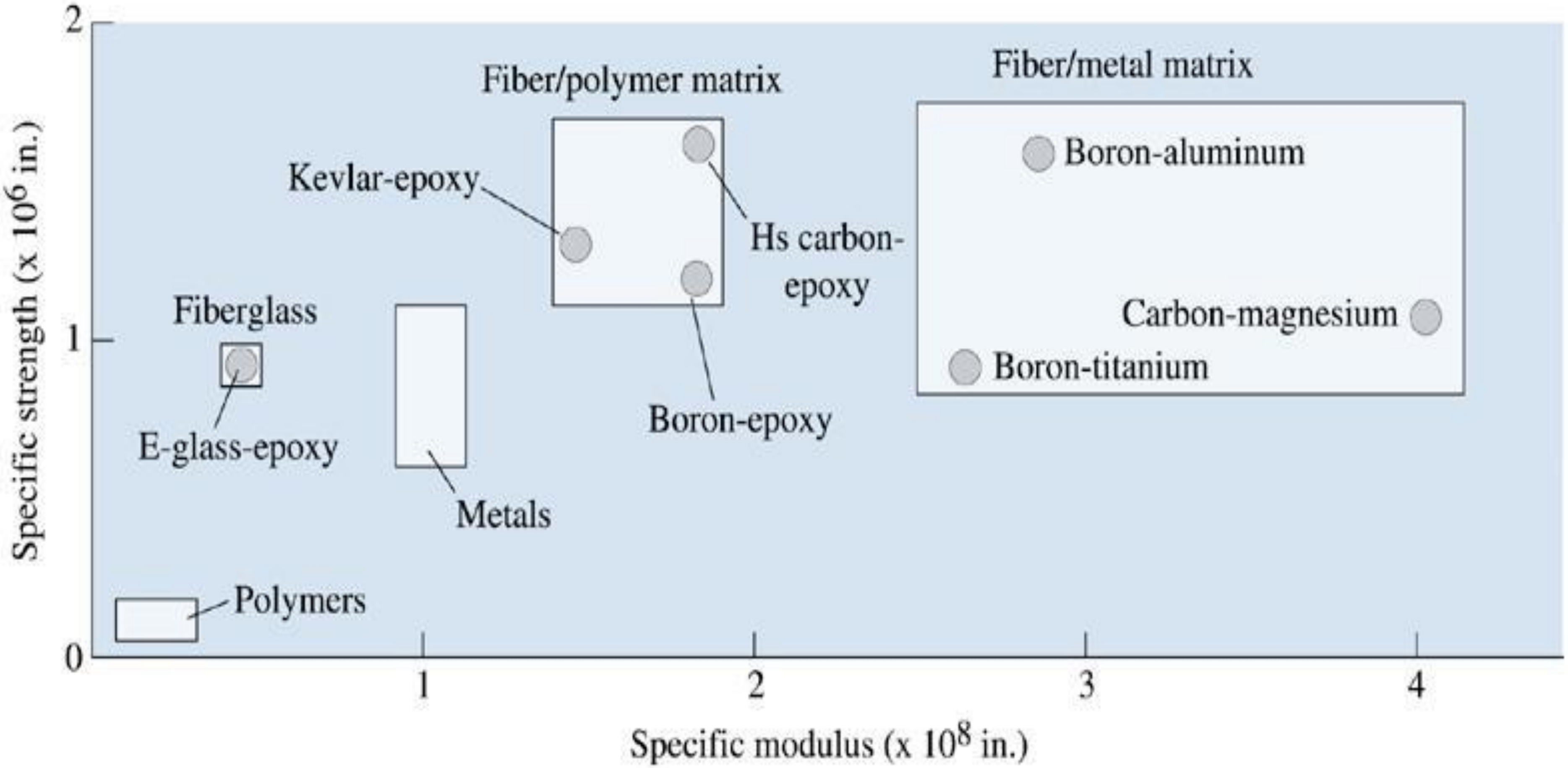
Advantages

- High productivity thus inexpensive
- Consistency

Disadvantages

- Low volume fraction.
- Only board can be made.

Polymer Matrix Composites (PMC)



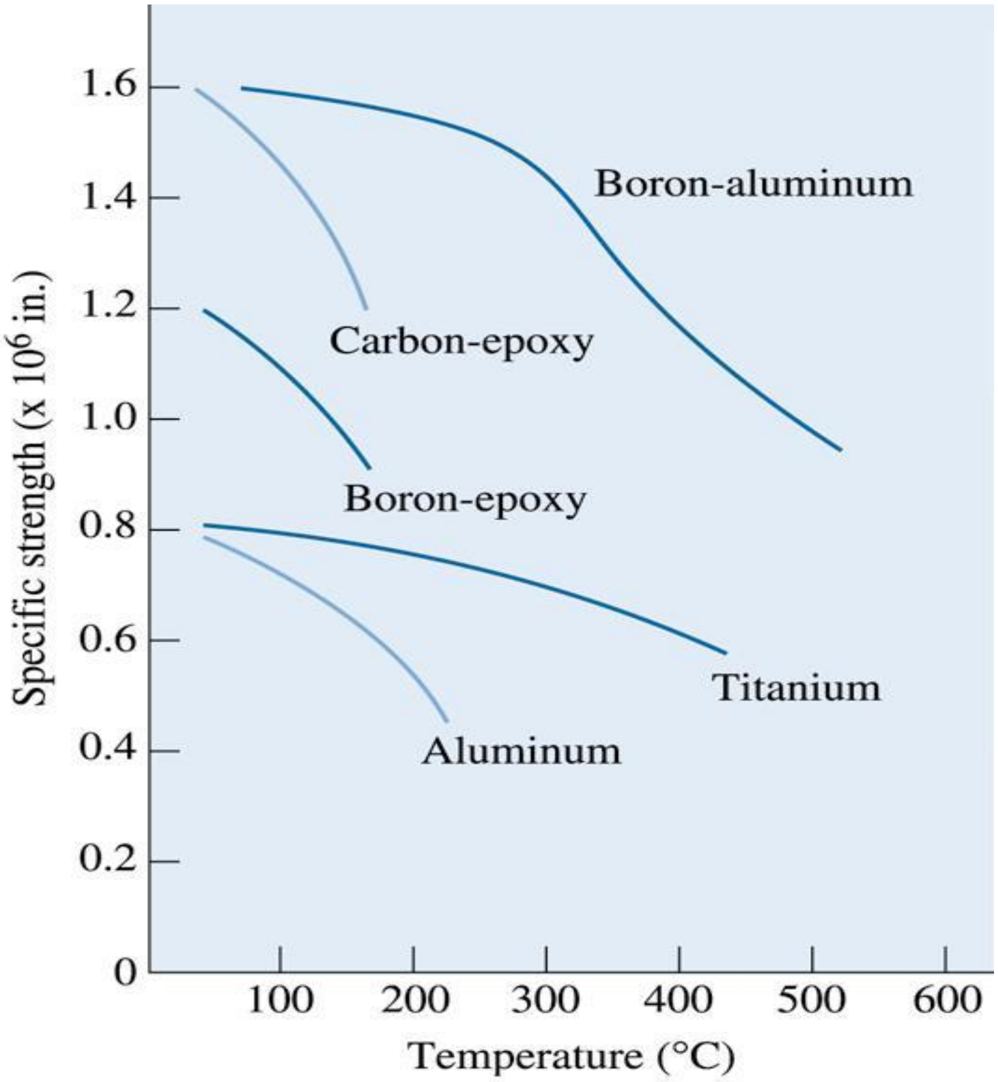
A comparison of the specific modulus and specific strength of several composite materials with those of metals and polymers.

Polymer Matrix Composites (PMC)

TABLE 16-3 ■ ***Examples of fiber-reinforced materials and applications***

Material	Applications
Borsic aluminum	Fan blades in engines, other aircraft and aerospace applications
Kevlar™-epoxy and Kevlar™-polyester	Aircraft, aerospace applications (including space shuttle), boat hulls, sporting goods (including tennis rackets, golf club shafts, fishing rods), flak jackets
Graphite-polymer	Aerospace and automotive applications, sporting goods
Glass-polymer	Lightweight automotive applications, water and marine applications, corrosion-resistant applications, sporting goods equipment, aircraft and aerospace components

Polymer Matrix Composites (PMC)



The specific strength versus temperature for several composites and metals.

Relations between the mechanical properties and structure

Mechanical properties of a metal are obtained using a bar or rod that is pulled in tension

The tensile strength σ, the elastic modulus in the direction of the load E, and the longitudinal strain ϵ_L are obtained from the stress-strain response

$$\sigma = E\epsilon_L$$

The Poisson's ratio is obtained by measuring the contraction strain ϵ_T across the sample

$$\upsilon = -\frac{\epsilon_T}{\epsilon_L}$$

Since the sample contracts, ϵ_T is negative and υ has a positive value less than 1.0

The shear modulus, G is related to E and υ by

$$G = \frac{E}{2 * (1 + \upsilon)}$$

The shear stress τ and shear strain γ are related by G:

$$\tau = G * \gamma$$

Relations between the mechanical properties and structure

In metal systems the material is generally assumed to be linear, isotropic, and elastic such that only a few tests are required to obtain basic tensile stiffness properties

Only two values, the tensile modulus E, and the Poisson's ratio v are required because of the small degree of isotropy or symmetry of the metal microstructure

Metals have an infinite number of symmetry planes

In contrast a material with no symmetry planes requires 21 material properties and extensive testing in order to design a structure

Most composites are developed in two dimensional form and have one plane of symmetry

For example a laminate plane is a unidirectional material and is transversely isotropic

The stress-strain law governing this material is complicated as there are 5 material properties (σ,τ,ε,γ,S)

Stress-strain law for metals: $\sigma = E * \epsilon$

For laminate composite:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} & E_{12} & 0 & 0 & 0 \\ & E_{22} & E_{23} & 0 & 0 & 0 \\ & & E_{22} & 0 & 0 & 0 \\ & & & 2(E_{22}-E_{23}) & 0 & 0 \\ Sym. & & & & E_{66} & 0 \\ & & & & & E_{66} \end{bmatrix} * \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix}$$

Where $E_{22} = E_{33}$, $E_{12} = E_{13} = -E_{11}/\upsilon_{12} = -E_{22}/\upsilon_{21}$,$E_{22} = -E_{22}/\upsilon_{23}$, $\frac{1}{E_{55}} = \frac{1}{E_{66}} + \frac{1}{G_{12}}$

Relations between the mechanical properties and structure

E_{11} is determined from a tensile test conducted in the direction of the fiber orientation
The value of Poisson's ratio, ν_{12} is obtained by measuring the lateral contraction strain

E_{22} is determined by cutting a laminate to pull it in tension transverse to the fiber direction
The value of Poisson's ratio, ν_{21} is obtained by measuring the lateral contraction strain but its value will be much less than ν_{12} due to fiber constraint

Measuring ν_{23} is hard. It is small and usually ignored because most composites are two dimensional (It is the ratio of the strain across the fibers relative to the thickness strain)

The value of G_{12}, the shear modulus is measured using simple circular tubes of the material. The tubes are twisted and the resultant shear stress and strain are determined

Relations between the mechanical properties and structure

The values of longitudinal modulus E_{11}, principle Poisson's ratio ν_{11}, and principle thermal expansion coefficient α_{11} can be expressed in terms of the matrix/fiber properties and the volume fraction of the respective ingredients according to the rule of mixtures:

$$E_{11} = V_f * E_f + V_m * E_m$$
$$\nu_{11} = V_f * \nu_f + V_m * \nu_m$$
$$\alpha_{11} = V_f * \alpha_f + V_m * \alpha_m$$

Certain assumptions are made to relate the microstructure of the ingredients to these properties:

- The composite ply is macroscopically homogeneous and linearly elastic
- The fibers are linearly elastic and homogeneous
- The matrix is linearly elastic and homogeneous
- Both the fiber and the matrix are free of voids
- The interface is completely bonded and there is no interphase between the matrix and reinforcement
- The mechanical properties of the individual constituents are the same whether they are made before or during the composite manufacturing process

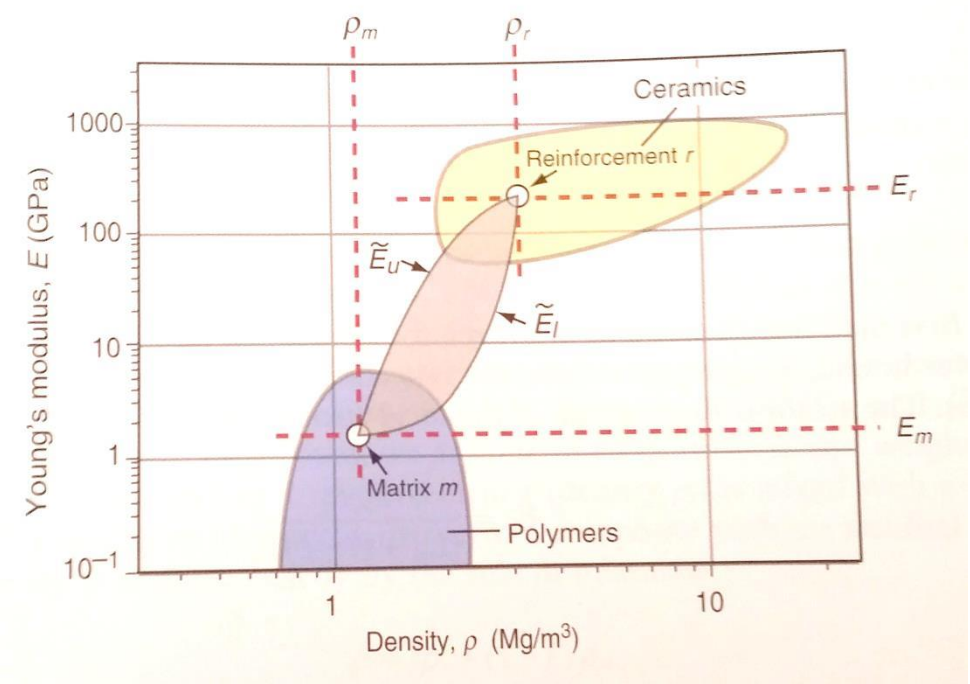
Relations between the mechanical properties and structure

The upper bound is found by assuming that the two components strain by the same amount, like springs in parallel

$$E_{11} = V_f * E_f + V_m * E_m$$

The lower bound is found by assuming that the two components carry the same stress, like springs in series

$$E_{11} = \frac{E_f * E_m}{V_f * E_f + V_m * E_m}$$

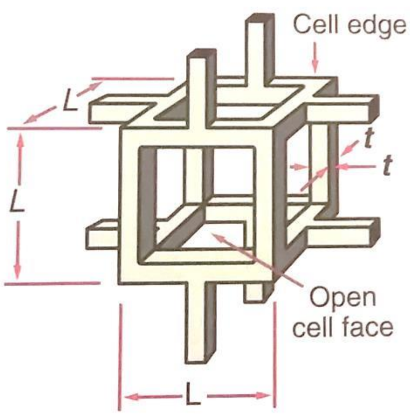


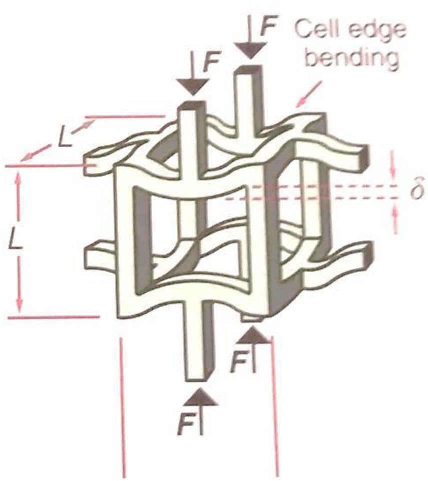
Relations between the mechanical properties and structure

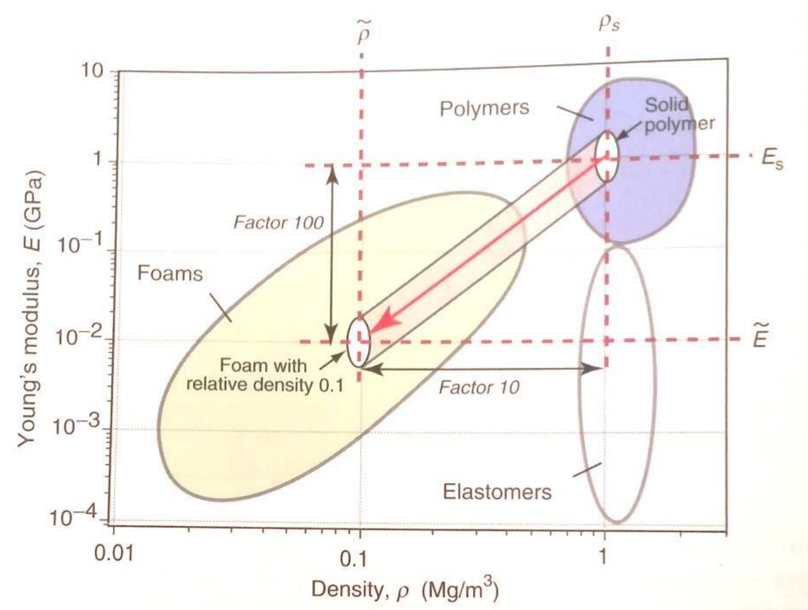
Cellular solids are characterized by their relative density, the fraction of the foam occupied by the solid

$$\frac{\rho_{foam}}{\rho_s} = \left(\frac{t}{L}\right)^2$$

$$\frac{E_{foam}}{E_s} = \left(\frac{\rho_{foam}}{\rho_s}\right)^2$$







Relations between the mechanical properties and structure

In a composite material with a metal matrix and ceramic fibers, the bulk of the energy would be transferred through the matrix.

In a composite consisting of a polymer matrix containing metallic fibers, the energy would be transferred through the fibers.

When the fibers are not continuous or unidirectional, the simple rule of mixtures may not apply.

For example, in a metal fiber-polymer matrix composite, coefficient of thermal expansion would be low and would depend on the length of the fibers, the volume fraction of fibers and how often the fibers touch one another.

Example – You have a unidirectional, graphite/epoxy composite with the following constituent properties and 65% volume loading of fiber:

E_f = 43 GPa

E_m = 0.5 GPa

ν_f = 0.2

ν_m = 0.4

$\alpha_f = 1.5*10^{-6}$/K

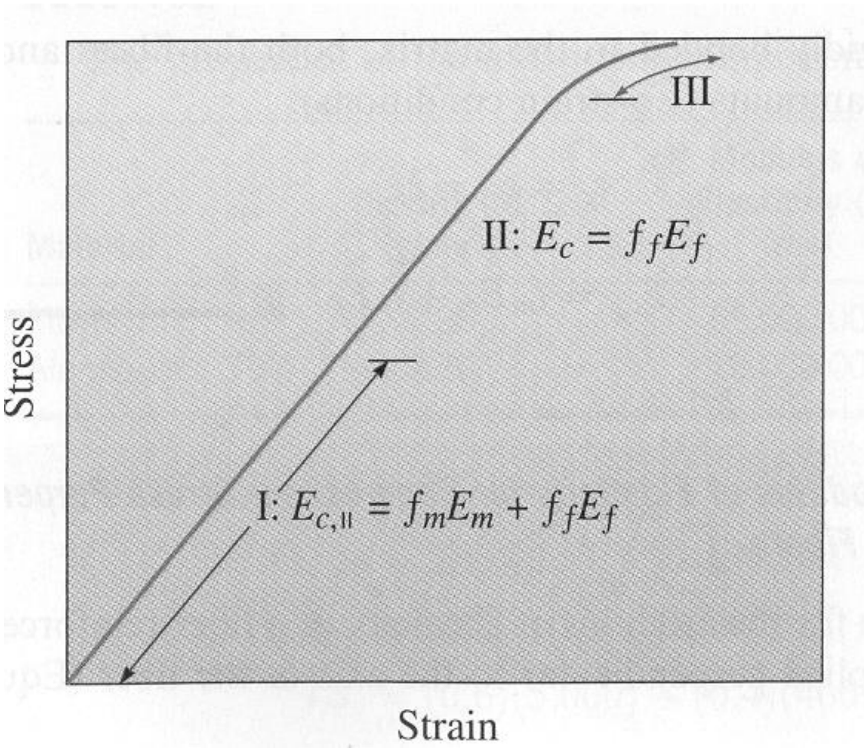
$\alpha_f = 40*10^{-6}$/K

Calculate the E_{11}, ν_{11}, and α_{11} using the rule of mixtures

RULE OF MIXTURES

Parallel to the fibers, the modulus of elasticity may be as high as:

$$E_c = f_m E_m + f_f E_f$$



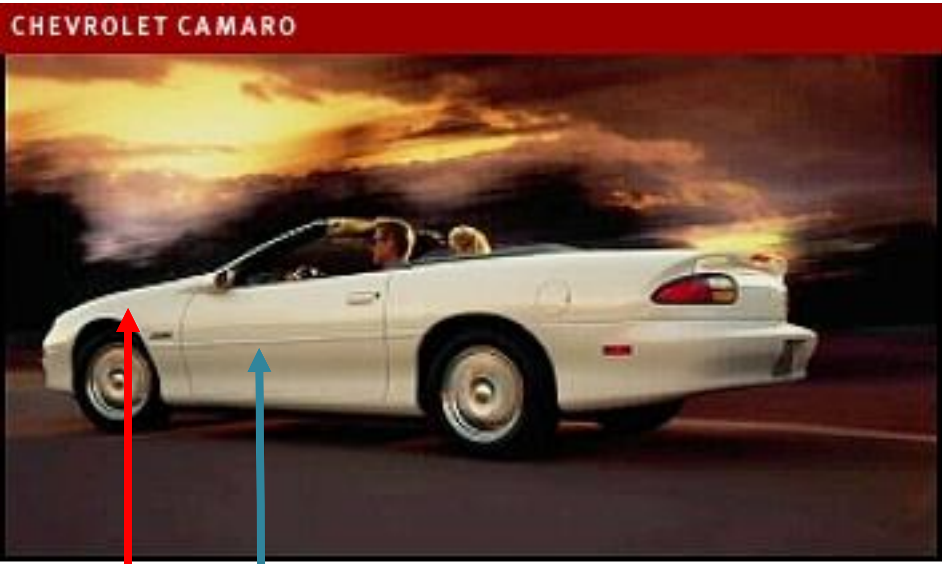
However, when the applied load is very large, the matrix begins to deform and the stress-strain curve is no longer linear. Since the matrix now contributes little to the stiffness, the modulus is approximated by:

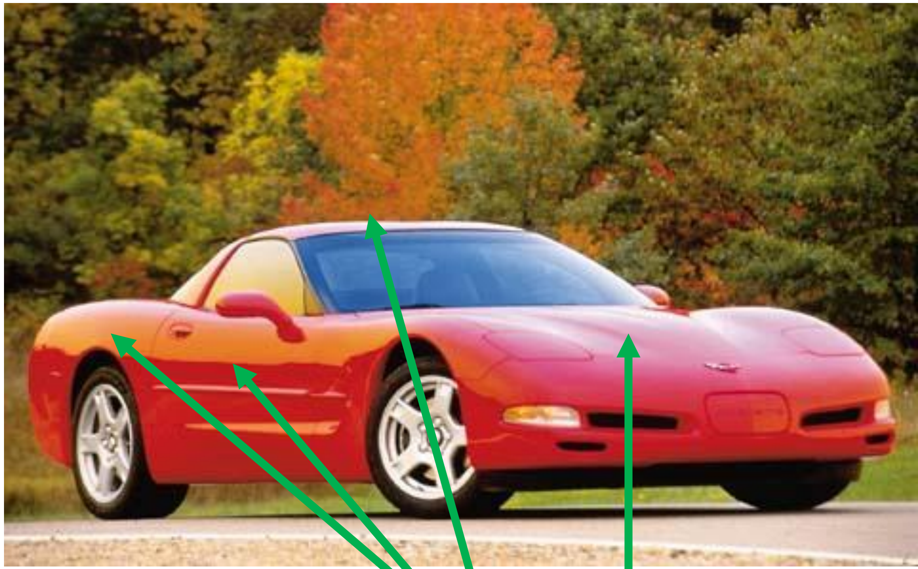
$$E_c = f_f E_f$$

Perpendicular to the fibers, the modulus of elasticity may be as high as:

$$\frac{1}{E_c} = \frac{f_f}{E_f} + \frac{f_m}{E_m}$$

Automotive Plastics and Composites Use





Plastic Fender

SMC
Sheet Molding Compound

SMC
Sheet Molding Compound

SPORTS

The fibers-reinforced composites for sports.