Composite Materials
Manufacturing processes for Polymer Matrix Composites
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 i.e.: 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.
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.
Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyetherimide, polyimide, 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 260° to 370 °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.
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

- 1995: Fokker C-PEI cargo floors Fokker 70 and 100
- 1999: G-PEI cargo floors Fokker 50
- 2000: C-PPS main landing gear door Fokker 50
- 2000: C-PPS single barrel acoustic liner for A380 engine air intake
- 2002: Tod’s Aerospace C/G-PEI reclining seat floor plinth
- 2003: DTC C-PPS brackets B787, A350, etc.
- 2003: Xperion C-PEI sidewall fixation rails A330/A340
- 2005: Fokker C-PEI floor/overwing pressure bulkhead G650
- 2005: Marquez G-PEI B787 PSU ducting and Global Express S2-PPS window bezel
- 2010: CDI C-PPS seat backs & pans
- 2012: Integrally-stiffened fuselage panel TAPAS

- Fokker C-PEEK torsion box demonstrator TAPAS
## Figure 3-2.—Comparison of General Characteristics of Thermoset and Thermoplastic Matrices

<table>
<thead>
<tr>
<th>Resin type</th>
<th>Process temperature</th>
<th>Process time</th>
<th>Use temperature</th>
<th>Solvent resistance</th>
<th>Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoset</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Toughened thermoset</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightly crosslinked thermoplastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermoplastic</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

### Table 3-1 — Production Techniques for Polymer Composites

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

**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.
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 advantages of this process include: low initial start up cost, easy to change mold/design, on-site production possible (portable process)
- The disadvantages 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
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
Processing of PMCs

Vacuum Bagging

- Provides increased part consolidation
- Reduces matched die mold costs
Vacuum Bagging

Applications:
Large, one-off cruising boats, racecar components, core-bonding in production boats
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
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 the **automated tape lay-up**
  - This process uses a large automated roller similar to a packing tape roller
  - The roller applies the tape 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 3D parts
Processing of PMCs

- 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.
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.
- 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.
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%.
Advantages:
- orientation of fibers can be changed
- consistent
- high productivity

Disadvantages:
- continuous process needs investment
- limited shelf life
- delamination
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
- Advantages: fast lay-up speed, very accurate and repeatable product, possibility to use continuous fiber, parts can have huge size
- Disadvantages: 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

- Example: pressure tanks
- Continuous filaments wound onto mandrel

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 are similar with the exceptions:
  – 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

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

Rovings  MAT

Platin Impregnation Resin

Preformed  Moulds

Traction  Cutting

Cutting
Processing of PMCs

Pultrusion

Advantages:
- Automated processes
- High speed
- Versatile cross-sectional shape
- Continuous reinforcement

Disadvantages:
- Die can be easily messed up
- Expensive die
- Constant cross-section
- Mainly thermoset matrix
Resin transfer molding is a manufacturing method that is quite similar to injection molding where material 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

Diagram showing the process:
- Pump
- Mixing Head
- Fiber Pack
- Mold (Closed before injection)
- Resin
- Catalyst
- Vent
Processing of PMCs

Vacuum Assisted Resin Transfer Molding

http://www.futuremediacreations.com/technoire/vartm.htm
# Processing of PMCs

## Resin Transfer Molding (RTM)

### Advantages

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.

### Disadvantages

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 requirements 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
It is both a process and reinforced composite material sheet moulding composite is a ready to mould glass-fibre reinforced thermoset material primarily used in compression moulding

The sheet is provided in rolls weighing up to 1000 kg
Processing of PMCs

Sheet Molding

resin / additives / fillers
Sheet Molding

**Advantages**
- High productivity thus inexpensive
- Consistency
- Weight reduction due to lower thickness
- Flexibility

**Disadvantages**
- Low volume components
- 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)

The specific strength versus temperature for several composites and metals.
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.
Parallel to the fibers, the modulus of elasticity may be as high as:

\[ E_c = f_mE_m + f_fE_f \]

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:

\[ E_c = f_fE_f \]

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
The fibers-reinforced composites for sports.