

Composite Materials

A composite material is a materials system composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents. The technological and commercial interest arise from the fact that the mechanical properties are not just different, they are often far superior;

- **Strength to weight ratios** are often several times greater than those of steel or aluminium
- **Fatigue properties** are generally better than for the common engineering materials.
- **Corrosion.** Composites can be designed that do not corrode like steel.
- **Combinations of properties.** It is possible to achieve combinations of properties not attainable with metals, ceramics or polymers alone.
- **Surface finish.** Better appearance and control of surface smoothness are possible with certain composite materials.

However, composites do have their disadvantages;

- Properties of many important composites are **anisotropic**.
- Many of the polymer based composites are subject to attack by chemicals or solvents.
- Composite materials are generally expensive.
- Shaping methods can be slow and expensive.

1 Technology and classification of composite materials

Composite materials can be classified in various ways. One way to group them is **traditional** and **synthetic** composites. Traditional composites are those that occur in nature or those that have been used by civilisations for many years. Examples may include wood or concrete. Synthetic composites are modern material systems that are first produced separately that are then combined in a controlled way to achieve the desired structure, properties and part geometry. These notes will focus on synthetic composites.

The simplest composite material consists of two phases; a primary phase called the **matrix** and the secondary phase that is embedded in the matrix called the **reinforcing agent**. Possible combinations in a two-component composite can be seen below;

Secondary phase (reinforcement)	Primary Phase (matrix)		
	Metal	Ceramic	Polymer
Metal	Powder metal parts infiltrated with a second metal	NA	Plastic molding compounds Steel-belted radial tires
Ceramic	Cermets* Fiber-reinforced metals	SiC whisker-reinforced Al_2O_3	Plastic molding compounds Fiberglass-reinforced plastic
Polymer	Powder metal parts impregnated with polymer	NA	Plastic molding compounds Kevlar-reinforced epoxy
Elements (C, B)	Fiber-reinforced metals	NA	Rubber with carbon black B or C fiber-reinforced plastic

NA = not applicable currently.
*Cermets include cemented carbides.

As you can see, some combinations are not feasible, such as a polymer in a ceramic matrix. You can also see that some composite are made up of two of the same material types, such as fibres of Kevlar (polymer) in a plastic (polymer) matrix.

1.1 The Matrix Phase

The matrix phase can be either polymer, metal or ceramic. The matrix serves several functions. First, it provides the bulk form of the part or product made of the composite material. Second, it holds the imbedded phase in place, usually enclosing it. Third, when a load is applied, the matrix shares the load with the secondary phase, in some cases deforming so that the stress is essentially born by the reinforcing agent.

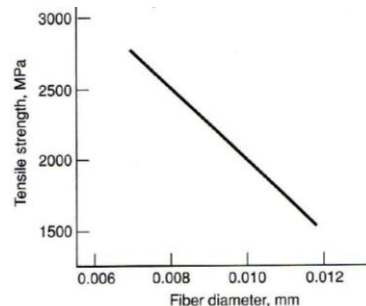
- **Metal Matrix Composites (MMCs)** include mixtures of ceramics and metals, such as cemented carbides and other cerments, as well as aluminium or magnesium reinforced by strong, high stiffness fibres.
- **Ceramic Matrix Composites (CMCs)** are the least common type of composite. Aluminium oxide and silicon carbide are materials that can be imbedded with fibres for improved properties, especially in high temperature applications.
- **Polymer Matrix Composites (PMCs)**. Thermosetting resins are the most widely used polymers in PMCs. Epoxy and polyester are commonly mixed with fibre reinforcement, and phenolic is mixed with powders.

1.2 The Reinforcing Phase

The reinforcing phase can also be polymer, metal or ceramic, or it may be an element such as carbon or boron. Its role is to reinforce the primary phase. The imbedded phase is typically a fibre, a particle or a flake;

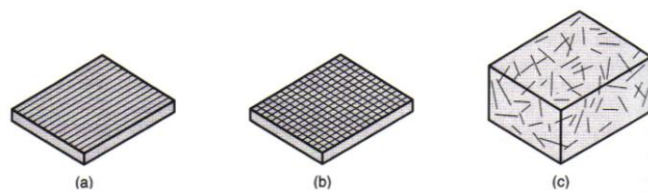


Fibres are filaments of reinforcement material, generally circular in cross-section. Diameters range from less than 0.0025mm to about 0.13mm, depending on the material. Fibre reinforcement provides the greatest opportunity for strength enhancement of composite structures. In fibre reinforced composites the fibre is often considered to be the principle constituent since it bears the major share of the load. The effect of fibre diameter on tensile strength can be seen in the figure below (shown for a carbon fibre reinforced epoxy). As the diameter is reduced the probability of defects in the structure decreases significantly. As a result, tensile strength increases dramatically;



Fibres used in composites can either be **continuous** or **discontinuous**. Continuous fibres are very long and in theory they provide a continuous path by which a load can be carried. In reality this is difficult to achieve and so discontinuous fibres (chopped sections of continuous fibres) are used. Fibre orientation is very important in composites, and can be classified as follows;

- **One dimensional** reinforcement, in which the maximum strength and stiffness are obtained in the direction of the fibre.
- **Planar** reinforcement, in some cases in the form of a two-dimensional woven fabric
- **Random** or **three dimensional**, in which the composite materials tend to possess isotropic properties.



Various fibres can be used as fibres in fibre-reinforced composites;

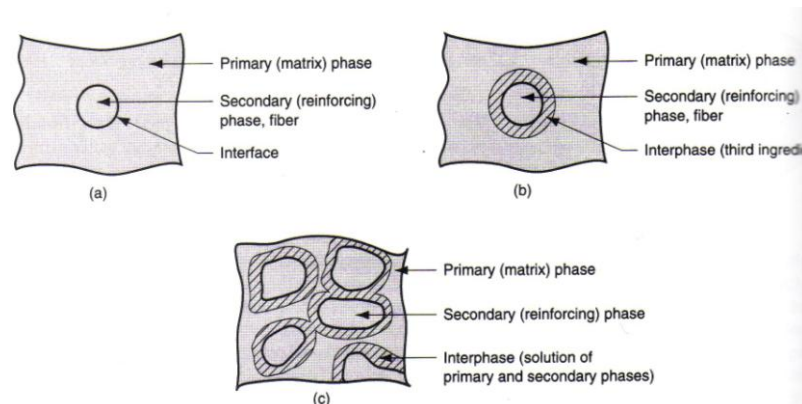
- **Glass.** Glass is the most widely used in polymer based composites. **Fibreglass** is a term used to describe glass fibre-reinforced plastic (GFRP).
- **Carbon.** Carbon can be made into high-modulus fibres. As well as high stiffness they also possess low density and low thermal expansion properties.
- **Boron.** Boron has a high elastic modulus, but its high cost limits applications to aerospace applications.
- **Kevlar 49.** This is the most important polymer fibre. Its specific gravity is low, giving it one of the highest strength to weight ratios of all fibres.
- **Ceramics.** Silicon Carbide (SiC) and aluminium oxide (Al_2O_3) are the main fibre materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low modulus metals such as aluminium and magnesium.
- **Metal.** Steel filaments, both continuous and discontinuous, are used as reinforcing fibres in plastics. Other metals are currently less common as reinforcing fibres.

Fiber Material	Diameter		Tensile Strength		Elastic Modulus	
	mm	mils ^a	MPa	lb/in ²	GPa	lb/in ²
Metal: Steel	0.13	5.0	1000	150,000	206	30×10^6
Metal: Tungsten	0.013	0.5	4000	580,000	407	59×10^6
Ceramic: Al_2O_3	0.02	0.8	1900	275,000	380	55×10^6
Ceramic: SiC	0.13	5.0	3275	475,000	400	58×10^6
Ceramic: E-glass	0.01	0.4	3450	500,000	73	10×10^6
Ceramic: S-glass	0.01	0.4	4480	650,000	86	12×10^6
Polymer: Kevlar	0.013	0.5	3450	500,000	130	19×10^6
Element: Carbon	0.01	0.4	2750	400,000	240	35×10^6
Element: Boron	0.14	5.5	3100	450,000	393	57×10^6

Particles. A second common shape of the imbedded phase is the particle, ranging from microscopic to macroscopic. The distribution of particles in composites is random so the other properties of the composite are usually isotropic. Microscopic particles (around 1 micro-metre) are distributed in the matrix in concentrations of up to 15%. These strengthen the matrix itself, and no significant portion of the applied load is carried by the particles. As the particle size increases to the macroscopic range the proportion of imbedded material can increase to 25%. The applied load is now shared between the matrix and the imbedded phase. Strengthening occurs due to the load carrying capacity of the particles and the bonding of particles in the matrix.

Flakes. Flakes are basically two dimensional particles. For example talc ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$) used in plastics. They are generally lower cost materials than polymers and they add strength and stiffness to plastic molded components.

The interface. There is always an interface between constituent phases in a composite material. For the composite to operate effectively, the phases must bond where they join. This joining could be direct joining (a), or a third ingredient called an **interphase** could be added which can be thought of as an adhesive. The last form of bonding that may occur is when the two primary components are not completely insoluble in each other and the interphase is a solution of the two primary phases.



2 Properties of composite materials

Properties of a composite material are a function of;

- The starting materials
- The geometric shape of the starting materials
- The manner in which the starting materials interact.

Rule of mixtures. The properties of a composite material are a function of the starting materials. Certain properties of a composite material can be computed by the rule of mixtures, which involves calculating a weighted average of the constituent material properties. Density is an example of this averaging rule;

$$m_c = m_m + m_r$$

m = mass

$$V_c = V_m + V_r + V_v$$

V = Volume, ρ = density

$$\rho_c = \frac{m_c}{V_c} = \frac{m_m + m_r}{V_c}$$

c = composite

$$f_m = \frac{V_m}{V_c}, f_r = \frac{V_r}{V_c}$$

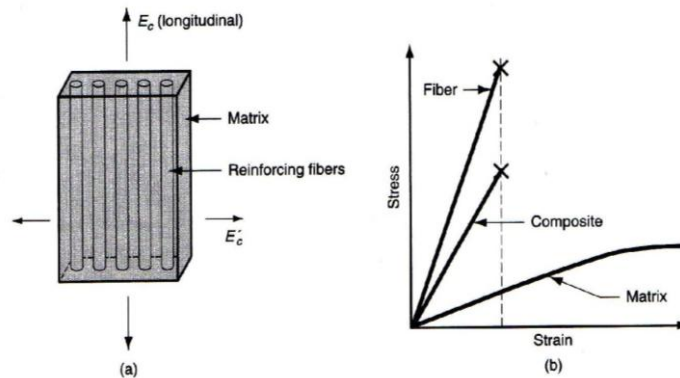
m = matrix

$$\rho_c = f_m \rho_m + f_r \rho_r$$

r = reinforcing phase

v = void

Determining the mechanical properties of composites from constituent properties is usually more involved. The rule of mixture can sometimes be used to estimate the modulus of elasticity of a fibre-reinforced composite made of continuous fibres here E_c is measured in the longitudinal direction, assuming the fibre material is much stiffer than the matrix and that the bonding between the two phases is secure;

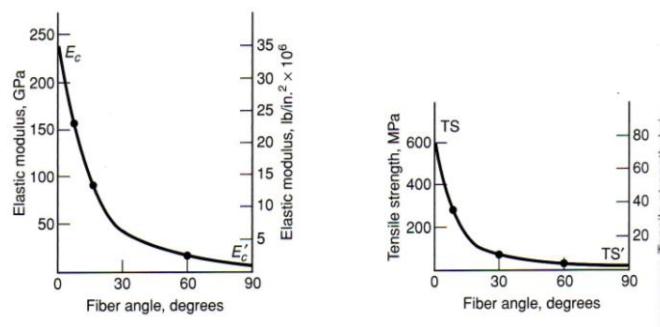


$$E_c = f_m E_m + f_r E_r$$

Perpendicular to the longitudinal direction, the fibres contribute little to the overall stiffness. The composite elastic modulus perpendicular to the fibre direction, E'_c , can be given by;

$$E'_c = \frac{E_m E_r}{f_m E_r + f_r E_m}$$

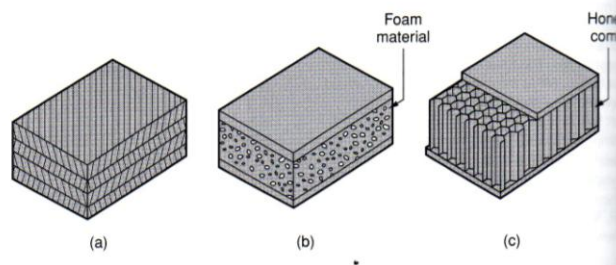
You can see in the previous two equations the significant anisotropy of the material due to the fibre direction as can be seen in the following carbon fibre reinforced epoxy;



Fibres illustrate the importance of geometric shape. Most materials have tensile strengths several times greater in fibrous form than in bulk. However, applications of fibres are limited by surface flaws, buckling then subjected to compression, and the inconvenience of the filament geometry when a solid component is needed. By embedding the fibres in a polymer matrix, a composite material is obtained that avoids the problems of fibres but utilizes their strengths. The matrix provides the bulk shape to protect the fibre surfaces and resist buckling; and the fibres lend their high strength to the composite. When a load is applied, the low-strength matrix deforms and distributes the stress to the high strength fibres, which carry the load. If individual fibres break, the load is redistributed through the matrix to other fibres.

Other composite structures. So far we have considered a reinforcing phase imbedded in a matrix phase. However, the following are also forms of composites;

- A laminar composite structure – e.g. plywood
- A sandwich structure which consists of a relatively thick core of low-density material or a honeycomb bonded on both faces to thin sheets of a different material.



Laminar Composite	Description (reference in text if applicable)
Automotive tires	A tire consists of multiple layers bonded together; the layers are composite materials (rubber reinforced with carbon black), and the plies consist of rubber-impregnated fabrics (Chapter 14).
Honeycomb sandwich	A lightweight honeycomb structure is bonded on either face to thin sheets, as in Figure 9.7(c).
FRPs	Multilayered fiber-reinforced plastic panels are used for aircraft, automobile body panels, and boat hulls (Chapter 15).
Plywood	Alternating sheets of wood are bonded together at different orientations for improved strength.
Printed circuit boards	Layers of copper and reinforced plastic are used for electrical conductivity and insulation, respectively (Section 36.2).
Snow skis	Skis are laminar composite structures consisting of multiple layers of metals, particle board, and phenolic plastic.
Windshield glass	Two layers of glass on either side of a sheet of tough plastic (Section 12.3.1).

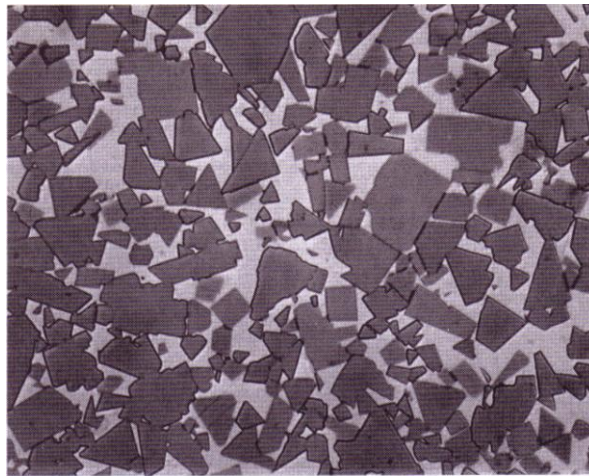
3 Metal Matrix Composites

Metal matrix composites (MMCs) consist of a metal matrix reinforced by a second phase which may particles of a ceramic or fibres of various materials (including other metals, ceramics, carbon and boron). A MMC with a ceramic reinforcing phase is known as a **cermet**.

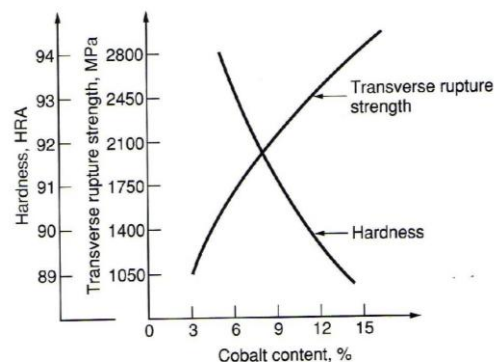
3.1 Cermets

In a **cermet** the ceramic often dominates the mixture, sometimes by up to 96% by volume. Cermets can be divided up into cemented carbides and oxide-based cermets;

- **Cemented Carbides.** The common cemented carbides are tungsten carbide (WC), titanium carbide (TiC) and chromium carbide (Cr_3C_2), these make up 80 – 95% of the total weight of the composite and are typically bonded with cobalt and nickel. The picture below shown tungsten carbide (85%) bonded with cobalt (15%) magnified 1500 times;



Even though the binder is only 5 to 15%, its effect on mechanical properties can be seen below;



The most common application of cermeted carbides is in cutting tools that are based on **tungsten carbide**. Other applications include wire drawing dies, rock-drilling bits, indenters for hardness testers, and other applications where hardness and wear resistance are critical requirements.

- **Oxide based cermets.** Mostly use Al_2O_3 as the particulate phase and chromium as the metal matrix. Applications include cutting tools and mechanical seals.

3.2 Fibre reinforced metal matrix composites

These combine the high tensile strength and modulus of elasticity of a fibre with metals of low density, thus achieving good strength to weight ratios. Typical metals used as the low density matrix are aluminium, magnesium, and titanium. Fibres such as boron and carbon are added as the reinforcement phase. Properties of fibre reinforced MMCs are anisotropic, with the greatest strength being in the direction of the fibres. The elastic modulus and tensile strength of the composite material increases with fibre volume. MMCs with fibre reinforcement have good high-temperature strength properties, and are good electrical and thermal conductors. Applications are typically components in aircraft and turbine machinery.

4 Ceramic Matrix Composites

Ceramics have high stiffness, hardness, hot hardness, compressive strength and relatively low density. However, they also have low toughness, bulk tensile strength and are susceptible to thermal cracking. Ceramic Matrix Composites (CMCs) are an attempt to keep the desirable characteristics whilst reducing the undesirable ones. The primary phase is a ceramic and the reinforcing phase consists of fibres. These materials are still being developed. Technical difficulties include thermal and chemical compatibility of the constituents. One promising area is the use of Al_2O_3 embedded with whiskers of SiC for use in metal cutting tools instead of cemented carbides. A magnification of this is shown below (magnified 3000 times);



5 Polymer Matrix Composites

A polymer matrix composite (PMC) consists of a polymer primary phase in which a secondary phase is imbedded in the form of fibres, particles or flakes. Commercially, PMCs are the most important of the three classes of synthetic composites.

Fibre-reinforced polymers (FRP) are composite materials that consist of a polymer matrix imbedded with high strength fibres. The polymer matrix is usually a thermosetting plastic but thermoplastics can also be used. Fibres in FRPs can be discontinuous, continuous or woven as a fabric. Principal fibre materials are glass, carbon and Kevlar 49. The most widely used form of the FRP is a laminar structure, made by stacking and bonding thin layers of fibre and polymer until the desired thickness is achieved. By varying the fibre orientation among the layers, a specified level of anisotropy in properties can be achieved in the laminate. This method is used to form parts with thin cross section such as aircraft wing and fuselage sections, automobile and truck body panels and boat hulls.

Properties. FRPs have a number of attractive mechanical properties;

- High strength to weight ratio
- High modulus to weight ratio
- Low specific weight

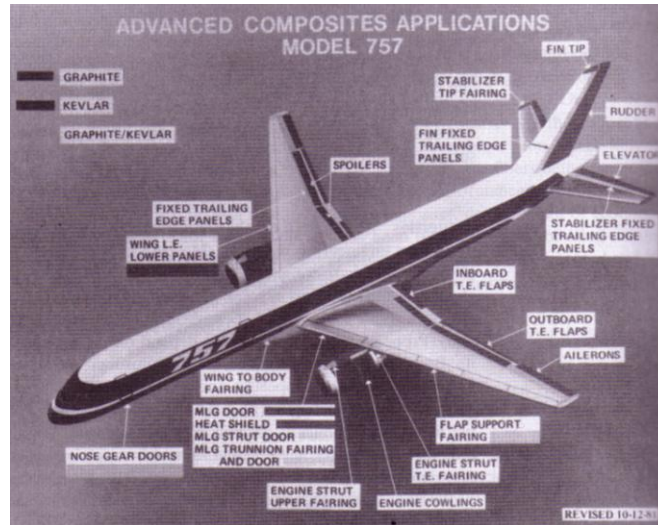
A typical FRP weighs about one fifth as much as steel yet has strength and modulus that are comparable in the fibre direction.

- Good fatigue strength
- Good corrosion resistance
- Low thermal expansion
- Significant anisotropy in properties

Material	Specific Gravity (SG)	Tensile Strength (TS)		Elastic Modulus (E)	
		MPa	lb/in ²	GPa	lb/in ²
Low-C steel	7.87	345	50,000	207	30×10^6
Alloy steel (heat treated)	7.87	3450	500,000	207	30×10^6
Aluminum alloy (heat treated)	2.70	415	60,000	69	10×10^6
FRP: fiberglass in polyester	1.50	205	30,000	69	10×10^6
FRP: Carbon in epoxy ^b	1.55	1500	220,000	140	20×10^6
FRP: Carbon in epoxy ^c	1.65	1200	175,000	214	31×10^6
FRP: Kevlar in epoxy matrix	1.40	1380	200,000	76	11×10^6

6 Applications

There has been a steady growth in the use of FRPs in products requiring high strength and low weight, often as substitutions for metals. The aerospace industry is one of the biggest users of advanced composites as designers strive to reduce aircraft weight to increase fuel efficiency and payload capacity.



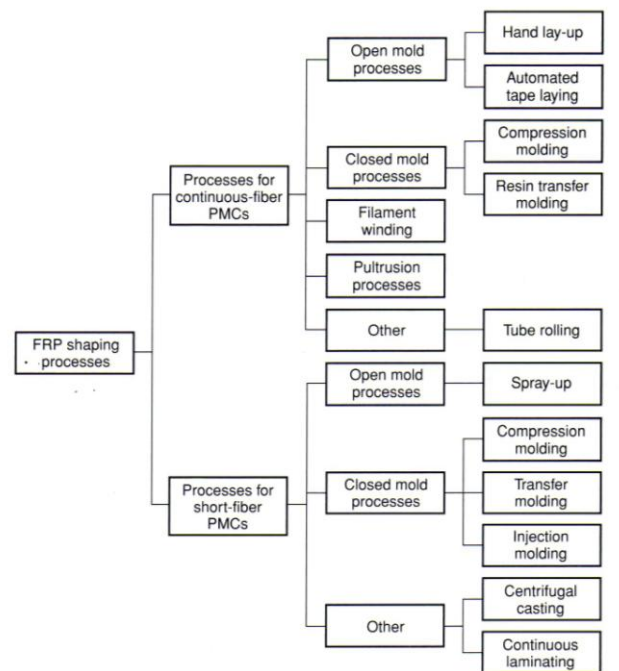
The automotive industry also uses FRPs for body panels for cars and trucks. With increased awareness of global warming the desire to reduce the weight of automobiles will increase. The continued use of low carbon sheet steel has been due to the low cost and processability of steel.

7 Processing of Polymer Matrix Composites

Shaping PMCs can be slow and labour intensive. In general, techniques for shaping composites are less efficient than manufacturing processes for other materials. There are two main reasons for this;

- Composites are more complex than other materials as they consist of at least two other materials. The way in which these two materials are combined significantly alters the mechanical properties of the composite.
- Processes for manufacture of composites are relatively new and have not been developed over many years, as they have for other materials.

In terms of commercial and technological importance the most important PMC are the fibre-reinforced-polymers (FRPs). The shaping processes used by FRPs can be summarised as follows. Some of these processes can be used with continuous fibres only, whilst some can also be used with short fibres;



- **Open mold processes.** Include some of the original manual procedures for laying resins and fibres onto forms.
- **Closed mold processes.** These are similar to those used in plastic molding.
- **Filament winding.** In which continuous filaments that have been dipped in liquid resin are wrapped around a rotating mandrel; when the resin cures, a rigid, hollow, generally cylindrical shape is created.
- **Pultrusion.** Is used to create long, straight sections of constant cross section; it is similar to extrusion, but adapted to include continuous fibre reinforcement.

7.1 Starting Materials for PMCs

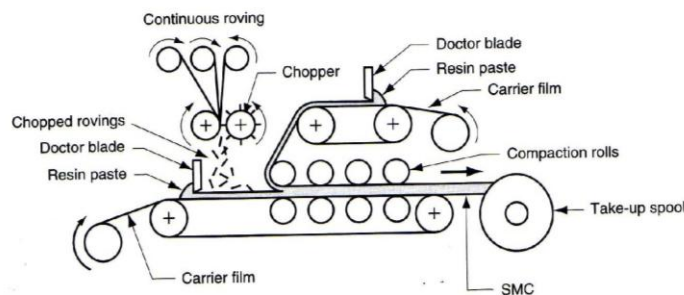
Thermoplastics, thermosets and elastomers can all be used in PMCs. However, thermosets are the most common matrix. FRPs tend to use glass, carbon, and the polymer Kevlar as reinforcement. Starting in various forms depending on the properties desired in the material and the process used in shaping the fibres are then combined with the polymer. In some applications the fibres are continuous, while in others they are chopped into short lengths. The following fibre forms may be used;

- **Roving.** A roving is a collection of untwisted (parallel) continuous strands.
- **Yarn.** A yarn is a twisted collection of filaments.
- **Cloth.** A cloth is a fabric of woven yarns.
- **Woven Roving.** A woven roving is a fabric consisting of untwisted filaments.
- **Mat.** A mat is a felt consisting of randomly oriented short fibres held loosely together with a binder. Mats may be cut into **performs** in some of the closed mold processes.

7.2 Combining Matrix and Reinforcement.

Incorporating the reinforcing agent into the polymer can be done before shaping or during. Examples of combining the materials during processing would include filament winding and pultrusion (see later). If the materials are combined before shaping they are combined in a form that is convenient for use in the shaping process. These can either be **molding compounds** or **preregs**.

Molding Compounds. Molding compounds are designed for use in molding operations. Most molding compounds for composite processing are thermosetting polymers, accordingly they have not been cured prior to shape processing. Curing is done during or after final shaping. FRP composite molding compounds consist of a resin matrix with short, randomly dispersed fibres. These can either be formed in sheets (**sheet molding compound**), as seen below, or in billet form (**bulk molding compound**). The process for producing sheet molding compounds is shown below;

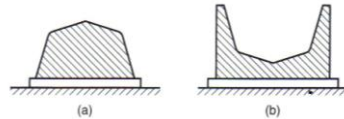


Prepregs. Another prefabricated form for FRP shaping operations is prepreg, which consists of fibres impregnated with partially cured thermosetting resins. Completion of curing is accomplished during or after shaping. Prepregs are available in the forms of tapes or cross-piled sheets or fabrics. The advantage of prepregs is that they are produced with continuous fibres rather than chopped random fibres, thus increasing strength and modulus of the final product.

7.3 Open mold processes

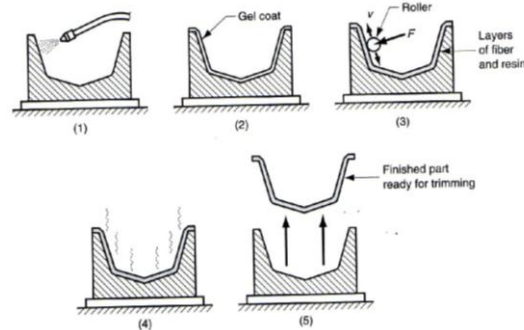
The distinguishing feature of this family of FRP shaping processes is the use of a single positive or negative mold surface to produce laminated FRP structures. The starting materials are applied to the mold in layers until the desired thickness is achieved. The part is then cured and removed from the mold. The advantage of an open mold is that the mold costs much less than if two matching molds were used. The disadvantage is that only one side of the finished product is smooth, whilst the other is rough.

There are several different open mold process that use different methods of applying the laminations to the mold.



7.3.1 Hand lay-up

This is the oldest open mold method dating back to the 1940s when it was first used on boat hulls, it is also the most labour intensive. Successive layers of resin and reinforcement are manually applied to an open mold to build up the laminated structure. The basic procedure can be seen below;

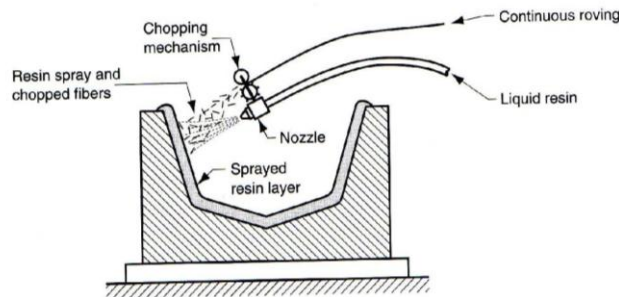


1. The mold is cleaned and treated with a mold release agent.
2. A thin gel (resin, possibly pigmented to colour) is applied, which will become the outside surface of the molding.
3. When the gel coat has partially set, successive layers of resin and fibre are applied, the fibre being in the form of mat or cloth and the liquid (uncured) resin is poured, brushed or sprayed on (this is known as **wet lay-up**). Each layer is rolled to fully impregnate the fibre with resin and remove air bubbles.
4. The part is cured.
5. The fully hardened part is removed from the mold.

An alternative method is using prepregs, in which the impregnated layers of fibre reinforcement are first prepared outside the mold and then laid onto the mold surface which results in closer control over the fibre-resin mixture and more efficient methods of adding the laminations. Molds can be made of plaster (one off prototypes), glass fibre reinforced plastics (medium volume runs), metal (high volume runs) or other materials depending on economics and required surface finish. Products suited to hand lay-up tend to be large size but low volume such as boat hulls and swimming pools.

7.3.2 Spray-up

This is an attempt to mechanise the hand lay-up process by spraying the resin layers directly onto the mold rather than laying mat or cloth. The disadvantage of this method is that it results in the fibres being oriented in a random fashion, as apposed to hand lay-up in which the fibres can be oriented if desired. Another difference is that the fibre content in spray-up is limited to about 35% (compared to a maximum of around 65% in hand lay-up). This significantly reduces the cycle time and the part can be manufactured in a sealed off area without humans present, thus eliminating exposure to emissions from the liquid resins that can be hazardous. However, rolling is generally required between each layer. Typical uses include bathtubs, shower bases, automotive panels and furniture.



7.3.3 Automated Tape-Laying Machines

This is another attempt to automate and accelerate step three in the hand lay-up process. An Automated tape-laying machine dispenses prepreg tape onto an open mold following a programmed path. A typical machine has an overhead gantry with a head which can have up to six axis. This again reduces cycle time, however more initial capital is required and the machine has to be programmed.

7.4 Closed Mold Processes

These molding operations are performed in molds consisting of two sections that open and close during each molding cycle. Tooling cost is thus more than twice the amount compared to open mold processes due to having two molds, matching the mold and having the necessary equipment to open and shut the molds. However they do have the following advantages;

- Good finish on both sides of the finished product
- Higher production rates
- Closer control over tolerances
- More complex three dimensional shapes can be formed.

Closed mold process can be classified as either **compression molding**, **transfer molding** or **injection molding**.

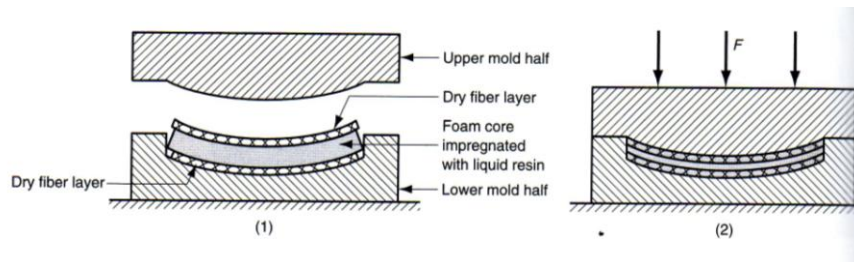
7.4.1 Compression Molding PMC processes

A charge is placed in the lower mold section, and the sections are brought together under pressure causing the charge to take the shape of the cavity. The mold halves are heated to cure the thermosetting polymer. There are three variations of compression moldings in PMC;

Sheet molding compound or bulk molding compounds can be cut to size and used as the starting charge in compression molding.

Preform molding. In which a precut mat is placed into the lower section along with a polymer charge (e.g. pellets or sheet). The materials are then pressed between heated mold halves, causing the resin to flow and impregnate the fibre mat to produce a fibre reinforced molding.

Elastic Reservoir Molding. The starting charge is a sandwich consisting of a polymer foam impregnated with liquid resin, between two dry fibre layers. As the core is compressed it releases the resin to wet the dry surfaces, curing produces a lightweight part consisting of a low density core and thin FRP skins.

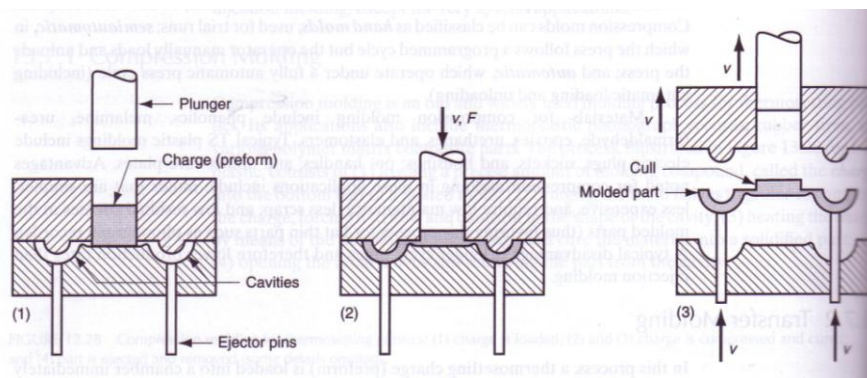


7.4.2 Transfer molding PMC processes

This is similar to transfer molding that is used for polymers and can be used to mold TS resins in which the fillers include short fibres to produce a FRP composite part. The basic process is as follows;

- Charge is loaded into pot
- Softened polymer/fibre mixture is pressed into the mold cavity and cured
- The part is ejected

Another form of transfer molding for PMCs is called **resin transfer molding**, when a perform mat is placed in the lower section before the mold is closed.

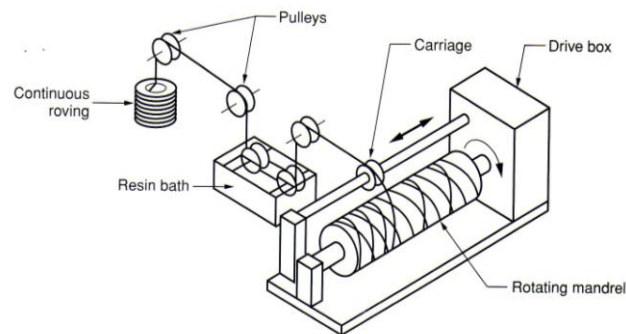


7.4.3 Injection Molding PMC processes.

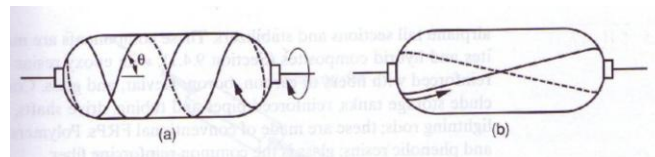
This process is similar that that used with plastics, with reinforcing fibres typically glass, in the mixture that is injected into the mold. This is used extensively in automotive applications such as bumpers and other body parts.

7.5 Filament Winding

Filament winding is a process in which resin-impregnated continuous fibres are wrapped around a rotating mandrel that has the internal shape of the desired product. The resin is then cured and the mandrel is removed. Hollow axisymmetric components are thus produced. There are several variations of this method, one of which being **wet winding** in which the filament is pulled through the liquid resin just prior to winding as shown below;



Two basic winding patterns are used in filament winding, **helical winding** and **polar winding**. In helical winding the filament is wound in a helix pattern at an angle θ , in polar winding the filament is wrapped around the long axis of the mandrel and the mandrel is then indexed.



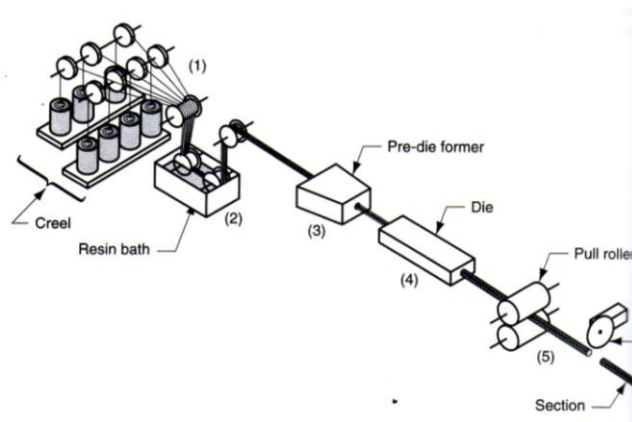
These two methods obviously result in PMCs with different fibre orientations and thus mechanical properties when compared to each other. Another possibility is to have one alternate layers that are helical then polar, resulting in a **bi-axial** winding.

The mandrel determines the geometry of the filament wound part. Mandrels must be capable of collapsing after winding and curing for part removal. Various designs are possible including inflatable/deflatable mandrels, collapsible metal mandrels, and mandrels made of soluble salts or plasters. Applications of filament windings include rocket-motor cases, missile bodies, helicopter blades and airplane tail sections and stabilizers.

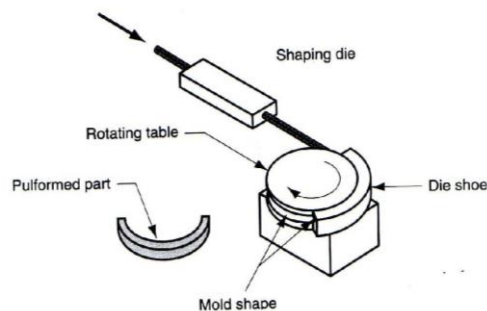
7.6 Pultrusion Processes

This is similar to extrusion but the part is pulled through the die rather than pushed through the die. The process is basically as follows;

- **Filament feeding**, in which the fibres are unreeled from a creel.
- **Resin impregnation**, in which the fibres are dipped in the uncured liquid resin.
- **Pre-die forming**. The collection of filaments is gradually shaped into the approximate cross section desired.
- **Shaping and curing**, in which the impregnated fibres are pulled through the heated die.
- **Pulling and cutting**. Pullers are used to draw the cured length through the die, after which it is cut by a cut-off wheel with SiC or diamond grits.



Typical uses of PMC produced using pultrusion are tubing, long flat sheets, tool handles for high voltage work and third rail covers for subways. A variation of pultrusion is **pulforming** in which an additional operation happens after exiting the shaping die to curve the part. This can then be used for applications such as automotive leaf springs.



8 Case studies

Hyundai QarmaQ (<http://www.autofieldguide.com/articles/050704.html>)



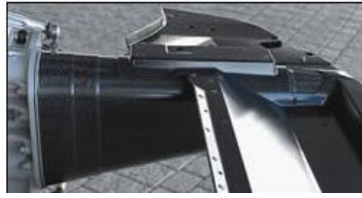
- concept car - “a safer, more environmentally responsible car.”
- unveiled at the 77th Geneva International Motor Show (March 2007)
- car’s hood made out of recycled soda bottles using approximately 900 PET bottles
 - thermoplastic composite
 - This material can handle the thermal and chemical requirements of e-coat
 - light, while meeting the European pedestrian safety requirements, the head-impact test, in particular
 - aluminum compression-molded tooling
- liftgate that is said to weigh half—10.4 kg—of what an equivalent steel/glass/rubber assembly would
 - carbon fiber frame with thin structural channels to support the polycarbonate backlight
 - the gas struts, the lift mechanism and electric motor are all lighter spec as a result

BMW M3 Roof (<http://www.autofieldguide.com/articles/080407.html>)



- "the world's first highly automated production process for CFP body components."
- Landshut's largest project has been the 1,400 roofs produced for the M3 CSL coupe in 2003
- A two-step process was used to make the roofs
 - five layers of carbon fiber are automatically positioned to form a mat
 - that is then placed in an 1,800-ton press and injected with transparent epoxy in a resin transfer molding (RTM) process.
- BMW claims that by automating the process it can make a roof in less than 20% of the time needed by traditional CFP production methods
- still brings total cycle time in at a lengthy 30 to 40 minutes
- 6 kg., the roof is more than 50% lighter than one made of steel.

Merc 2008 SLR crash structure (<http://www.autofieldguide.com/articles/wip/0807wip02.html>)



- carbon fiber structure highlighted by conical side elements designed to progressively absorb accident energy

Ford GT (<http://www.autofieldguide.com/articles/wip/0205wip01.html>)



- deck lid inner is a rather large component, measuring approximately 7 x 5 ft, as it encompasses the engine and rear wheel wells because of the clamshell-cover configuration.
- Initially, the deck lid inner was to be a four-piece aluminum assembly. But based on an analysis of weight and costs (manufacturing, tooling, assembly), an alternative was sought
 - unidirectional carbon fiber-epoxy composite
- The completed decklid weighs just over 14 lb.

Porsche Carrera GT (<http://www.autofieldguide.com/articles/090301.html>)



- carbon fiber-intensive chassis
 - The passenger box portion is fashioned from carbon fiber reinforced plastic (CFRP) and integrates the windshield frame and roll bar for maximum rigidity. (The Carrera GT is an open top car but it has better torsional stiffness than the closed 911.)
 - The CFRP is made up of an upper and lower layer of carbon fiber that sandwiches a honeycomb layer of aluminum or a resin-impregnated material called Nomex
- 1,000 different pieces of CFRP are used on the chassis and each one is arranged by hand to provide maximum strength
- Each chassis takes five days to produce

Review Questions

1. What is a composite material?
2. What does the term anisotropic mean?
3. How are traditional composites distinguished from synthetic composites?
4. Name the three basic categories of composite materials?
5. Give some examples of commercial products which are laminar composite structures.
6. What is the rule of mixtures?
7. What is a cermet?
8. What is the difference between a roving and a yarn?
9. What is sheet molding compound?
10. How is prepreg different from a molding compound?
11. Why are laminated FRP products made by the spray-up method not as strong as similar products made by hand lay-up?
12. What are some of the advantages of the closed mold process for PMCs relative to open mold processes?
13. What is a filament winding?
14. Describe the pultrusion process?
15. How are FRPs cut?

Notes adapted from/further reading

Fundamentals of Modern Manufacturing, Mikell P. Groover