

Internal Assessment Test – IV (Improvement test)

Sub:	Material Science	Code:	15ME32
Date:	28/ 11/ 2016	Duration:	90 mins
		Max Marks:	50
		Sem:	III
		Branch:	Mechanical
Answer Any FIVE FULL Questions			

	Marks	OBE	
		CO	RBT
1 (a) Derive atomic packing factor for FCC structure. Calculate the atomic radius of aluminum if it crystallizes in FCC structure with a lattice parameter of 0.405 nm.	[10]	CO1	L1
2 (a) Define the following. a. Unit cell b. Space lattice c. Atomic packing factor d. Coordination number.	[10]	CO1	L1
3 (a) Find the coordination number and average number of atoms present in each of the following unit cells. a. SC b. BCC c. FCC d. HCP	[10]	CO1	L1
4 (a) Derive the following. a. Modulus of resilience b. Modulus of toughness c. True stress and Engineering stress d. Engineering strain and true strain	[10]	CO1	L1
5 (a) A tensile test was conducted on a steel specimen having 12 mm diameter and 50 mm gauge length. The loads recorded corresponding to the upper and lower yield points are 46 KN and 44 KN. The maximum and fracture loads were 75 KN and 50 KN respectively. The final diameter and length of the specimen were 8.5 mm and 65 mm respectively. On the load extension diagrams, load and extension found to be proportional till 20 KN. Determine the following. i. Young's modulus ii. Upper yield stress iii. Lower yield stress iv. Ultimate tensile stress v. Fracture stress.	[10]	CO1	L1
6 (a) Explain the stress strain curves for the following materials. a. Ductile materials b. Brittle materials c. Polymers	[10]	CO1	L1

Course Outcomes		PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO1:	Describe the mechanical properties of metals, their alloys and various modes of failure.	3	1	3	2	-	-	-	-	--	-	--	1
CO2:	Understand the microstructures of ferrous and non-ferrous materials to mechanical properties.	3	-	3	2	-	-	-	-	-	-	-	1
CO3:	Explain the processes of heat treatment of various alloys.	3	-	3	2	-	-	-	-	-	-	-	1
CO4:	Understand the properties and potentialities of various materials available and material selection procedures.	3	-	3	-	-	-	-	-	-	-	3	-
CO5:	Know about composite materials and their processing as well as applications.	3	-	3	2	-	-	-	-	-	-	-	-
Cognitive level	KEYWORDS												
L1	List, define, tell, describe, identify, show, label, collect, examine, tabulate, quote, name, who, when, where, etc.												
L2	summarize, describe, interpret, contrast, predict, associate, distinguish, estimate, differentiate, discuss, extend												
L3	Apply, demonstrate, calculate, complete, illustrate, show, solve, examine, modify, relate, change, classify, experiment, discover.												
L4	Analyze, separate, order, explain, connect, classify, arrange, divide, compare, select, explain, infer.												
L5	Assess, decide, rank, grade, test, measure, recommend, convince, select, judge, explain, discriminate, support, conclude, compare, summarize.												
<p>PO1 - <i>Engineering knowledge</i>; PO2 - <i>Problem analysis</i>; PO3 - <i>Design/development of solutions</i>; PO4 - <i>Conduct investigations of complex problems</i>; PO5 - <i>Modern tool usage</i>; PO6 - <i>The Engineer and society</i>; PO7- <i>Environment and sustainability</i>; PO8 - <i>Ethics</i>; PO9 - <i>Individual and team work</i>; PO10 - <i>Communication</i>; PO11 - <i>Project management and finance</i>; PO12 - <i>Life-long learning</i></p>													

Fiber-Reinforced Composites

fiber-reinforced composite
specific strength
specific modulus

Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. Design goals of **fiber-reinforced composites** often include high strength and/or stiffness on a weight basis. These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity. Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low-density fiber and matrix materials.

As noted in Figure 16.2, fiber-reinforced composites are subclassified by fiber length. For short fiber, the fibers are too short to produce a significant improvement in strength.

16.4 INFLUENCE OF FIBER LENGTH

The mechanical characteristics of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase. Important to the extent of this load transmittance is the magnitude of the interfacial bond between the fiber and matrix phases. Under an applied stress, this fiber–matrix bond ceases at the fiber ends, yielding a matrix deformation pattern as shown schematically in Figure 16.6; in other words, there is no load transmittance from the matrix at each fiber extremity.

Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length l_c is dependent on the fiber diameter d and its ultimate (or tensile) strength σ_f^* , and on the fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) τ_c according to

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \tag{16.3}$$

Critical fiber length—dependence on fiber strength and diameter, and fiber-matrix bond strength/matrix shear yield strength

For a number of glass and carbon fiber–matrix combinations, this critical length is on the order of 1 mm, which ranges between 20 and 150 times the fiber diameter.

When a stress equal to σ_f^* is applied to a fiber having just this critical length, the stress–position profile shown in Figure 16.7a results; that is, the maximum fiber load is achieved only at the axial center of the fiber. As fiber length l increases, the fiber reinforcement becomes more effective; this is demonstrated in Figure 16.7b, a stress–axial position profile for $l > l_c$ when the applied stress is equal to the fiber strength. Figure 16.7c shows the stress–position profile for $l < l_c$.

Fibers for which $l \gg l_c$ (normally $l > 15l_c$) are termed *continuous*; *discontinuous* or *short fibers* have lengths shorter than this. For discontinuous fibers of lengths

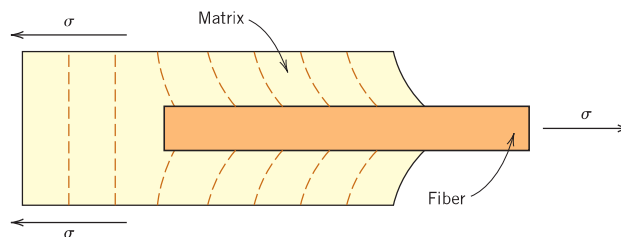
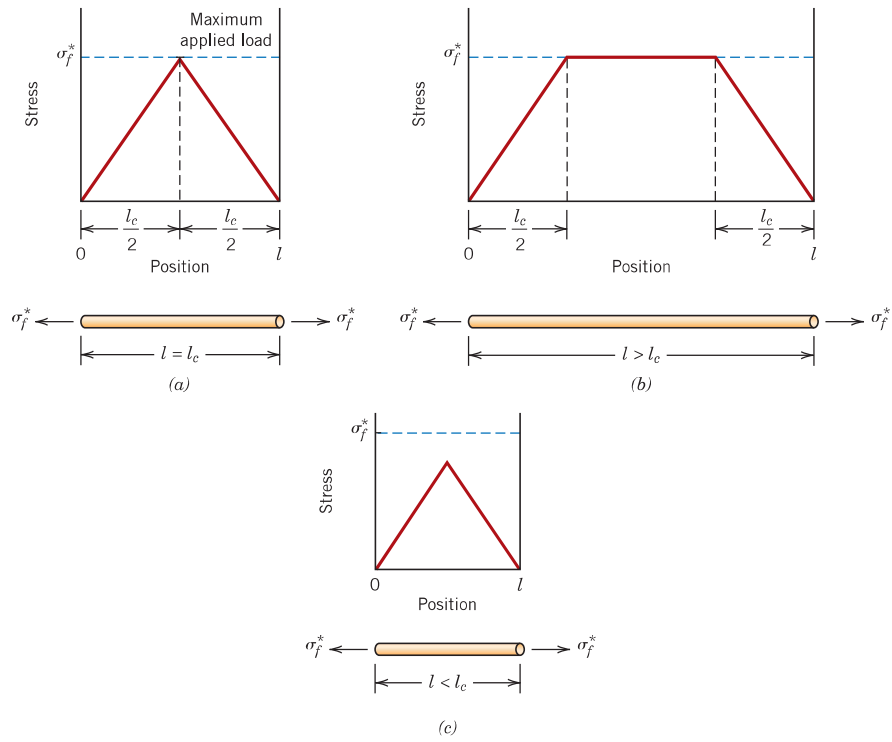


Figure 16.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

586 • Chapter 16 / Composites

Figure 16.7
 Stress–position profiles when fiber length l (a) is equal to the critical length l_c , (b) is greater than the critical length, and (c) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^* .



significantly less than l_c , the matrix deforms around the fiber such that there is virtually no stress transference and little reinforcement by the fiber. These are essentially the particulate composites as described above. To affect a significant improvement in strength of the composite, the fibers must be continuous.

16.5 INFLUENCE OF FIBER ORIENTATION AND CONCENTRATION

The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. With respect to orientation, two extremes are possible: (1) a parallel alignment of the longitudinal axis of the fibers in a single direction, and (2) a totally random alignment. Continuous fibers are normally aligned (Figure 16.8a), whereas discontinuous fibers may be aligned (Figure 16.8b), randomly oriented (Figure 16.8c), or partially oriented. Better overall composite properties are realized when the fiber distribution is uniform.

Continuous and Aligned Fiber Composites

Tensile Stress–Strain Behavior—Longitudinal Loading

Mechanical responses of this type of composite depend on several factors to include the stress–strain behaviors of fiber and matrix phases, the phase volume fractions, and, in addition, the direction in which the stress or load is applied. Furthermore, the properties of a composite having its fibers aligned are highly anisotropic, that is, dependent on the direction in which they are measured. Let

16.5 Influence of Fiber Orientation and Concentration • 587

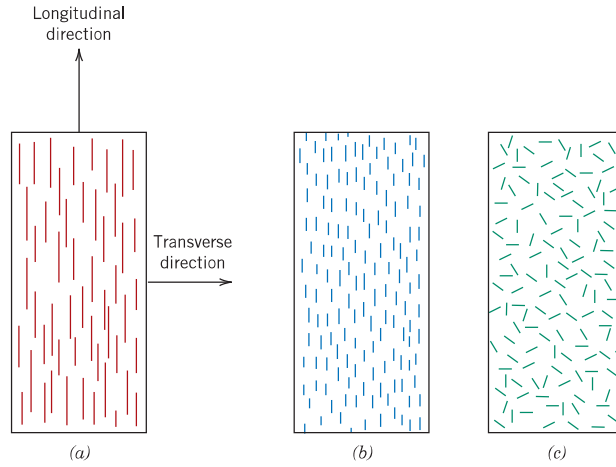


Figure 16.8 Schematic representations of (a) continuous and aligned, (b) discontinuous and aligned, and (c) discontinuous and randomly oriented fiber-reinforced composites.

longitudinal direction

us first consider the stress–strain behavior for the situation wherein the stress is applied along the direction of alignment, the **longitudinal direction**, which is indicated in Figure 16.8a.

To begin, assume the stress versus strain behaviors for fiber and matrix phases that are represented schematically in Figure 16.9a; in this treatment we consider the fiber to be totally brittle and the matrix phase to be reasonably ductile. Also indicated

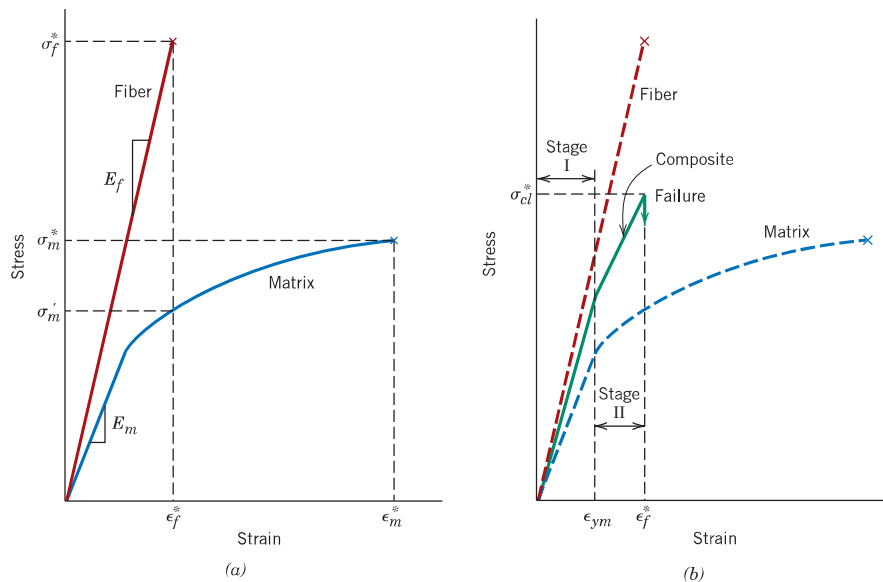


Figure 16.9 (a) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (b) Schematic stress–strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment; curves for the fiber and matrix materials shown in part (a) are also superimposed.

588 • Chapter 16 / Composites

in this figure are fracture strengths in tension for fiber and matrix, σ_f^* and σ_m^* , respectively, and their corresponding fracture strains, ϵ_f^* and ϵ_m^* ; furthermore, it is assumed that $\epsilon_m^* > \epsilon_f^*$, which is normally the case.

A fiber-reinforced composite consisting of these fiber and matrix materials will exhibit the uniaxial stress–strain response illustrated in Figure 16.9b; the fiber and matrix behaviors from Figure 16.9a are included to provide perspective. In the initial Stage I region, both fibers and matrix deform elastically; normally this portion of the curve is linear. Typically, for a composite of this type, the matrix yields and deforms plastically (at ϵ_{ym} , Figure 16.9b) while the fibers continue to stretch elastically, inasmuch as the tensile strength of the fibers is significantly higher than the yield strength of the matrix. This process constitutes Stage II as noted in the figure; this stage is ordinarily very nearly linear, but of diminished slope relative to Stage I. Furthermore, in passing from Stage I to Stage II, the proportion of the applied load that is borne by the fibers increases.

The onset of composite failure begins as the fibers start to fracture, which corresponds to a strain of approximately ϵ_f^* as noted in Figure 16.9b. Composite failure is not catastrophic for a couple of reasons. First, not all fibers fracture at the same time, since there will always be considerable variations in the fracture strength of brittle fiber materials (Section 12.8). In addition, even after fiber failure, the matrix is still intact inasmuch as $\epsilon_f^* < \epsilon_m^*$ (Figure 16.9a). Thus, these fractured fibers, which are shorter than the original ones, are still embedded within the intact matrix, and consequently are capable of sustaining a diminished load as the matrix continues to plastically deform.

Elastic Behavior—Longitudinal Loading

Let us now consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction of fiber alignment. First, it is assumed that the fiber–matrix interfacial bond is very good, such that deformation of both matrix and fibers is the same (an *isostrain* situation). Under these conditions, the total load sustained by the composite F_c is equal to the sum of the loads carried by the matrix phase F_m and the fiber phase F_f , or

$$F_c = F_m + F_f \quad (16.4)$$

From the definition of stress, Equation 6.1, $F = \sigma A$; and thus expressions for F_c , F_m , and F_f in terms of their respective stresses (σ_c , σ_m , and σ_f) and cross-sectional areas (A_c , A_m , and A_f) are possible. Substitution of these into Equation 16.4 yields

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad (16.5)$$

and then, dividing through by the total cross-sectional area of the composite, A_c , we have

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c} \quad (16.6)$$

where A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases, respectively. If the composite, matrix, and fiber phase lengths are all equal, A_m/A_c is equivalent to the volume fraction of the matrix, V_m , and likewise for the fibers, $V_f = A_f/A_c$. Equation 16.6 now becomes

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad (16.7)$$

The previous assumption of an isostrain state means that

$$\epsilon_c = \epsilon_m = \epsilon_f \quad (16.8)$$

16.5 Influence of Fiber Orientation and Concentration • 589

and when each term in Equation 16.7 is divided by its respective strain,

$$\frac{\sigma_c}{\epsilon_c} = \frac{\sigma_m}{\epsilon_m} V_m + \frac{\sigma_f}{\epsilon_f} V_f \quad (16.9)$$

Furthermore, if composite, matrix, and fiber deformations are all elastic, then $\sigma_c/\epsilon_c = E_c$, $\sigma_m/\epsilon_m = E_m$, and $\sigma_f/\epsilon_f = E_f$, the E 's being the moduli of elasticity for the respective phases. Substitution into Equation 16.9 yields an expression for the modulus of elasticity of a continuous and aligned fibrous composite *in the direction of alignment (or longitudinal direction)*, E_{cl} , as

$$E_{cl} = E_m V_m + E_f V_f \quad (16.10a)$$

or

$$E_{cl} = E_m(1 - V_f) + E_f V_f \quad (16.10b)$$

since the composite consists of only matrix and fiber phases; that is, $V_m + V_f = 1$.

Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases. Other properties, including density, also have this dependence on volume fractions. Equation 16.10a is the fiber analogue of Equation 16.1, the upper bound for particle-reinforced composites.

It can also be shown, for longitudinal loading, that the ratio of the load carried by the fibers to that carried by the matrix is

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \quad (16.11)$$

The demonstration is left as a homework problem.

EXAMPLE PROBLEM 16.1

Property Determinations for a Glass Fiber-Reinforced Composite—Longitudinal Direction

A continuous and aligned glass fiber-reinforced composite consists of 40 vol% of glass fibers having a modulus of elasticity of 69 GPa (10×10^6 psi) and 60 vol% of a polyester resin that, when hardened, displays a modulus of 3.4 GPa (0.5×10^6 psi).

- Compute the modulus of elasticity of this composite in the longitudinal direction.
- If the cross-sectional area is 250 mm² (0.4 in.²) and a stress of 50 MPa (7250 psi) is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.
- Determine the strain that is sustained by each phase when the stress in part (b) is applied.

Solution

- The modulus of elasticity of the composite is calculated using Equation 16.10a:

$$\begin{aligned} E_{cl} &= (3.4 \text{ GPa})(0.6) + (69 \text{ GPa})(0.4) \\ &= 30 \text{ GPa} (4.3 \times 10^6 \text{ psi}) \end{aligned}$$

For a continuous and aligned fiber-reinforced composite, modulus of elasticity in the longitudinal direction

Ratio of load carried by fibers and the matrix phase, for longitudinal loading

590 • Chapter 16 / Composites

(b) To solve this portion of the problem, first find the ratio of fiber load to matrix load, using Equation 16.11; thus,

$$\frac{F_f}{F_m} = \frac{(69 \text{ GPa})(0.4)}{(3.4 \text{ GPa})(0.6)} = 13.5$$

or $F_f = 13.5 F_m$.

In addition, the total force sustained by the composite F_c may be computed from the applied stress σ and total composite cross-sectional area A_c according to

$$F_c = A_c \sigma = (250 \text{ mm}^2)(50 \text{ MPa}) = 12,500 \text{ N (2900 lb}_f\text{)}$$

However, this total load is just the sum of the loads carried by fiber and matrix phases; that is,

$$F_c = F_f + F_m = 12,500 \text{ N (2900 lb}_f\text{)}$$

Substitution for F_f from the above yields

$$13.5 F_m + F_m = 12,500 \text{ N}$$

or

$$F_m = 860 \text{ N (200 lb}_f\text{)}$$

whereas

$$F_f = F_c - F_m = 12,500 \text{ N} - 860 \text{ N} = 11,640 \text{ N (2700 lb}_f\text{)}$$

Thus, the fiber phase supports the vast majority of the applied load.

(c) The stress for both fiber and matrix phases must first be calculated. Then, by using the elastic modulus for each (from part a), the strain values may be determined.

For stress calculations, phase cross-sectional areas are necessary:

$$A_m = V_m A_c = (0.6)(250 \text{ mm}^2) = 150 \text{ mm}^2 (0.24 \text{ in.}^2)$$

and

$$A_f = V_f A_c = (0.4)(250 \text{ mm}^2) = 100 \text{ mm}^2 (0.16 \text{ in.}^2)$$

Thus,

$$\sigma_m = \frac{F_m}{A_m} = \frac{860 \text{ N}}{150 \text{ mm}^2} = 5.73 \text{ MPa (833 psi)}$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11,640 \text{ N}}{100 \text{ mm}^2} = 116.4 \text{ MPa (16,875 psi)}$$

Finally, strains are computed as

$$\epsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73 \text{ MPa}}{3.4 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

$$\epsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4 \text{ MPa}}{69 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

Therefore, strains for both matrix and fiber phases are identical, which they should be, according to Equation 16.8 in the previous development.

16.5 Influence of Fiber Orientation and Concentration • 591

Elastic Behavior—Transverse Loading**transverse direction**

A continuous and oriented fiber composite may be loaded in the **transverse direction**; that is, the load is applied at a 90° angle to the direction of fiber alignment as shown in Figure 16.8a. For this situation the stress σ to which the composite as well as both phases are exposed is the same, or

$$\sigma_c = \sigma_m = \sigma_f = \sigma \quad (16.12)$$

This is termed an *isostress* state. Also, the strain or deformation of the entire composite ϵ_c is

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f \quad (16.13)$$

but, since $\epsilon = \sigma/E$,

$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f \quad (16.14)$$

where E_{ct} is the modulus of elasticity in the transverse direction. Now, dividing through by σ yields

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \quad (16.15)$$

For a continuous and aligned fiber-reinforced composite, modulus of elasticity in the transverse direction

which reduces to

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f) E_f + V_f E_m} \quad (16.16)$$

Equation 16.16 is analogous to the lower-bound expression for particulate composites, Equation 16.2.

EXAMPLE PROBLEM 16.2**Elastic Modulus Determination for a Glass Fiber-Reinforced Composite—Transverse Direction**

Compute the elastic modulus of the composite material described in Example Problem 16.1, but assume that the stress is applied perpendicular to the direction of fiber alignment.

Solution

According to Equation 16.16,

$$\begin{aligned} E_{ct} &= \frac{(3.4 \text{ GPa})(69 \text{ GPa})}{(0.6)(69 \text{ GPa}) + (0.4)(3.4 \text{ GPa})} \\ &= 5.5 \text{ GPa} \quad (0.81 \times 10^6 \text{ psi}) \end{aligned}$$

This value for E_{ct} is slightly greater than that of the matrix phase but, from Example Problem 16.1a, only approximately one-fifth of the modulus of elasticity along the fiber direction (E_{cl}), which indicates the degree of anisotropy of continuous and oriented fiber composites.

Unit – 8

COMPOSITE MATERIALS

8.1 INTRODUCTION

A *composite material* (or *composites* for short) can be defined as a combination of two or more *constituent materials* (*individual materials*) with different physical or chemical properties, and which remain separate and distinct on a microscopic or macroscopic* level within the finished structure. In other words, the constituents do not dissolve or merge into each other, although they act together to form a single material.

The engineering importance of a composite material is that, two or more distinctly different materials combine to form a composite material that possesses properties that are superior to those of the individual materials. A simple example of a composite is the *plywood*—a type of man-made wood. Plywood is a wood product manufactured out of many sheets of wood veneer, pressed together and glued. When layers like this are put together it produces a very sturdy and durable wood. Plywood is used instead of plain wood because of its resistance to cracking, shrinkage, and twisting/warping, and its general high degree of strength. As known, they are used for a wide variety of applications like computer tables, chairs, wardrobes, etc. Another simple example of a composite is the *concrete*, which is made up of cement, sand, & stones used in construction works.

Most composites are made up of just two materials, representing as *matrix (binder)* and *reinforcement (dispersed phase)*. The *matrix* surrounds and binds together a cluster of fibres, particles, or fragments of a much stronger material called the *reinforcement*. The following examples illustrate the matrix and the reinforcement phase, and how their combination results in better properties.

- Consider the example of a concrete, which is made up of cement and sand/stones (gravel). The cement forms the matrix, while sand/gravel particles forms the reinforcement.
- Reinforced concrete is another excellent example of a composite structure in which the concrete and steel create structures that are rigid and strong. Concrete, which forms the matrix is rigid

* *Microscopic level ranges from 10^{-4} to 10^{-2} cm, in size, while macroscopic level from about 10^{-2} cm or greater. An example of composite material at the macroscopic level would be steel-reinforced concrete since concrete and steel can be distinctly recognized by the naked eye. A metal alloy such as plain-carbon steel containing ferrite and pearlite could be called a composite material at the microscopic scale, since the ferrite and pearlite are distinctly recognized when observed in the optical microscope.*

and has good compression strength, thereby enabling to carry compression loads, while steel, which forms the reinforcement has high tensile strength enabling it to carry the tensile loads. Thus the composite material is stronger and performs better than the individual materials.

- Another simple example is a *rubber tyre*. A typical radial car tyre is a combination of a rubber compound, which forms the matrix, and steel as the reinforcement. Steel in the form of belts provide puncture resistance and help the tyre stay flat so that it makes the best contact with the road. The rubber acts as a matrix, holding the reinforcement in place.
- Cutting tools used for machining very hard materials are also composites. They are made by combining fine ceramic particles such as tungsten carbide or titanium carbide (reinforcement) embedded in a metal matrix such as cobalt or nickel. Ceramics have high strengths, high values of tensile modulus and high hardness, but are brittle in nature. By comparison, the metals are weaker and less stiff, but ductile. By incorporating ceramic particles, often about 80% by volume, in a metal matrix, a composite can be produced which is strong, hard and tough and can be used as a tool material.

8.2 ROLE OF CONSTITUENTS IN A COMPOSITE

A composite is made up of two constituent materials, *matrix* and *reinforcement*. Both the materials have specific roles to perform resulting in the function of the composite. In addition, the *interface* between the matrix and the reinforcement has also some specific role to perform, which is discussed in the present section.

Consider a composite material in its simplest form as shown in figure 8.1.

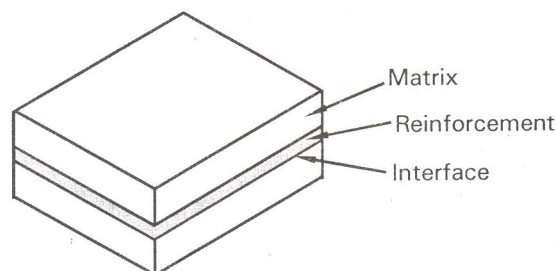


Figure 8.1 Composite

a) Role of Matrix

In a composite, the matrix performs the following functions:

- Holds the reinforcement material together and keep them aligned in a predetermined direction.
- Protects the reinforcement from mechanical and environmental attack.
- Distributes the loads evenly between the reinforcement material so that the entire reinforcement is subjected to the same amount of strain.

- Provides shape and form to the composite material.
- Improves impact and fracture resistance of the composite material.
- Helps to avoid propagation of crack growth through the reinforcement by providing alternate failure path along the interface between the reinforcement and the matrix.
- Carry interlaminar shear.

b) Role of Reinforcement

In a composite, the reinforcement performs the following functions:

- Carry the load and provide strength and stiffness to the composite.
- Reinforcement help the composite to obtain the desired property in the direction preferred.
- Reinforcement serves certain additional purpose of heat resistance or conduction, resistance to corrosion, and provides rigidity. Reinforcement can be made to perform all or one of these functions as per the requirements.
- Reinforcement helps to deflect the crack front in matrix thereby hindering crack growth.

c) Role of Interface

The interaction between the reinforcement and the matrix is also important in designing damage tolerant composite structures. Following are a few characteristics to be understood at the interface:

- The interface is usually a discontinuity in terms of chemical nature, crystal structure, molecular structure, mechanical properties, etc. Hence, failure of a composite usually takes place at the interface.
- The matrix transfers the load to the reinforcement via the interface. A strong interface is required to produce a high strength composite, and this is achieved when the bond between the matrix and the reinforcement is strong. However, a strong bond increases the chances of brittle failure.
- Large differences in coefficient of thermal expansion between the matrix and the reinforcement materials can result in thermal stresses resulting in plastic deformation at the interface.
- Other properties like creep resistance, fatigue resistance, and environmental degradation are also affected by the characteristic of the interface.

8.3 COMPOSITES v/s CONVENTIONAL MATERIALS

Composites have properties superior than those of conventional materials (wood, metal, plastic, etc.), and this makes them to be preferred for a wide range of applications. A few common properties which can be compared are listed and discussed briefly below.

a) High specific strength / Modulus

Specific strength is a term that relates strength to weight ratio. Aluminum for example is light in weight, but possesses low tensile strength and hence cannot be used in high strength applications. On the other hand, although steel possess high tensile strength, it is heavier. However, composites

overcome these limitations because they can be designed for both light weight (lighter than wood or plastic) and high strength. In fact, composites are used to produce the highest strength to weight ratio structures known to man. For this reason, they are widely preferred in aircraft and automobile applications.

Also, the specific modulus (ratio of material stiffness to density) is nearly 3 – 5 times greater than that of steel and aluminum.

b) High strength

Metals for example have equal strength in all directions. But composites can be engineered and designed to have strength in a specific direction. If a composite has to resist bending in one direction, most of the fiber reinforcement can be oriented at 90° to the bending force. This creates a very stiff structure in one particular direction. However in case of metals, if greater strength is required in any one direction, the material must be made thicker overall, which adds weight to the material thereby posing a disadvantage.

c) Corrosion resistance

Metals tend to corrode in the presence of moisture or aqueous environments. But, composites provide long-term resistance to severe chemical and temperature environments. This is why the marine industry depends on composites for various applications. Composites are the material of choice for outdoor exposure, chemical handling applications, and severe environment service.

d) Design Flexibility

Composites can be formed into complex and accurate shapes easier than other materials. This gives designers the freedom to create any shape or configuration. Boats are a good example of the success of composites. Boats can be made out of a variety of materials – wood, aluminum, steel, and even cement. However, composites are preferred because they can be easily molded into complex shapes.

e) Design stability

Composites retain their shape, size, and features irrespective of the environment it is put in to use, i.e., hot or cool, wet or dry, etc. But, wood may swell or shrink, metals may corrode, and plastics can become hard and brittle in similar environments.

f) Durability

Composite structures have an exceedingly long life span. Coupled with low maintenance requirements, the longevity of composites is a benefit in critical applications. In a half-century of composites development, well-designed composite structures have yet to wear out.

g) Low Relative Investment

In majority of the engineering applications, composites are cost competitive when compared to metals due to low cost, low relative investment in setting up manufacturing facility, and high volume manufacturing methods.

h) Conductive/Non-conductive

Certain composites, like those made from fiberglass are non-conductive (do not conduct electricity). This property makes them suitable for such items as electricity utility poles, circuit boards, etc. If electrical conductivity is needed, it is possible to make some composites conductive. An example to compare this property with metals is *ladder*. Aluminum ladders are light in weight, but can be an electrocution hazard, while ladders made with fiberglass are not a risk, if the ladder was to cross a power line.

8.4 CLASSIFICATION OF COMPOSITES

Composite materials are commonly classified at two distinct levels:

- With respect to matrix constituent, and
- With respect to reinforced constituent

8.4.1 Classification with respect to matrix constituent

Composites classified with respect to the matrix constituent include:

- Polymer matrix composite
- Metal matrix composite, and
- Ceramic matrix composite.

8.4.1.1 Polymer Matrix Composites (PMCs) or Fiber reinforced polymers (FRPs)

Composites are classified as *Polymer matrix composite*, when the *matrix* is made from a *polymer resin material*. The reinforcement material is usually in the form of *fibers* made from materials like glass, carbon/graphite, boron, etc. Two kinds of polymers viz., *thermosets* and *thermoplastics* are in use for matrix materials. Figure 8.2 shows the kinds of thermoplastics and thermosets. The characteristics regarding thermoplastics and thermosets are given in table 8.1 in a comparison form.

Polymers make ideal materials as they are light in weight; abrasion and chemical resistant, can be processed easily, and possess other desirable mechanical properties. However they possess low tensile strength and low impact strength.

PMCs are used for the manufacture of secondary load bearing aerospace structures, boat hulls, canoes, automotive parts, brake and clutch linings, golf clubs, skis, tennis racquets, fishing rods, bullet proof vests, armor parts, etc.

Fiber reinforced composites can be further divided based on discontinuous or continuous type of fibres. Continuous fiber-reinforced composites contain fibre reinforcements having lengths much greater than their cross-sectional dimensions as shown in figure 8.3(a). On the other hand, a composite is considered to be a discontinuous fiber or short fiber composite if its properties vary with fiber length as shown in figure 8.3(b). Discontinuous fibers can be randomly oriented as shown in figure 8.3(c). Most practical composites that are being developed for engineering applications contain discontinuous fibers.

The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. Fibers are generally anisotropic* and include glass, aramids, carbon (or graphite), boron, ceramic (silicon carbide and aluminum oxide) and metal fibers (steel, tungsten, beryllium, etc., in the form of wires).

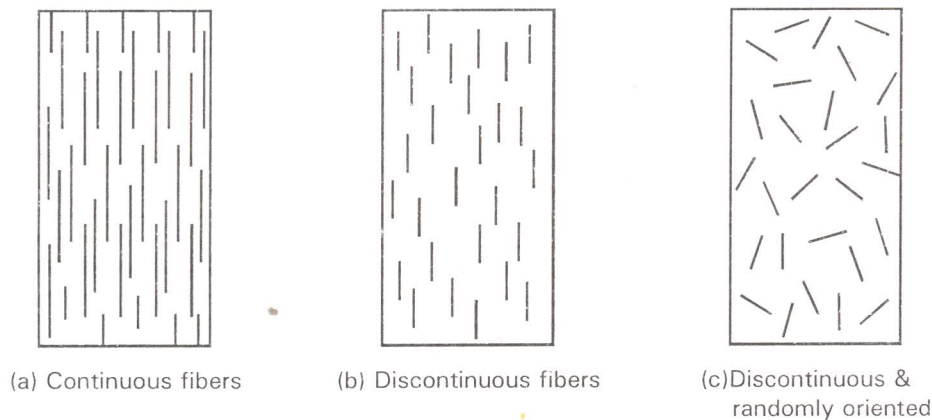


Figure 8.3 Continuous & Dis-continuous fibers

Note While use of the term *carbon* for *graphite* is permissible, there is one basic difference between the two. Carbon fibers contain about 93–94 % carbon and are produced at 1320°C, while graphite fibers have up to 99 % carbon, and are produced between 2000–3000°C. The method of fabrication of carbon/graphite fibers is provided herein for the benefit of readers.

Fabrication of carbon/graphite fibers

Carbon fibers are produced by carbonizing process making use of PAN (poly-acrylo-nitrile) precursor. Figure 8.4 shows the line diagram of the process. The various steps involved are:

- **Stabilization**

The precursor (PAN) is stretched to about 5–10 times their original length and then heated to about 200–300°C to stabilize the dimension.

* When the properties of a material vary with different crystallographic orientations, the material is said to be anisotropic. Alternately, when the properties of a material are the same in all directions, the material is said to be isotropic.

- **Carbonization**

In the carbonizing zone, the precursor fiber is heated in the range of about 1000–1500°C in the presence of an inert atmosphere like argon and nitrogen. All the elements except carbon are eliminated from the precursor fiber thereby forming ribbons of carbon aligned with the fiber axis. The carbon fibers at this stage are subjected to surface treatment to provide adequate wettability to encourage formation of a strong, durable bond.

The carbon fibers are collected in spools for future use. However if the modulus of elasticity is to be made still higher, then the fibers should undergo an additional process called *graphitization*. The modulus of elasticity of the carbon fibers is increased at the expense of tensile strength. The fibers thus produced are called graphite fibers.

- **Graphitization**

In graphitization, the carbon fibers at the end of the carbonizing process are further heated to about 2000–3000°C. Higher temperatures are necessary to drive out completely any remaining elements (except carbon) still present. In both the carbonizing and graphitization process, the fibers are subjected to tension to develop a high degree of orientation to the fibers.

The fibers at the end of graphitization process are given surface treatment to provide adequate wettability that aid in the subsequent production of the composite. The fibers are then collected in spools for further use.

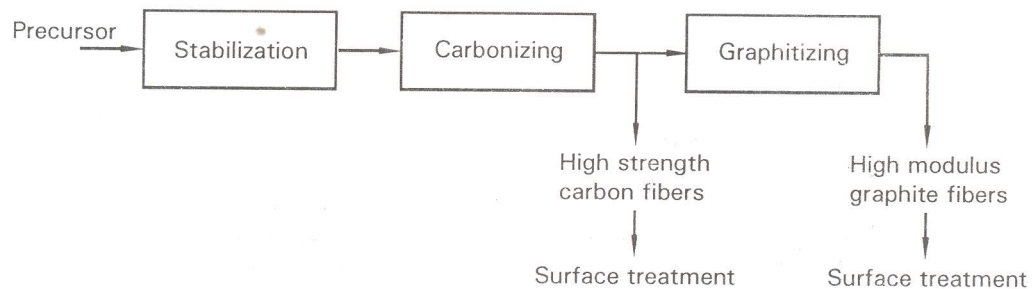


Figure 8.4 Carbonizing

8.4.2.2 Particulate composites

In particulate composites, the reinforcement consists of small particles embedded in a matrix. Refer figure 8.5. The particles are either flakes* or in powder form, and may be spherical, cubic, tetragonal, a platelet, or other regular or irregular shape, but is approximately equiaxed. They are usually isotropic because the particles are added randomly.

Very small particles less than 0.25 micron in diameter and finely distributed in the matrix impede movement of dislocations and deformation of the material. In general, particles are not very effective

* Flakes are often used in place of fibers as can be densely packed. Metal flakes that are in close contact with each other in polymer matrices can conduct electricity or heat, while mica flakes and glass can resist both. Flakes are not expensive to produce and usually cost less than fibers.

in improving fracture resistance but they enhance the stiffness of the composite to a limited extent. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. A typical example is concrete, wherein sand, gravel (reinforcement), and cement (matrix) are mixed together.

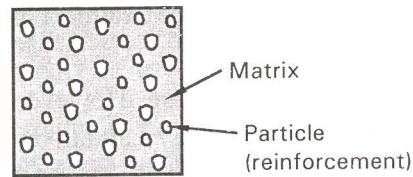


Figure 8.5 Particulate composites

8.4.2.3 Laminated composites

Laminated composites are composed of layers of reinforcement materials held together by matrix. Sandwich structures fall under this category. Refer figure 8.6 (a). Plywood is another example wherein thin sheets of veneer wood are bonded together to obtain a stronger laminated structure. Refer figure 8.6(b). Plywood layers (called veneers) are glued together with adjacent plies having their grain at right angles to each other for greater strength. There are usually an odd number of plies so that the sheet is balanced, and also reduces warping. This arrangement makes the plywood very hard to bend it perpendicular to the grain direction.

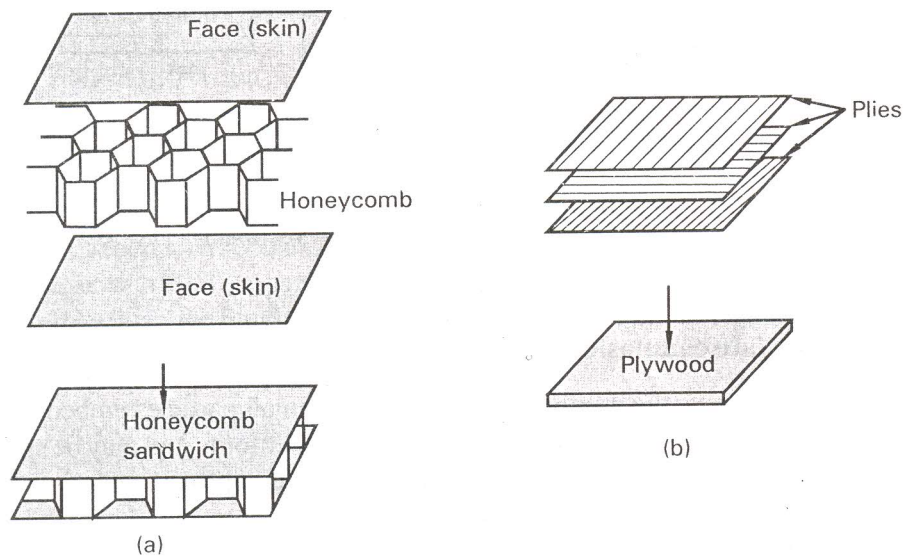


Figure 8.6 Laminated composites

In laminated composites, layers of sheets are stacked and subsequently cemented together such that the orientation of the high-strength direction varies with each successive layer. Laminations

may also be constructed using fabric material such as cotton, paper or woven glass fibers embedded in a plastic matrix. Thus a laminar composite has relatively high strength in a number of directions in the 2D plane; however the strength in any given direction is, of course, lower than it would be if all the fibers were oriented in that direction.

Metals too are examples of laminated composites. The cladding of an aluminum-copper alloy with aluminum to give a material with a better corrosion resistance is a good example. Galvanized steel can be considered a further example, the layer of zinc on the steel giving better corrosion resistance.

8.5 ADVANTAGES & LIMITATIONS OF COMPOSITES

Listed below are a few major advantages and limitations exhibited by composite materials:

Advantages

- a) Composites possess high strength to weight ratio. Weight savings are significant, ranging from 25–45% of the weight of conventional metallic designs.
- b) High resistance to fatigue and *corrosion degradation*.
- c) Durable – long service life.
- d) Excellent structural damping features.
- e) Composites are *dimensionally stable*. They have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements to minimize thermal stresses.
- f) Due to greater *reliability*, there are fewer inspections and structural repairs.
- g) Directional *tailoring capabilities* to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- h) Composites offer improved *torsional stiffness*. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing & assembly costs are thus reduced.
- i) There is no limit to shape and size of components to be produced.
- j) Manufacture and assembly are simplified because of part integration (joint & fastener reduction) thereby reducing cost.
- k) Close tolerances can be achieved without machining.
- l) Improved friction and wear properties.

Limitations of Composites

- a) High cost for raw materials and fabrication. Although manufacturing processes are often more efficient when composites are used, the raw materials are expensive. Composites will never totally replace traditional materials like steel, but in many cases they are just what we need.
- b) Transverse properties may be weak.

- c) Reuse and disposal may be difficult.
- d) Repair introduces new problems, for the following reasons:
 - Constituent materials require refrigerated transport & storage, & have limited shelf life.
 - Hot curing is necessary in many cases requiring special tooling.
 - Hot/cold curing consumes more time.
- e) Matrix can be subjected to environmental degradation.
- f) Composites do not have a high combination of strength and fracture toughness compared to metals. (Metals show an excellent combination of strength and fracture toughness compared to composites).
- g) Mechanical characterization of a composite structure is more complex than that of a metal structure. Unlike metals, most composite materials are not isotropic, that is, their properties are not the same in all directions. Therefore, they require more material parameters. For example, a single layer of a graphite/epoxy composite requires *nine stiffness* and strength constants for conducting mechanical analysis. In the case of a monolithic material such as steel, one requires only *four* stiffness and strength constants. Such complexity makes structural analysis computationally and experimentally more complicated and intensive.

Note For a composite to be isotropic in a specific property, such as coefficient of thermal expansion or Young's modulus, the reinforcing elements, whether fibers or particles, have to be randomly oriented. However, this is not easily achieved in case of discontinuous fibers, since most processing methods tend to impart a certain orientation to the fibers.

8.6 APPLICATIONS OF COMPOSITES

To list the various applications of composites is an endless process. A few major applications of composites in various fields are listed below.

- **Aircraft**

Used to make rotor blades, fins, rudders, wing body, fuel tanks, propeller blades, helicopter frames, canopies, radomes, fairings, engine cowlings, landing gear doors, floor panels, fan ducts, interior parts like overhead bins, sidewall panels, ceilings, partitions, cargo floor board liners, etc.

- **Spacecraft**

Rocket motor casings, rotor blades, heat shields and nozzles, panel doors, structural truss elements, fuel tanks, turbine and combustion chamber components, high gain antenna boom, etc.

- **Marine**

Propeller vanes, fans and blowers, condenser shells, valves and strainers, gear cases, small boats, hulls, etc.

- **Automobiles**

Combustion engine components, disc brakes, brake parts, drive shaft components, steering wheel, bumpers, door and roof linings, radiator tank and supports, etc.

- **Construction industry**

Doors, door hinges, window frames, paneling, water tanks, furniture, interiors, sanitary ware, pipes, kitchen sinks, partitions, ceilings, wall panels, long span roof structures, bridge structural components, etc.

- **Electrical/Electronics**

Power line insulators, switch gear frames, parabolic antenna, Street light canopies, ladders, insulation brackets, junction boxes, circuit breaker components, brush holders, fuse blocks, knobs, fan regulator cover, meter covers, electricity utility poles, circuit boards, etc.

- **Medical**

Artificial parts made from composites to replace lost arms and legs, teeth, optical lenses, spinal braces, crutches, wheel chairs, etc.

- **Sports**

Drum sticks, tennis racquets, ice hockey sticks, snowboards, golf rods, archery equipment, bicycle frames, racing boats, ski poles, canoes, protective sportswear, etc.

- **Consumer products**

Washing machine parts, camera parts, wrist watch components, household mixer casings, refrigerator & air conditioner components, chairs, tables, chimney duct parts, etc.

8.7 PRODUCTION OF FIBER REINFORCED PLASTICS (or PMCs)

Fiber reinforced plastics or polymer matrix composites are manufactured by several methods as listed below.

a) Open mould Process

- Hand lay-up process
- Spray lay-up process
- Bag moulding process
 - Pressure bag moulding
 - Vacuum bag moulding
 - Autoclave process
- Filament winding process, etc.

b) Closed mould process

- Pultrusion process (continuous process)
- Compression moulding
- Injection moulding
- Sheet moulding compound (SMC) process
- Resin transfer moulding
- Thermoforming
- Blow moulding
- Pulforming, etc.

A few commonly used processes are discussed briefly in the following sections.

8.8 OPEN MOULD PROCESS

8.8.1 Hand Lay-up (Wet lay-up) Process

Hand lay-up is the simplest and the oldest method of fabricating fiber reinforced plastic. The process is shown in its simplest form in figure 8.7.

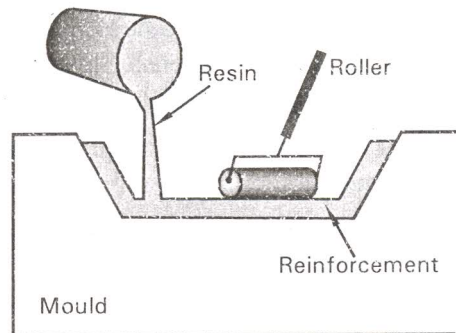


Figure 8.7 Hand lay-up process

To produce a part, a mould having the shape of the desired part is initially made of wood, wax, clay, or plastics. A gel coat is applied to the open mould so that the finished component can be easily stripped from the mould without adhering to it. The fiber glass reinforcement which is normally in the form of a woven cloth, chopped strand, or mat is manually placed in the mould. The plastic resin (matrix), usually epoxy, polyster, or phenolic resin mixed with catalysts* and accelerators is then applied by pouring or brushing. Rollers or squeezers are used to thoroughly wet the reinforcement with the resin matrix material to enable good compaction, and also to remove entrapped air. To increase the thickness of the composite being produced, successive layers of fiber glass mat and resin may be added as desired. The mould is allowed for a certain duration to complete full curing of the composite. The finished composite is then removed carefully from the mould.

Advantages

- Simple in operation.
- Low investment and manufacturing cost
- Both large and small components can be manufactured.

Disadvantages

- Labour intensive and operator dependent.
- Low volume production process.

* Since resins are stored at low temperatures with stabilizers in them, they require catalysts and accelerators to start the curing action.

- Lo
- Mo

Applic

- The
- etc.

8.8.2

Spray la
reinforc

To produc
or plastics
stripped fi
The fiber g
spray gun
carrying th
cases with
glass fiber
directly on
simultane
layers as w
desired par
application

Advantag

- Simple

- Longer cure times. It requires days for the final cured product.
- More material waste.

Applications

- The process is used in the manufacture of boat hulls, tanks, building panels, architectural mouldings, etc.

8.8.2 Spray Lay-up process

Spray lay-up process is similar to hand lay-up process except in the application of the matrix and reinforcement materials. Figure 8.8 shows the schematic of spray lay-up process.

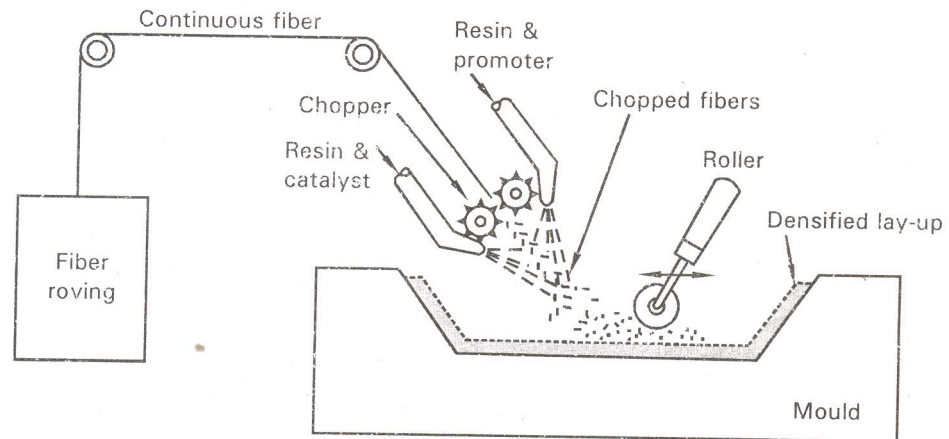


Figure 8.8 Spray lay-up process

To produce a part, a mould having the shape of the desired part is initially made of wood, wax, clay, or plastics. A gel coat is applied to the open mould so that the finished component can be easily stripped from the mould without adhering to it.

The fiber glass reinforcement which is normally in the form of continuous strand is fed through a spray gun-chopper combination equipment. The gun can have separate feeder pipes: one for carrying the premixed resin (matrix)+catalyst, and another for catalyst+accelerator, or in some cases with single feeder pipe carrying resin, catalyst and accelerator together. The continuous glass fibers are first cut in lengths of 50 mm in the chopper and then ejected into a resin stream directly onto the mould. With this arrangement, the chopped fibers and the catalyzed resin are simultaneously deposited into the mould. The deposited materials are then rolled to compact the layers as well as to remove entrapped air bubbles. Multiple layers may be added to produce the desired part thickness. Curing is usually at room temperature, or it may be accelerated by the application of a moderate amount of heat.

Advantages

- Simple in operation.

- Quick depositing of fibers and resin.
- Both large and small components can be manufactured.

Disadvantages

- Labour intensive and operator dependent. Parameters like spray distance and spraying time need to be appropriately controlled.
- Only short fibers are incorporated, & this limits the mechanical properties of the composite.
- Low viscosity resins need to be employed, and this generally compromises their favourable properties.
- Difficult to control thickness of composite.

Applications

- The process is used in the manufacture of lightly loaded structural panels like caravan bodies, truck fairings; shower trays, bathtubs, etc.

8.8.3 Bag Moulding

Bag moulding is a method of forming and curing reinforced plastic laminates by employing a flexible bag or mattress to apply pressure uniformly over one surface of the laminate. A preform comprising a fibrous sheet (reinforcement) impregnated with a resin (matrix) is placed in a rigid mold forming one surface of the component. The bag is applied to the other surface and pressure is applied by a vacuum, an autoclave, a press or by inflating the bag. Thus bag moulding can be classified into 3 types: *Vacuum bag moulding*, *Pressure bag moulding*, and *Autoclave bag moulding*.

8.8.3.1 Vacuum bag moulding

Vacuum bag moulding is used to produce high-performance laminates usually of fiber-reinforced-epoxy systems. The method is primarily suited to prepreg* materials.

To produce a part by vacuum moulding process, a mould having the shape of the desired part is prepared suitably. Refer figure 8.9. A thin layer of gel coat is applied to aid easy removal of the cured component from the mould. The prepreg material, or layers of prepreg material depending upon the desired thickness, is stacked in the required orientation in the mould. The layer is covered by a airtight flexible sheet, or bag (frequently rubber), which is sealed around the edges of the mould by a sealant.

Vacuum is drawn from the lay-up (under the bag) with the help of a pump. In other words, the space between the bag and the mould is evacuated so that atmospheric pressure (up to 1 Bar) is

* *Prepregs are rolls of uncured composite materials which consists of a reinforcement material (long carbon fibers) pre-impregnated with a resin matrix in controlled quantities, i.e., they already contain an amount of the matrix material used to bond them together and to other components during manufacture. The prepregs are mostly stored in cooled areas since activation is most commonly done by heat.*

applied over the surface of the lay-up. Refer figure 8.9 (b). The vacuum created results in the elimination of voids, entrapped air and excess resin while producing a compact effect on the lay-up. The lay-up is allowed to cool to the room temperature and then ejected out of the mould. To reduce the curing time, an oven may be employed.

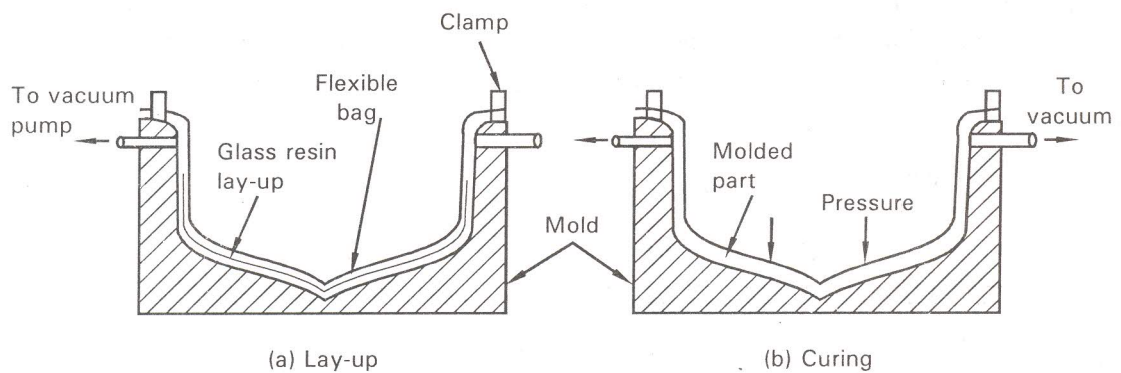


Figure 8.9 Vacuum bag moulding

Advantages

- Simple in operation.
- Both large and small components can be manufactured.
- Can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content.
- High reinforcement to resin ratio can be achieved, i.e., higher fiber content laminates can be produced.

Disadvantages

- Labour intensive and operator dependent.
- Problems in disposable bagging materials.
- Primarily suited for prepreg materials.

Applications

- An important process used in aircraft and aerospace, and other low temperature applications. For example, the technique has been used to make automobile body, aircraft component, and prototype molds for certain process.

8.8.3.2 Pressure bag moulding

Pressure bag molding is similar to the vacuum bag molding method, except that air pressure is applied to a rubber bag, or sheet that covers the lay-up composite to force out entrapped air and excess resin. Pressurized steam may be used instead, to accelerate the cure. Figure 8.10 shows the schematic of pressure bag moulding.

To produce a part by pressure moulding process, a mould having the shape of the desired part is prepared suitably. A thin layer of gel coat is applied to aid easy removal of the cured component from the mould. The prepreg material, or layers of prepreg material depending upon the desired thickness, are stacked in the required orientation in the mould, and a flexible bag is placed over the lay-up after a separating sheet, such as cellophane is laid down. The bag is then inflated with an air pressure of about $1.4\text{--}3.5\text{ kg/cm}^2$. The high pressure air causes the prepreg material to take the shape of the contours of the mold. After the part is hardened, the bag is deflated and the part is removed.

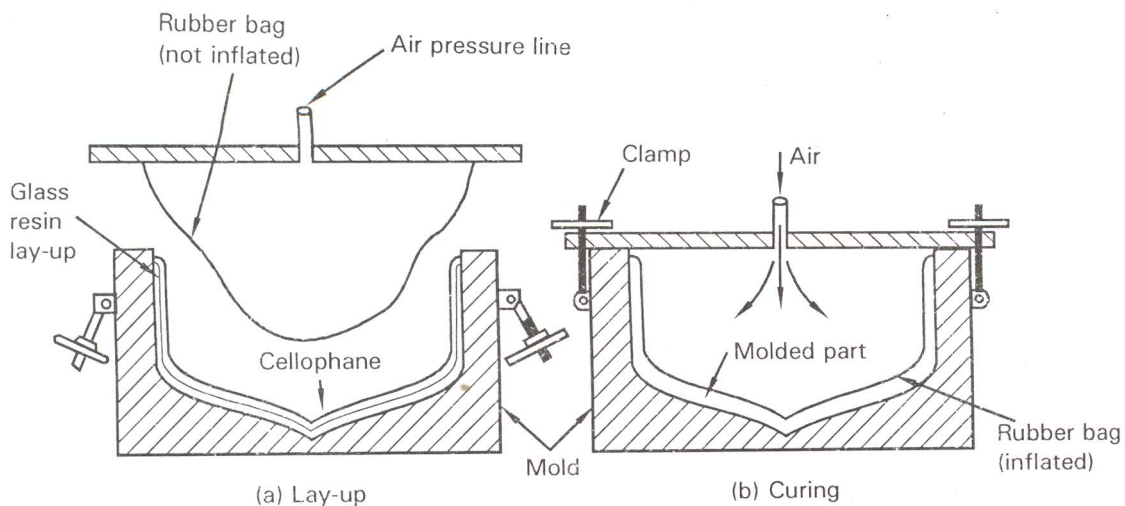


Figure 8.10 Pressure bag moulding

Advantages

- Simple in operation.
- Both large and small components can be manufactured.
- Can produce laminates with a uniform degree of consolidation.
- High reinforcement to resin ratio can be achieved, i.e., higher fiber content laminates can be produced.

Disadvantages

- Labour intensive and operator dependent.
- Moulds need to be robust in order to withstand the high pressure application.
- Primarily suited for prepreg materials.

Applications

- Used for production of high quality components like radomes, small cases, helmets, simple sections such as tubes, etc.

8.8.3.3 Autoclave Moulding

An autoclave is simply a large, heated pressure vessel. Autoclave moulding is a combination of vacuum and pressure bag moulding process. The process as shown in figure 8.11 in its simplest form is used to produce high quality composites. Nowadays it is usually used with prepreg materials.

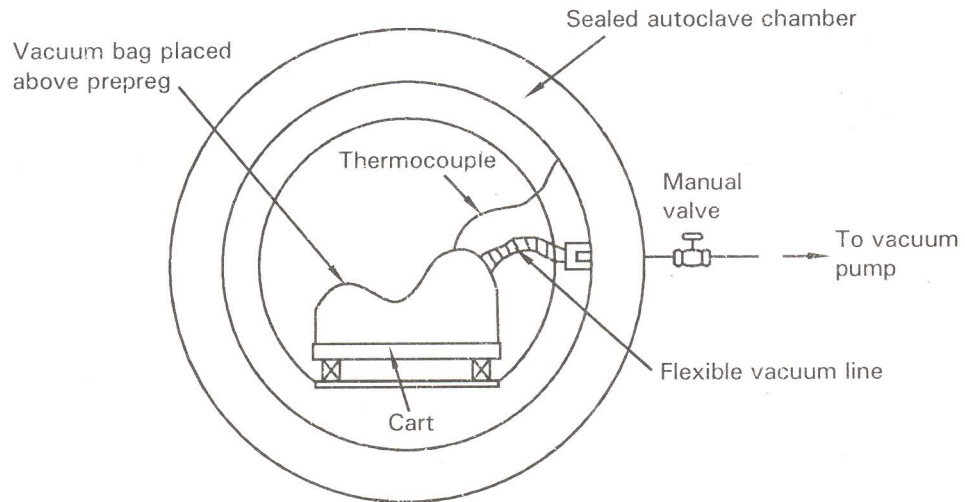


Figure 8.11 Autoclave moulding

Layers of prepreg material are laid in the desired orientation on the mould having the shape of the desired composite to be produced. Bleed cloth (absorbs resin from lay-up during curing), release film and vacuum bag are placed over the prepreg and sealed on the mould using partial vacuum. The mould and its contents are then loaded into the autoclave, which is also closed and sealed. Inside the autoclave, the laminae (lay-up) is subjected to vacuum, pressure, and heat (gas heating) simultaneously. This ensures that all air is extracted from the lay-up, and full consolidation (compaction) and curing is achieved. The mould assembly is taken out of the autoclave and the part is ejected from the mould.

Advantages

- Simple in operation.
- Both large and small components can be manufactured.
- Can produce laminates with a uniform degree of consolidation, and minimum void content.
- Laminate thickness can be easily controlled compared to vacuum and bag process.

Disadvantages

- Labour intensive and operator dependent.
- Moulds need to be robust in order to withstand the high pressure application.
- Primarily suited for prepreg materials.
- High equipment costs.

Applications

- Many large primary structural components for aircraft, such as fins, wing spars and skins, fuselages and flying control surfaces, are manufactured by this method, as it guarantees reproducibility.

8.8.4 Filament Winding Process

Filament winding is an automated process, primarily used for producing *hollow*, generally circular or oval sectioned components, such as pipes and tanks. Figure 8.12 shows the schematic of filament winding process, wherein continuous strands of glass fiber (filament) or roving is fed from a reel, passes through a resin bath (matrix) before being wound onto a mandrel in the desired orientation.

The mandrel is usually made of sand with water-soluble polyvinyl alcohol as binder. Other mandrel materials include low-melting alloys, eutectic salts, soluble plasters, etc. The shape of the mandrel is similar to the *internal geometry* of the component desired. The mandrel rotates at a predetermined speed while the carriage carrying the resin bath moves horizontally. Consolidation pressure is achieved through tensioning the fibers as they are wound onto the mandrel. Once the mandrel is completely covered to the desired thickness, the mandrel is placed in an oven to solidify (set) the resin. When the resin has cured, the mandrel is removed, leaving the hollow final product.

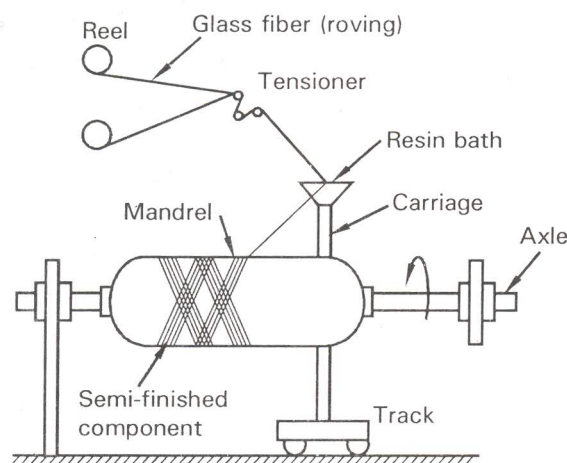


Figure 8.12 Autoclave moulding

Advantages

- Excellent mechanical properties due to use of continuous fibers.
- Highest strength to weight ratio.
- Fast and economical method for fabricating hollow components.
- Can produce components with a uniform degree of consolidation

- Winding patterns can be polar, helical or circumferential type, and hence can be selected depending on the needs.
- Since the fibers are subjected to tension effect, excess resin is effectively squeezed out.
- Process can be automated.

Disadvantages

- High cost.
- Only one smooth surface can be obtained, i.e., inner surface is smooth, but poor external finish.
- Difficult to wind complex shapes.
- Process is limited to convex shaped parts.
- Requires low viscosity resins, which lowers its mechanical properties.

Applications

Used in the fabrication of chemical storage tanks and pipelines, gas cylinders, rocket motors, launch tubes, pressure vessels, missile cases, drive shafts, fishing rods, golf pipes, bicycle forks, lamp posts, yacht masts, etc.

8.9 CLOSED MOULD PROCESS

8.9.1 Pultrusion Process

Pultrusion* is a continuous fiber reinforcement plastic molding process, used for producing parts that have a constant cross-section profile, such as I-beam, channels, tubes, pipes, etc. Figure 8.13 shows the process in its simplest form.

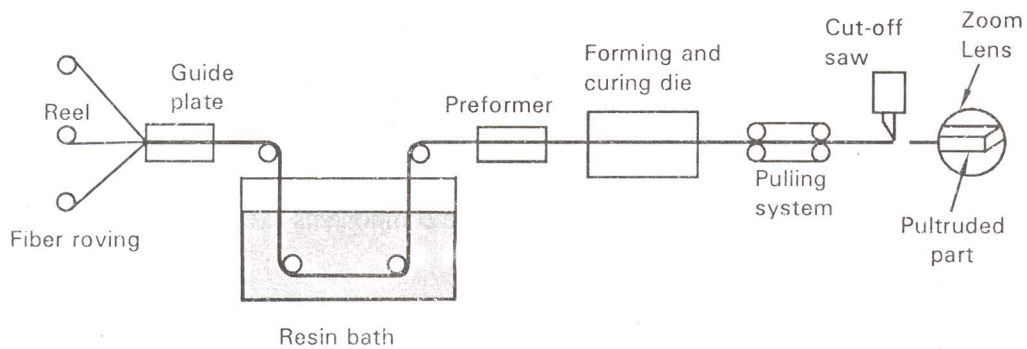


Figure 8.13 Pultrusion process

* The term pultrusion combines the words, 'pull' and 'extrusion'. Extrusion is the pushing of material, such as a billet of aluminum, through a shaped die. Whereas, pultrusion is the pulling of material, such as fiberglass and resin, through a shaped die.

The pultrusion process starts with raw fibers or fiber roving being pulled off the reels and guided through a resin bath or resin impregnation system (matrix). The resin is usually a thermosetting resin, and is sometimes combined with fillers, catalysts, and pigments. The fiber reinforcement becomes fully impregnated (wetted-out) with the resin such that all the fiber filaments are thoroughly saturated with the resin mixture.

The wet fibers exit the bath and enter the preformer where the excessive resin is squeezed out from the fibers and pre-compacted to the approximate profile. The preformed fiber passes through a heated steel or ceramic die, which has the shape similar to the part to be produced. The heat energy transferred inside the metal die activates the curing or polymerization of the thermoset resin changing it from liquid to solid state. The part that exits the die is now a cured pultruded Fiber Reinforced Polymer (FRP) composite. The cured product is cut to the desired length by the cut-off saw as shown in the figure.

Advantages

- High productivity.
- Process parameters are easily controllable.
- Low waste (Material scrap rate is low).
- Low labour cost.
- Precise cross-section dimensions of the products.
- Good surface quality of the products.
- Homogeneous distribution and high concentration of the reinforcing fibers in the material is achieved.

Disadvantages

- High investment cost.
- Long tooling time.
- Limited to constant or near constant cross-section profiles

Applications

Used in the fabrication of constant cross-section profile components like I-beam, channels, tubes, pipes, poles, tanks, etc.

8.9.2 Compression Moulding

Compression molding is a closed mold process in which the charge is squeezed into a preheated mold taking the shape of the mold cavity and performing curing (cross-linking) due to heat and pressure applied to the material. Compression molding process as shown in figure 8.14 involves the following steps:

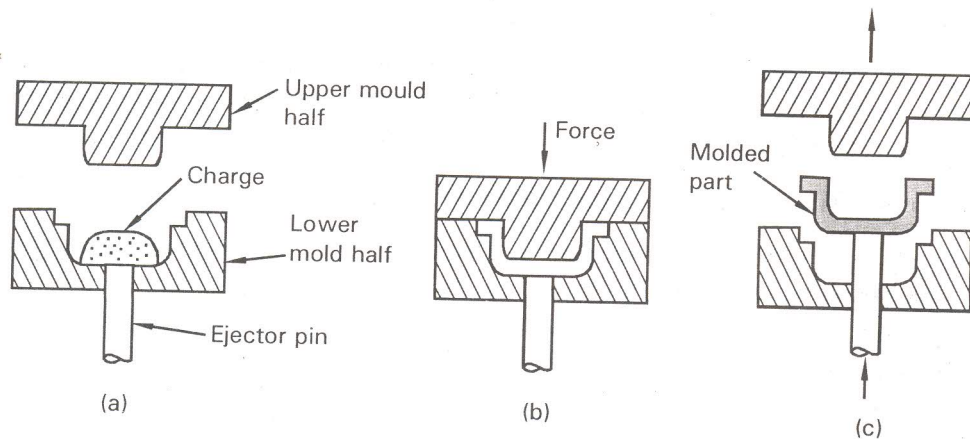


Figure 8.14 Compression moulding

A pre-weighed amount of a polymer (commonly thermosetting resin) mixed with chopped reinforcing fibers, hardening agent, anti-adhesive agent and pigment (charge) is placed into the lower half of the mold. The charge may be in form of powders, pellets, or pre-formed* sheets. The charge is usually preheated prior to placement into the mold. Preheated polymer becomes softer resulting in shortening the molding cycle time. The upper half of the mold moves downwards, pressing on the charge & forcing it to fill the mold cavity. The mold, equipped with a heating system, provides curing (cross-linking) of the polymer matrix. Heat & pressure are maintained until the molding material has cured. The mold is opened and the part is removed from it by means of the ejector pin.

Advantages

- High productivity.
- Ability to mould large and intricate parts.
- Precise cross-sectional dimensions of the products.
- Good surface quality of the products.
- Low waste.

Disadvantages

- High investment cost.
- Moulds need to be fabricated with high degree of surface finish and accuracy.
- High impact composites make flash control & part removal difficult.
- Secondary operations are sometimes required.

* *Preform* - An object that has been subjected to preliminary, usually incomplete shaping or molding before undergoing complete or final processing

Applications

Components produced by compression moulding are generally electrical components and fittings as thermosets are good electrical insulators e.g. electrical switches and sockets. The process is also used for panels, housings, container caps, dishes and body panels and hoods for automobiles.

8.9.3 Injection Moulding (Liquid injection moulding)

Injection moulding is a closed mould process, in which *molten* polymer (commonly thermoplastic) is mixed with very short reinforcing fibers and injected (forced) under high pressure into a mould cavity having the shaped of the component to be produced. Figure 8.15 shows the details of injection moulding process.

The Polymer-fiber mixture in form of pellets is fed into an Injection Moulding machine through a hopper. The material is then conveyed forward by a feeding screw, which can move forward and backward according to the steps of the moulding cycle. The pellets flow into the heated barrel, where it is melted by heating elements. The screw now acts as a ram in the filling step, wherein the molten polymer-fiber mixture is injected into the mould (under pressure) through the nozzle and sprue as shown in the figure. When the material cools and solidifies, the part is ejected by means of ejector pins. The mold is equipped with a cooling system providing controlled cooling and solidification of the material.

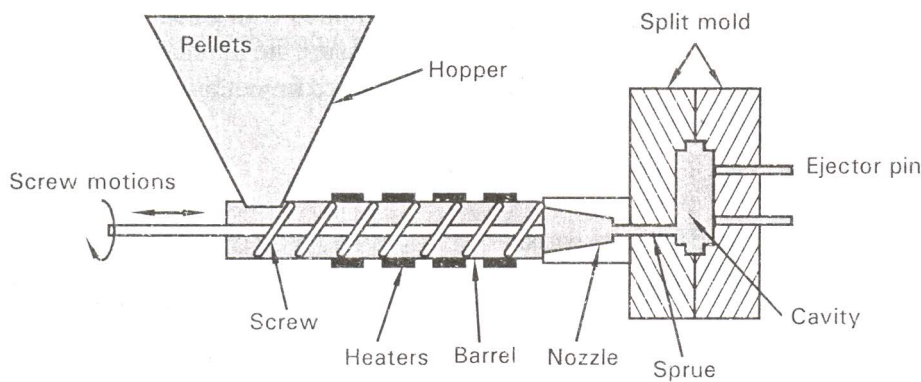


Figure 8.15 Injection moulding

Advantages

- High productivity. Suitable for mass production.
- Process parameters are easily controllable.
- Low waste (Material scrap rate is low).
- Precise cross-section dimensions of the products.
- Good surface quality of the products.
- Ability to mould large and intricate parts.

Disadvantages

- High investment cost.
- Limited length of fibers decreases their reinforcing effect.

Applications

Mainly used in automotive industries for the production of front and rear bumpers as well as front and rear fenders and other parts.

8.9.4 Sheet Moulding Compound (SMC) Process

The compression moulding process is most commonly called the SMC process in reference to the precursor sheet moulding compound (SMC) material it uses. In simple words, sheet moulding compound (SMC) refers to both a material and a type of compression moulding process for producing glass fiber reinforced polyester resin based components. Figure 8.16 shows the SMC processing machine for producing moulding compound in sheet form.

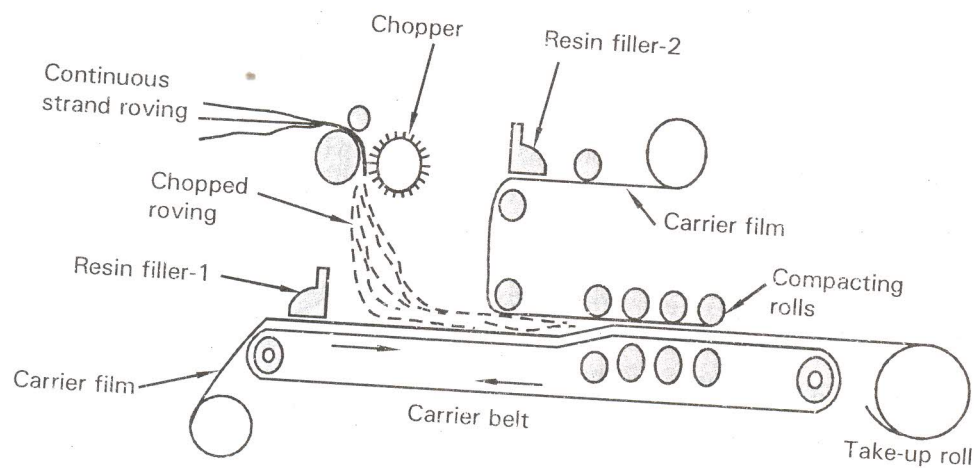


Figure 8.16 SMC Process

Process

In this process, an exact amount of plastic resin paste (similar to plastic wrap) is deposited over a travelling polyethylene film (sheet) with the help of a filler-1. On top of this resin paste, continuous strand fiber glass roving cut to suitable lengths by a chopper is deposited as shown in the figure. Simultaneously, another layer of polyethylene film and resin paste from filler-2 is added over this combination to form a continuous sandwich of fiber glass and resin. The sandwich that is covered with polyethylene sheet on its top as well as at its bottom is pressed further onto each other with the help of compacting rollers, forming them into single solid piece. They are then placed on a take-up roll while the material matures, which occurs in an oven type controlled area for at least 48 hours.

It is then placed into a cooling area. Once reaching the cooling area, it must be used within 30 days. The sheet moulded rolls thus produced serve as raw material to make a composite material by another process, say compression moulding process.

Advantages

- High volume production
- Improved surface quality.
- Provides better chemistry and mixing before forming into products.
- Precise cross-section dimensions of the products.
- Ability to mould large and intricate parts.

Disadvantages

- High investment and processing cost.
- SMC material must be stored suitably to withstand thermal and moisture degradation.
- SMC sheet-forming line must be properly protected to prevent toxic vapor emissions.

Applications

Generally used for electrical components and fittings as thermosets are good electrical insulators e.g. electrical switches and sockets. The process is also used for panels, housings, container caps, dishes and body panels and hoods for automobiles.

8.9.5 Resin Transfer Moulding

Resin Transfer Molding (RTM) is a low pressure closed mould process primarily used for molding polymer composites with thermosetting resin matrices, but some thermoplastic parts may also be produced by the process. Figure 8.17 shows the RTM process.

The mould cavity is initially given a gel coat, filled with reinforcing preformed fibers, and then the mould is closed. A pre-weighed amount of a polymer mixed with additives and fillers is placed in the transfer pot as shown in figure 8.17(a). The charge is heated in the pot by means of heating elements, due to which it softens and reaches semi-molten state.

The plunger, mounted on the top plate, moves downwards, pressing on the polymer charge and forcing (transferring) it into the mold cavity through the sprue thereby impregnating the fibers present in the mould cavity. The mold, equipped with a heating system, provides curing (cross-linking) of the polymer (if thermoset is processed). The mold is opened and the part is removed from it by means of the ejector pin.

Resin transfer moulding is capable of producing very large parts (car body shell), more complicated than compression moulding, but not as complicated as injection moulding process.

Advantages

- Components will have good surface finish on both sides.

- Selective reinforcement and accurate fiber management is achievable.
- Uses only low pressure injection.
- Ability to produce near net shape moldings, reducing material wastage.
- Process can be automated, resulting in higher production rates with less scrap.
- Ability to mold complex structural and hollow shapes.

Disadvantages

- Mould design is critical
- Control of flow pattern or resin uniformity is difficult. Radii and edges tend to be resin rich.
- High investment costs

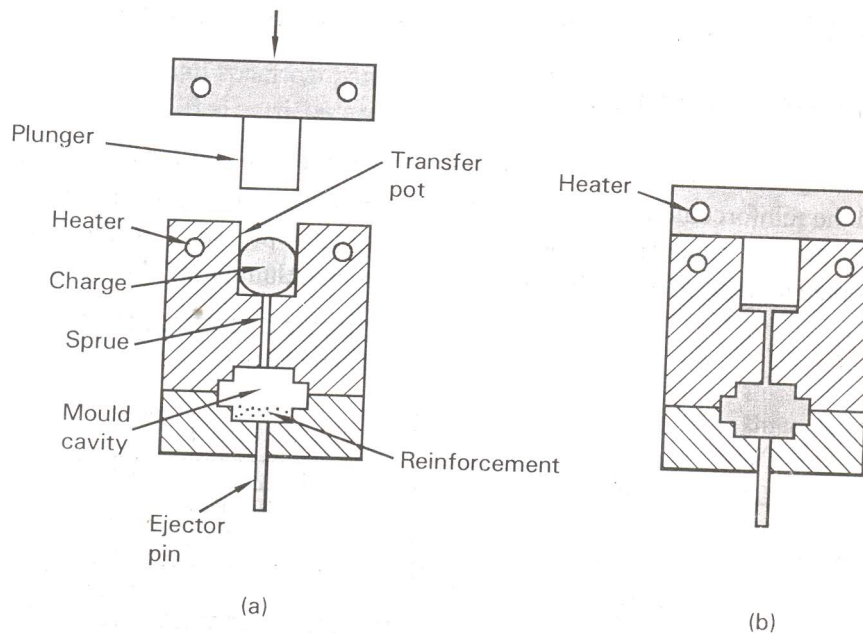


Figure 8.17 Resin transfer moulding

8.10 PRODUCTION OF METAL MATRIX COMPOSITES (MMCs)

Metal matrix composites are manufactured by several methods as listed below.

- a) Solid state method
- Diffusion bonding
 - Explosive welding
 - High Energy Rate Forming (HERF)
 - Powder Metallurgy Technique

- b) Liquid state method
 - Stir casting
 - Squeeze casting
 - Spray deposition
- c) Vapour co-deposition method
 - Plasma spray Technique
 - High Velocity Oxy-Fuel (HVOF) process
 - Osprey Process
- d) In-Situ Fabrication technique

A few commonly used processes are discussed briefly in the following sections.

8.11 DIFFUSION BONDING

Diffusion bonding is a solid state fabrication method of MMCs, wherein the matrix in the form of thin foils and the reinforcement in the form of long continuous fibers are stacked in a particular order and then pressed at elevated temperatures and suitable pressure. Refer figure 8.18. The process is adopted for producing MMCs with light alloys like Aluminum, Magnesium, or Titanium.

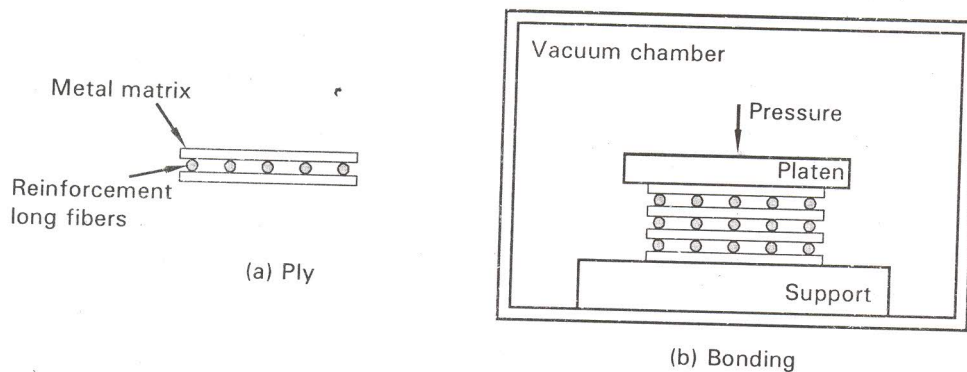


Figure 8.18 Diffusion bonding

The process begins by stacking of aluminum foils (matrix) and silicon carbide coated boron fibers (reinforcement) in the desired sequence as shown in figure 8.18(a). This arrangement is called *ply*. An acrylic binder is used to retain the fiber between two aluminum foils.

A number of such plies are built to the desired dimensions of the composite required and then enclosed in an evacuated chamber as shown in figure 8.18(b). The assembly is heated to a temperature of about 300°C and then compacted in a die at a pressure of 35MPa . The high temperature is sufficient to cause mutual diffusion of atoms/molecules between the matrix and the reinforcement material. The high pressure associated with the diffusion process results in a strong bond between the matrix and the reinforcement phase.

8.12 POWDER METALLURGY TECHNIQUE

Powder Metallurgy Technique

Powder metallurgy is the process of making components from metallic powders. The process involves blending (mixing) fine powdered materials, pressing them into a desired shape (compaction), and then heating the compacted material in a controlled atmosphere (sintering process) to bond the material. The details of the process are described below.

Step 1 Powder manufacture

There are various methods available for production of powders, depending upon the type and nature of metal. Figure 8.19 shows the widely used *atomization* process, wherein a stream of water (or air) strikes the molten raw material, causing the molten metal to disintegrate and in turn solidify in the form of small spherical particles (powder particles) during their fall through the atomizing tank. The solidified particles are then collected at the bottom of the tank.

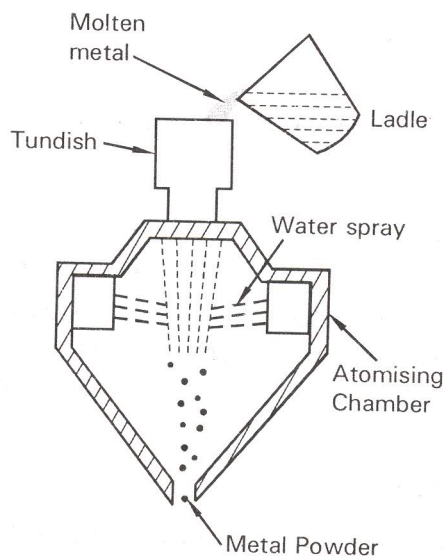


Figure 8.19 Atomization

Step 2 Powder mixing/blending

Blending is the process of mixing metal powders either in the wet or dry state by means of a mixer. The process helps to obtain uniform distribution of particle sizes. Lubricants are added to the powders before mixing.

Step 3 Compacting (Powder pressing)

Compacting is a process of compressing loose metal powder particles into the desired shape and size by the application of high pressures. The process is usually carried out in a die-punch assembly, and the resulting product is ejected from the die cavity as shown in figure 8.20. The main purpose

of this step is to obtain sufficient green strength and to increase apparent density. Compacting pressures may vary from 80–800 MPa.

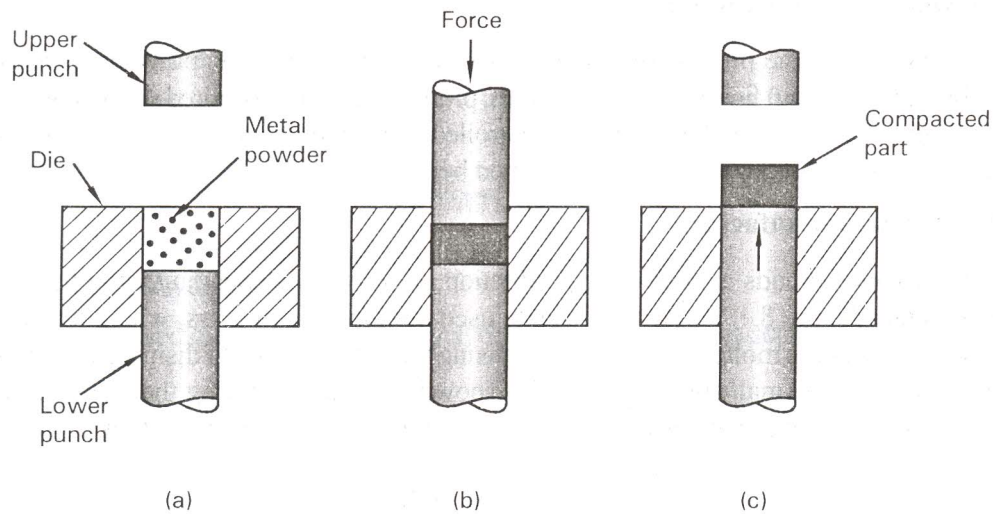


Figure 8.20 Compaction

Step 4 Sintering

Green compact after compacting operation is not very strong and hence the compacted powders have to be sintered. Sintering imparts strength, density, and hardness to the compacted powders.

Sintering consists of heating the compacted component in a furnace under controlled atmosphere for certain time duration at a suitable temperature. Under the influence of heat, bonding takes place between the porous aggregate particles and once cooled, the powder gets bonded to form a solid piece resulting in high strength and hardness.

Step 5 Finishing Operations

These are secondary operations intended to provide dimensional tolerances, physical and better surface finish, and other characteristics to the product. Finishing operations include: sizing, infiltration, coining, heat treatment, machining, plating, etc.

Advantages of Powder Metallurgy

- Components produced are clean, bright and ready for use.
- Components can be produced with good surface finish and close tolerance.
- High production rates.
- Complex shapes can be produced.
- Wide range of properties such as density, porosity and particle size can be obtained for particular applications.

- f) In many cases, there is usually no need for subsequent machining or finishing operations.
- g) The process facilitates mixing of both metallic and non-metallic powders to give products of special characteristics.
- h) Porous parts can be produced efficiently which could not be made by other processes.
- i) Skilled labours is not a requirement.

Limitations

- a) Metal powders and the equipment used are very costly.
- b) Storing of powders offer great difficulties because of possibility of fire and explosion hazards.
- c) Parts manufactured by this process have poor ductility.
- d) Sintering of low melting point powders like lead, zinc, tin etc., offer serious difficulties.

Applications

Powder metallurgy techniques are used for making large number of components. A few of them include:

- a) Self-lubricating bearing and filters
- b) Friction materials like clutch liners and brake bands.
- c) Gears and Pump Rotors
- d) Production of refractory materials like tungsten, molybdenum, tantalum and niobium.
- e) Electrical contacts and resistance welding electrodes.
- f) Soft magnetic materials that are used in D.C. motors, or generators as armatures and in measuring instruments.
- g) Cemented carbide cutting tools, wire drawing dies and deep drawing dies.
- h) Diamond impregnated tools for cutting porcelain, glass, and similar materials.

8.13 STIR CASTING

Stir Casting is a liquid state method of composite material fabrication, wherein, the reinforcement (ceramic particles or short fibers) is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional metal forming technologies. Stir casting is the simplest and the most cost effective method of liquid state fabrication methods. The schematic of the stir casting process is shown in figure 8.21.

In the stir casting process, the alloy matrix, say aluminum, is melted at a controlled temperature and the desired quantity of reinforcement material is added to the molten alloy. Argon is usually used as the carrier gas to assist injection of the reinforcements in clean form. The molten alloy is stirred continuously to create a vortex to force the slightly lighter particles into the melt. Stirring continues to disperse the reinforcement particles as uniformly as possible in a short time. The molten mixture

is then transferred into a preheated and pre-coated transfer ladle. The material is stirred again and then poured into preheated permanent molds having the desired shape of the composite to be produced. Sufficient time is allowed for solidification of the material, which in turn is cut to shape and surface cleaned.

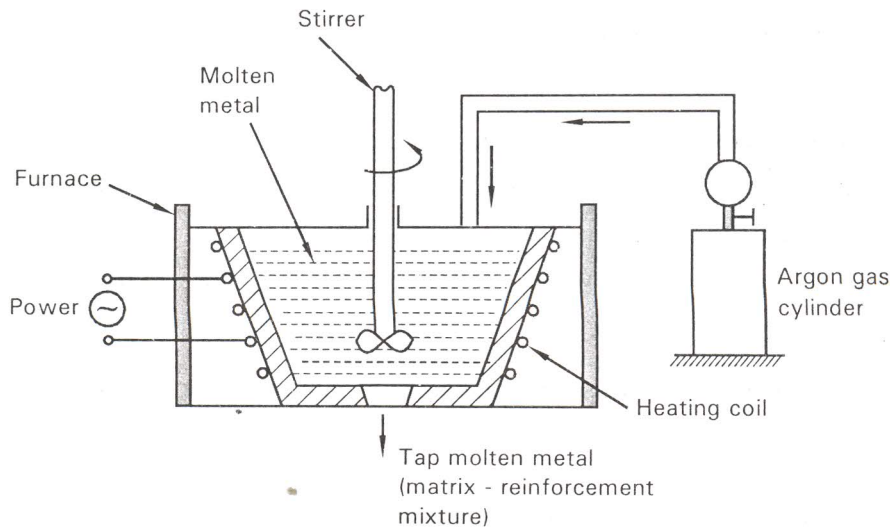


Figure 8.21 Stir Casting

8.14 SQUEEZE CASTING

Squeeze Casting is a forced infiltration method of liquid phase fabrication of MMC's, carried out by using a movable mold part (ram) for applying pressure on the molten metal (matrix) and forcing it to penetrate into a performed (reinforcement), placed into the lower fixed mold part. Figure 8.22 shows the sequence of operations involved in the process.

The process makes use of two dies: bottom die and top die, cast and machined in such a way that upon mating leaves a cavity similar to the shape of the desired component. Refer figure 8.22(a). The reinforcement material, generally discontinuous alumina fibers are placed into the bottom die, which is located in the bed of hydraulic press. Refer figure 8.22(b). The molten matrix metal, generally aluminum, in a predetermined amount is poured into the bottom die, which is usually preheated to about 200°C. The top die (ram) under the influence of pressure, moves downwards to force the liquid metal to infiltrate the reinforcement. The applied pressure may be in the range of 70 – 100 MPa. Refer figure 8.22(c). The infiltrated material solidifies under the applied pressure. The part is then ejected from the mold by means of the ejector pin located in the hydraulic bed. Refer figure 8.22(d).

Advantages

- Metals which have poor fluidity characteristics can be cast by this process.
- Low shrinkage and gas porosity, because of applied pressure during solidification.