Introduction to Composite Materials

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Abstract This chapter gives an overview of the important aspects of composite materials. The need for composite materials and the advantages over conventional materials are discussed. The definition of composite materials is given with suitable examples. The classification of composites based on the matrix and reinforcement is explained in this chapter. The fundamental aspects like, load transfer and rule of mixtures are discussed in detail. The important characteristics of different fibres and matrices are explained briefly. Manufacturing methods for polymer, metal and ceramic matrix composites are briefly explained in this chapter. Some of the important applications of composites are also highlighted here.

Materials with unusual combination of properties are required for modern technologies. Since the properties of conventional materials are limited, they cannot meet the requirements. In general, the high strength materials are heavy or brittle. The material property combinations have been extended with composite materials. It is possible to produce a composite material with high strength and light weight. Like this, materials with unusual combination of properties can be made with composite materials. For example, cemented carbide, the composite of tungsten carbide and cobalt, has very high hardness and appreciable toughness. Similarly light weight composites can be made with good electrical properties, chemical resistance or optical properties.

Composite materials are a combination of two or more materials in such a way that there are certain desired properties or improved properties. The nature itself is making many composites because of their high performance. Wood and bone are the common examples of natural composites. The constituents of wood are cellulose fibre and lignin matrix, whereas in bone, soft and strong collagen surrounds hard and brittle apatite. The principle of combined action is utilised in composites to get better properties. For example, the polymer composite gets flexibility and light weight from polymer matrix and high strength from the fibre reinforcement.

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The composite materials have many advantages over conventional materials. Most of the composites are made with light-weight materials. However, their mechanical properties are significantly high. Hence, the specific strength and modulus values of composites are very high. They have very good chemical resistance and weather resistance. There are many reinforcements and a variety of matrix materials available. By a suitable selection of reinforcement and matrix material, it is possible to get the desired properties from the final composite. When the fibres are used as reinforcements, a composite with directional properties can be obtained by aligning the fibre reinforcement in the required direction. This type of composites is very useful for structures, which require different properties in different directions. A variety of manufacturing techniques are available to produce polymer composites. Hence, it is very easy to manufacture composites with complex shapes. Because of their high specific strength and stiffness, composites can lead to a significant weight reduction. In the present scenario of energy crisis and environmental consciousness, this is very important to increase the fuel efficiency of transport vehicles.

In a composite material, the discontinuous constituent is called reinforcement and the continuous constituent surrounding the reinforcement is called matrix. Composites are generally heterogeneous materials, consisting of two or more materials. There are some composites made with the same material, but in different forms. A few examples are silicon carbide fibre reinforced silicon carbide and carbon fibre reinforced carbon composites.

There are many factors, which control the final properties of a composite material. The most important factor is the properties of constituents, viz. the reinforcement and the matrix. The next important factor is the concentration of constituents, i.e. the quantity of reinforcement and matrix. Apart from these factors, the size, shape, orientation and the nature of the distribution of reinforcement also play a major role in controlling the properties of the composites. These factors are schematically illustrated in Fig. 1. It is desirable to use very fine fibrous reinforcements, which are uniformly distributed throughout the matrix to achieve good and reliable properties in the composites. The orientation of the reinforcement controls the directional properties. It is possible to achieve very high mechanical properties by aligning the reinforcement fibres along the loading direction. In general, the reinforcements have better mechanical properties than the matrix materials. Hence, the composites with higher quantity of reinforcements have better mechanical properties than that of composites with lesser quantity of reinforcements.

The approximate properties of composites can be estimated by using the rule of mixtures, which is given below:

$$X_c = V_r X_r + V_m X_m \tag{1}$$

where, X_c is the property of composites and X_r and X_m are the properties of reinforcement and matrix respectively. V_r and V_m are the volume fractions of

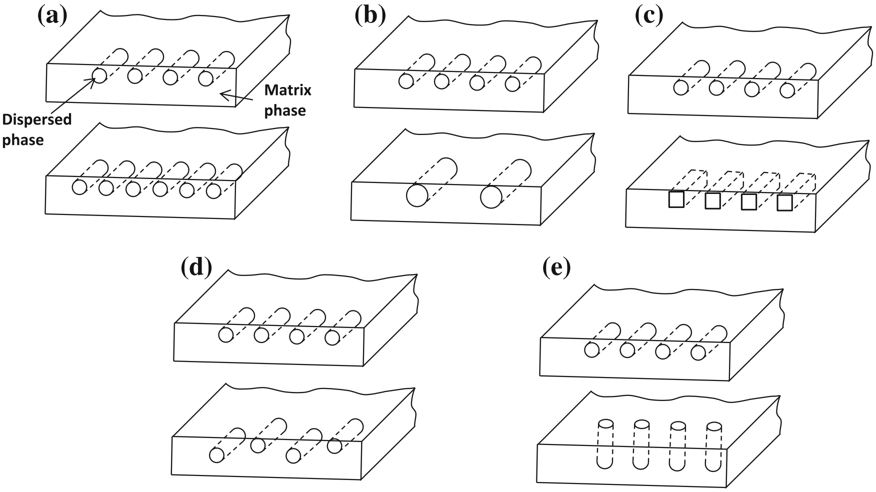

Fig. 1 Schematic of geometrical and spatial characteristics of reinforcements in composites: **a** concentration, **b** size, **c** shape, **d** distribution, and **e** orientation [1]

reinforcement and matrix, respectively. For example, the modulus of a composite material is,

$$E_c = V_r E_r + V_m E_m \tag{2}$$

In practice, it is very difficult to take the reinforcement and matrix on volume basis. The volume and weight of materials are related to each other through density. Once the density values of the constituents are available, it is possible to find out the weight from the volume, or vice versa using the following equations.

$$W_r = \frac{V_r \rho_r}{V_r \rho_r + V_m \rho_m} \tag{3}$$

$$V_r = \frac{W_r / \rho_r}{W_r / \rho_r + W_m / \rho_m} \tag{4}$$

where, ρ is density and W is weight fraction. When the porosity of a composite is negligible, $1 - V_f$ can give the volume fraction of matrix, V_m.

The rule of mixtures can predict the structure insensitive properties with reasonable accuracy, whereas there will be very large deviations for the structure sensitive properties. Some of the structure insensitive properties are elastic modulus, thermal conductivity and electrical conductivity. An example of structure sensitive properties is strength.

1 Types of Composites

Composite materials can be classified into polymer matrix composites (PMC), metal matrix composites (MMC) and ceramic matrix composites (CMC) based on the matrix material. Among these three composites, polymer matrix composites are very common because of low fabrication temperature and cost. Many PMCs are fabricated at room temperature itself. However, PMCs can be used only at room temperature or slightly above room temperature. The maximum service temperature for PMC is about 300 °C. The MMCs can be used up to 1200 °C. The fabrication of MMCs is somewhat difficult compared to that of PMCs. The CMCs can be used beyond 1200 °C. However, they need very high fabrication temperature or some special fabrication techniques. Because of this, the CMCs are very expensive materials. Cementitious composites are also coming under the category of CMCs. However, these composites can be fabricated at room temperature.

Depending on the type of reinforcement, the composites are classified as particulate composites and fibre reinforced composites. The performance level of fibre reinforced composites is very high compared to particulate composites. The fibre reinforced composites can be further classified as short fibre reinforced composites and continuous fibre reinforced composites. There are two categories of short fibre reinforced composites based on the alignment of fibres. They are aligned and randomly oriented short fibre reinforced composites. Whiskers can also be considered as short fibres, but each fibre is a single crystal. The continuous fibre reinforced composites can be further classified into unidirectional, bidirectional and multidirectional composites depending on the orientation of fibres.

There are two types of structural composites, which are laminates and sandwich composites. The laminates are multilayered composites, in which the fibres are oriented in the same or different directions in each layer. The sandwich composites consist of composite skin layers with a light weight core material. The core can be foam or a honeycomb structure, depending on the application. The sandwich composites are light in weight with high stiffness. When more than one type of reinforcements is used, then the composite is known as hybrid composite.

The composites can also be classified based on the size of reinforcement into macro, micro and nanocomposites. The macro composites are made with more than millimetre size reinforcements. Micrometre size reinforcements are used in microcomposites. The glass and carbon fibre reinforced composites are the examples of microcomposites. In nanocomposites, at least one of the dimensions of the reinforcement should be less than 100 nm. Many nanocomposites are becoming popular now because of significant improvement in properties with less quantity of reinforcements. Another advantage is that the same processing equipment used for the matrix material can also be used to produce the nanocomposites. The nanocomposites can be further divided into zero, one, two and three dimensional nanocomposites depending on the dimensionality of reinforcements.

2 Fundamental Aspects

Most of the composites produced today are fibre reinforced composites. Fibres are excellent reinforcements compared to particulates because of the following characteristics.

1. Very high strength
2. High aspect ratio (length to diameter ratio)
3. High flexibility

According to Griffith's theory, the fracture strength and flaw size are inversely related.

$$\sigma_f = \sqrt{\frac{2E\gamma}{\pi c}} \tag{5}$$

where, σ_f is the fracture strength, E is Young's modulus, γ is surface energy and c is surface crack length. Most of the fibre reinforcements used in composites have diameter in the range of 6–15 μm. The flaw size is restricted by the diameter of the fibre, since it may not be possible to have a flaw, which is larger than the diameter of fibre. Larger crack along the fibre direction may be possible, but they will not propagate during loading, since they are parallel to the loading direction. The smaller flaw size is responsible for the high strength of fibre reinforcements.

The flexibility of any material is controlled by its elastic modulus and the moment of inertia of its cross-section. For any specific material, the modulus value is constant and the flexibility can be modified by changing the dimensions. The inverse of product of bending moment and radius of curvature is a measure of flexibility. According to the bending theory of circular rod, the flexibility can be written as:

$$\frac{1}{MR} = \frac{64}{E\pi d^4} \tag{6}$$

where, M is bending moment, R is the radius of curvature, E is modulus and d is diameter. Since the fibres can be considered as fine rod like material, this theory is applicable to them also. From this equation, it is evident that the flexibility is a sensitive function of diameter. Hence, a flexible fibre can be obtained from any brittle material by reducing the diameter. The glass and other ceramic fibres are flexible because of this reason. The diameter for various fibre forming materials to have equal flexibility as that of 25 μm polyamide fibre is shown in Fig. 2. The flexibility is very essential during the manufacturing of composites with complex shapes.

In a composite material, the reinforcements have better mechanical properties compared to the matrix. Hence, they are the load bearing members. For the effective transfer of load to the reinforcements, the aspect ratio should be very high. Fibrous materials generally have high aspect ratio because of smaller diameter and higher length. When a tensile load is applied to the composite material, both the fibre and

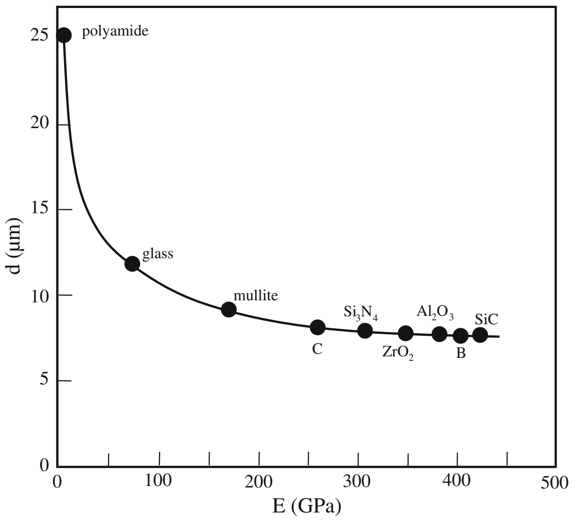

Fig. 2 Diameter of fibre from different materials to have flexibility equal to that of a 25 µm diameter polyamide fibre [2]

matrix will try to deform. Since the modulus of fibre is generally high, there will be less deformation in the fibre. When the bonding between fibre and matrix is good, the fibre will prevent the excessive deformation of matrix. That means the load is now transferred to the fibre. The load transfer is not effective at fibre ends, since the fibre will try to separate from the matrix. The load transfer to the fibre will increase from the fibre end towards the centre of fibre. The applied load transferred is reaching a maximum after certain length. The length at which the maximum applied load is transferred to the fibre is called load transfer length. This length varies with the applied load. A load transfer length, which is independent of applied load, is defined as critical fibre length. It is based on the applied load equivalent to the failure load of fibre. When the fibre length is equal to critical fibre length, the maximum load transfer occurs at the fibre midpoint. This load transfer behaviour for various fibre lengths is illustrated in Fig. 3. To have maximum load transfer at large area of fibre, the fibre length should be at least 15 times greater than the critical fibre length.

Even with continuous fibres, it may not be possible to get the reinforcement effect when the fibre content is less than a minimum. Only above certain minimum fibre volume fraction, the strength of a composite starts increasing with increasing fibre content. Above this minimum fibre volume fraction, the composite failure is controlled by the fibre failure. The composite will fail immediately after the failure of fibre. Thus, the composite strength can be written as:

$$\sigma_{cu} = \sigma_{fu} V_f + \sigma_m^* \left(1 - V_f\right) \tag{7}$$

where, σ_{fu} is the failure strength of fibres and σ_{m}^* is the stress in the matrix at the fibre failure strain. When the fibre content is less, the failure of the composite is controlled by the matrix failure. Even after the failure of all fibres, the matrix can

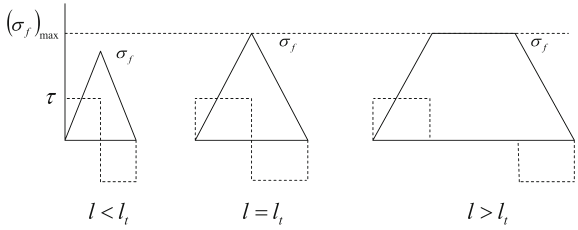

Fig. 3 Variations of fibre stress and interface shear stress for different fibre lengths [3]

take the load and continue to deform. The composite will fail after the failure of the matrix. At this condition, the failure strength of the composite is given as:

$$\sigma_{cu} = \sigma_{mu}\left(1 - V_f\right) \tag{8}$$

The minimum fibre content, at which the failure of composite is controlled by fibre failure is called the minimum fibre volume fraction. It can be given as:

$$\sigma_{cu} = \sigma_{fu}V_f + \sigma_m^*\left(1 - V_f\right) \geq \sigma_{mu}\left(1 - V_f\right) \tag{9}$$

Hence,

$$V_f, \text{ i.e. } V_{\min} = \frac{\sigma_{mu} - \sigma_m^*}{\sigma_{fu} + \sigma_{mu} - \sigma_m^*} \tag{10}$$

The critical fibre volume fraction can be defined as the volume fraction above which the composite failure strength is greater than matrix ultimate strength. That is:

$$\sigma_{cu} = \sigma_{fu}V_f + \sigma_m^*\left(1 - V_f\right) \geq \sigma_{mu} \tag{11}$$

$$V_f, \text{ i.e. } V_{crit} = \frac{\sigma_{mu} - \sigma_m^*}{\sigma_{fu} - \sigma_m^*} \tag{12}$$

The minimum and critical fibre volume fractions are illustrated in Fig. 4. As mentioned earlier, the properties of composites are mainly controlled by the relative proportions of the constituents. Once the concentrations are known, it is possible to predict the property of composite based on the properties of constituents. The prediction of Young's modulus of a fibre reinforced composite is described below.

Consider a fibre reinforced composite material, in which all the fibres are aligned in a single direction. A tensile load of F_c is applied to this composite in the fibre direction. This load will be shared by the fibre and matrix.

$$F_c = F_f + F_m \tag{13}$$

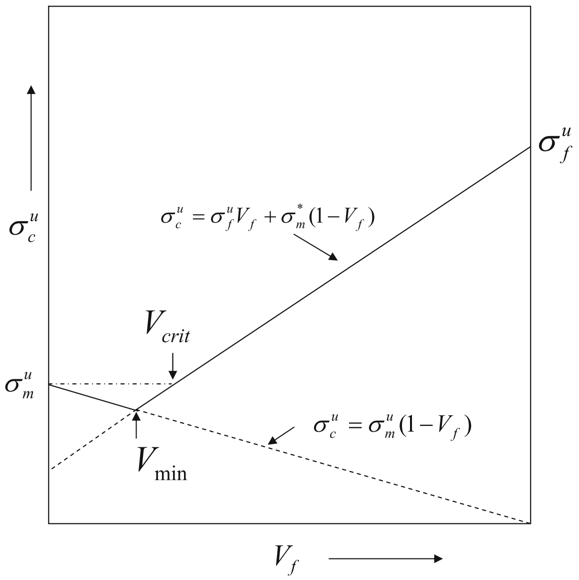

Fig. 4 Tensile strength of unidirectional composite as a function of fibre volume fraction [4]

Since stress, $\sigma = F/A$, hence $F = \sigma A$

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m \tag{14}$$

where, σ_c, σ_f and σ_m are stresses in the composite, fibre and matrix, respectively and A_c, A_f and A_m are the cross-sectional areas of the composite, fibre and matrix, respectively.

On dividing the Eq. 14 by the cross-sectional area of the composite, then

$$\sigma_c = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_c} \tag{15}$$

For a given length, the area fraction is equal to the volume fraction. Therefore,

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \tag{16}$$

Assuming that the constituents are undergoing elastic deformation and obey Hooke's law, i.e.

$$\frac{\sigma}{\varepsilon} = E \tag{17}$$

Then,

$$E_c \varepsilon_c = E_f \varepsilon_f V_f + E_m \varepsilon_m V_m \tag{18}$$

When the bonding between fibre and matrix is perfect, then $\varepsilon_c = \varepsilon_f = \varepsilon_m$ (iso-strain condition)

So,

$$E_c = E_f V_f + E_m V_m \tag{19}$$

When the porosity of the composite is negligible, then $V_m = 1 - V_f$
Now,

$$E_c = E_f V_f + E_m \left(1 - V_f\right) \tag{20}$$

This is the rule of mixtures to predict the modulus of a composite in the fibre direction.

When the load is applied transverse to the fibre direction, the stresses in the composite, fibre and matrix are equal for a given length, i.e. $\sigma_c = \sigma_f = \sigma_m$ (iso-stress condition). The deformation in the composite is the summation of deformations in the fibre and matrix.

$$\delta_c = \delta_f + \delta_m \tag{21}$$

Since, $\varepsilon = \frac{\delta}{t}$, where t is thickness.

$$\varepsilon_c t_c = \varepsilon_f t_f + \varepsilon_m t_m \tag{22}$$

Divide by t_c, then

$$\varepsilon_c = \varepsilon_f \frac{t_f}{t_c} + \varepsilon_m \frac{t_m}{t_c} \tag{23}$$

For a given cross-sectional area of the composite, $\frac{t_f}{t_c} = V_f$ and $\frac{t_m}{t_c} = V_m$
Therefore,

$$\varepsilon_c = \varepsilon_f V_f + \varepsilon_m V_m \tag{24}$$

Again by assuming elastic deformation of constituents, $\varepsilon = \frac{\sigma}{E}$, then

$$\frac{\sigma_c}{E_c} = \frac{\sigma_f V_f}{E_f} + \frac{\sigma_m V_m}{E_m} \tag{25}$$

Since, the stresses are equal,

$$\frac{1}{E_c} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad or \quad \frac{1}{E_c} = \frac{V_f}{E_f} + \frac{\left(1 - V_f\right)}{E_m} \tag{26}$$

This is the equation to predict the modulus in the transverse direction. The properties of real composites lie in between the values predicted by Eqs. 20 and 26.

3 Types of Matrix

As mentioned earlier, there are three major classes of matrix materials. They are polymeric, metallic and ceramic matrix materials. The majority of the composites produced today are based on polymer matrices, since they are relatively cheap and easily processable.

3.1 *Polymer Matrix*

Polymer is a macromolecule consisting of one or more units repeating in large numbers. For example, the very common polymer, polyethylene is made-up of hundreds of ethylene ($–CH_2–CH_2–$) repeating units. A polymeric material is the collection of many polymeric molecules of similar chemical structure. The polymeric chains are either randomly arranged or randomly arranged with some chain orientation in a polymeric material. The former is an amorphous polymer and the latter is a semicrystalline polymer. The same polymer can be obtained in the amorphous state or semi-crystalline state depending on the processing conditions. The polymers are further classified into thermosetting and thermoplastic polymers. In a thermosetting polymer, the polymer molecules form a three dimensional network structure with strong covalent bonds between the chains. Once this type of network structure is formed, it is very difficult to deform the material. It is similar to cement setting. In the context of composites, thermoset polymers have many advantages and hence they are widely used compared to thermoplastics. Some of the advantages are:

- easy fabrication of composites, since they are available in liquid form
- good wetting with the reinforcements
- high thermal stability
- good creep resistance
- good chemical resistance

However, there are a few disadvantages also; which are:

- high brittle nature
- long fabrication time
- relatively short storage life

In a thermoplastic material, the polymer molecules are held together by weak van der Waals forces. Hence, by applying heat and presence, it is easy to deform a thermoplastic material. That means, it is possible to reuse it. Hence, it is not necessary to fabricate the final shape by a single stage processing. Some regular shapes can be made in bulk and then they can be deformed to the final shape at a later date. Apart from this advantage, there are some additional advantages also. The fabrication time with thermoplastics is less and they have good toughness. The thermoplastic materials can be stored for longer time. Even with these advantages, the thermoplastics are not commonly used because of the requirement of high processing temperatures, poor wettability to reinforcements and high melt viscosity. These problems are addressed to some extent and thermoplastic composites are now becoming popular. The details of commonly used polymer matrix materials are given in the following sections.

3.1.1 Polyester Resin

This is the most commonly used polymeric material in composites. It is a thermosetting polymer. This is unsaturated polyester with a number of double bonds in the chain. An ester is an organic compound formed between an acid and alcohol. When there are two reactive groups in each constituent, they can form polyester. These resins are generally prepared using an unsaturated acid and alcohol. The number of unsaturated groups present in the polyester resin can be modified by introducing a saturated acid. A variety of polyester resins is available depending on the type of unsaturated acid, saturated acid and alcohol. The unsaturated polyester resin is generally dissolved in a reactive diluent, such as styrene to reduce the viscosity and facilitate the easy fabrication of composites. The common varieties of polyester resins are orthophthalic, isophthalic, and terephthalic resins.

The liquid resin transforms to a solid after the curing reaction. These resins can be cured at room temperature or high temperature by suitably selecting a catalyst. An accelerator is also added to increase the speed of reaction. During curing, the double bond is attacked by the catalyst and form a reactive group. This reactive group attacks the double bond present in styrene, which in turn attack the double bond of another polyester molecule. In this way cross-links are established between polyester molecules through styrene. This curing reaction is illustrated in Fig. 5. The properties of polyester resin depend on the cross-link density, which is controlled by the number of double bonds. A brittle product is obtained at higher cross-link density, whereas a flexible product is obtained at lower cross-link density. UV resistant additives and fire retardants are also added to the resin, depending on the applications. The required additives are added into the resin, just before the fabrication of composites and then the composite part is fabricated. In the presence of catalyst and accelerator, the resin will start solidify after a few minutes. The fabrication of the composite should be completed before the gelation of the resin. Polyester resin based composites are widely used in boat hulls, instrument covers, wind-mill blades, roofing, storage tanks, etc.

3.1.2 Epoxy Resins

Epoxy resins have better adhesive strength and chemical resistance than polyester resin. However, they are more expensive. Polymers containing epoxy groups are called epoxy resins. An epoxy group is a cyclic group formed by two or more carbon atoms and an oxygen atom. The reactivity of epoxy increases with

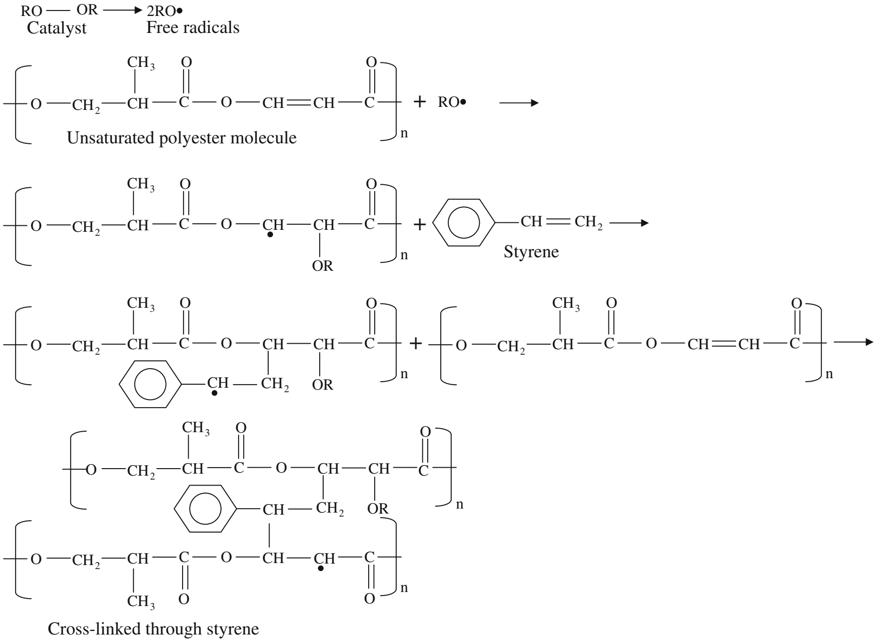

Fig. 5 Curing reaction of thermoset polyester resin [3]

decreasing number of carbon atoms in the epoxy group. The epoxy group consisting of two carbon atoms and one oxygen atom is more reactive. Like polyester resin, there are a variety of epoxy resins available in the market depending on the remaining organic groups. One of the very common epoxy resins is diglycidylether of bisphenol A (DGEBA) resin. There are aliphatic epoxy resins as well as aromatic epoxy resins. Generally, the aromatic epoxy resins have better mechanical and thermal properties than aliphatic epoxy resins.

Unlike polyester resins, hardeners are used to cure the epoxy resins. The hardeners become the part of network structure after curing. Hence, the properties of epoxy resins are also controlled by the nature of hardeners. There are a variety of hardeners available to cure the epoxy resin at room temperature or at high temperature. The amine curing agents are very commonly used with epoxy resin. Apart from these, acid anhydride curing agents are also available. The curing of epoxy resin proceeds in two stages. In the first stage, linear polymer chains are produced by the reaction of epoxy groups and amine groups. The cross-links are then formed by the reaction of remaining epoxy groups and secondary amine groups. The curing behaviour of epoxy resin is illustrated in Fig. 6. It is possible to stop the curing of epoxy resin at the intermediate stage. Epoxy resin based prepregs (pre-impregnated fibres) are made by stopping the curing at the intermediate stage (B-stage). The prepregs are generally made with high temperature curing systems. After certain curing, the curing reaction is stopped by lowering the temperature. To avoid the

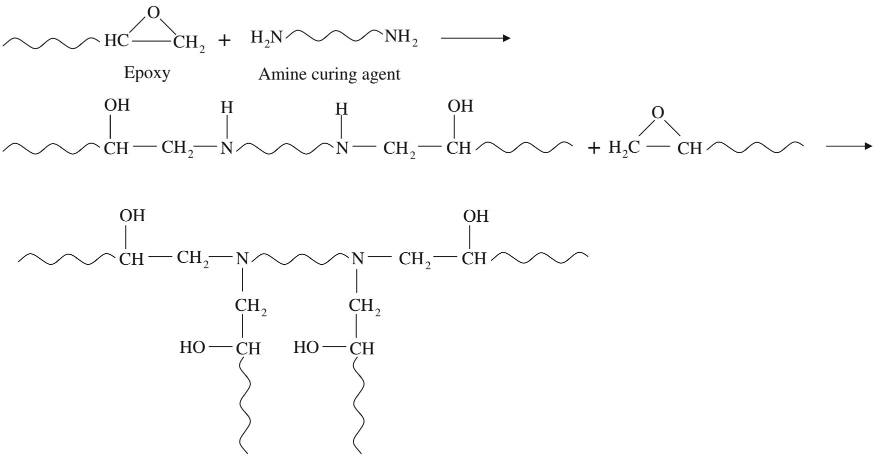

Fig. 6 Curing reaction of epoxy resin [5]

progression of curing reaction, the prepregs need to be stored at −18 °C. At this temperature, it is possible to store the prepregs up to 6 months. Prepregs are made in the form of thin tapes. The composite part is fabricated with this prepreg and then cured at high temperature, generally in an autoclave. The required fibre content and orientation are easily achieved with these prepregs and hence composites with the desired properties can be fabricated. Since the epoxy resins are expensive, they are mainly used in aerospace and sporting goods applications.

3.1.3 Vinyl Ester Resins

They have intermediate properties between epoxy and polyester resins. The curing behaviour is similar to polyester resins. Since they have many –OH groups along the chain, the adhesion with glass fibre is good.

3.1.4 Phenolic Resins

They are based on phenol formaldehyde. The reaction between phenol and formaldehyde leads to the formation of phenol formaldehyde. These resins show low fire spread and smoke emission. Hence, the composites based on phenolic resins are widely used where fire resistance is very important, such as under-ground railway lines and panels for low cost housing. The main problem with these resins is the volatile emission during curing. Hence, it is essential to cure the resin under pressure to avoid pore formation. There are two types of phenolic resins, depending on the phenol-formaldehyde ratio. When the ratio is less than 1, it is called resole and more than 1, it is called novolac resin. The high temperature properties of novolac resin are better than that of resole resin. The ablative composites used in re-entry vehicles are also made with phenolic resin. On high temperature ablation under inert conditions, this resin transforms into carbon matrix.

3.1.5 Polyimide Resins

Polyimide resins can be used up to 230 °C for long periods and up to 315 °C for short durations. Apart from high temperature resistance, they also offer high chemical and solvent resistance. However, these resins are inherently brittle and their composites are prone to microcracking. This problem can be solved to some extent by the incorporation of a thermoplastic polyimide. They form a semi-interpenetrating network, which leads to better toughness. Some of the examples of polyimide resins are bismaleimides, PMR-15 (polymerisation of monomer reactants) and acetylene terminated polyimide.

3.1.6 Thermoplastics

Thermoplastics have good toughness and resistance to damage from low velocity impacts due to their high ductility. Most of the thermoplastics are used in commodity applications, where high mechanical performance is not needed. However, there are a few thermoplastics with good mechanical properties and high temperature resistance. High performance thermoplastics contain aromatic rings that impart rigidity and high temperature stability to these materials. The incorporation of reinforcements significantly improves the mechanical properties and creep resistance. Some of the thermoplastic matrix materials used in composites meant for room temperature applications are polyamides, polypropylene and polyethylene terephthalate. Polyether ether ketone, polyphenylene sulphide, polysulphone and thermoplastic polyimides are the examples of high performance thermoplastic matrices.

3.2 Metal Matrix

Metal matrix includes metals and alloys. Light weight metals and alloys based on aluminium, magnesium and titanium are generally used in composites. Metals have more toughness and hardness than polymeric materials. Moreover, they can be used at relatively higher temperatures. However, the fabrication temperatures of metal matrix composite are high (more than 600 °C). Because of this, the fabrication of MMCs with continuous fibres is very difficult or more expensive. It is not possible to use the natural and synthetic organic fibres with metal matrix. High temperature resistant fibres, such as carbon, silicon carbide and alumina fibres can only be used, but they are very expensive. Even the glass fibres cannot be used with metal matrix, since they will deform at the processing temperature. Ceramic particulates and short fibres, including whiskers are generally used in MMCs. The metal matrix should have good wettability with the reinforcements, but there should not be any adverse reaction between them. This is very critical during the fabrication of composites. Many MMCs are commercially produced now and they are replacing many metallic parts and also some PMCs. Most of the MMCs are based on aluminium, magnesium and titanium alloys and some intermetallic materials. The details of these matrices are given in the following sections.

3.2.1 Aluminium Alloys

They are the most commonly used metal matrices. These alloys have very good corrosion resistance and mechanical properties. They are light in weight and relatively inexpensive compared to other matrices used in MMCs. Aluminium-silicon alloys are used when the composite is fabricated by melt route and aluminium-copper or aluminium-magnesium alloys are used when the composite is fabricated by powder metallurgy technique. Alumina, silicon carbide and fly ash particles are generally used for the fabrication of composites with these alloys. Many in situ composites with TiC/TiB_2 particles are also processed with these alloys.

3.2.2 Magnesium Alloys

This is one of the lightest metals with the density of 1.74 g/cm^3. Since magnesium has hexagonal close packed structure, it is very difficult to deform this material at room temperature. Great care should be taken during the fabrication of composites with these alloys because they undergo vigorous reaction with oxygen and sometimes trigger explosion.

3.2.3 Titanium Alloys

The aluminium and magnesium based composites are useful for room temperature or slightly above room temperature applications. When the service temperature is more than 300 °C, these matrices may not be suitable. Since the melting point of titanium is 1672 °C, it can be used up to 1000 °C. For example, the skin temperature of supersonic aircraft may go beyond 300 °C. Aluminium alloy based composites are not suitable for this application, whereas titanium alloy based composites can be used. Titanium exists in two crystalline forms, viz. α and β forms. The α-form has hexagonal structure and is stable up to 885 °C, whereas the β–form has cubic structure, which is stable above 885 °C. The alloying elements can modify this transformation temperature. Aluminium stabilises the α-form and hence the transformation temperature is increased beyond 885 °C. Elements like V stabilise β-form and thus the transformation temperature is reduced. A very common titanium alloy is Ti-6Al-4V alloy. This alloy has a mixture of α and β forms. Although the corrosion resistance of Ti alloys is good, they have great affinity to gases like O_2 and H_2 at high temperatures. Hence, the processing of composites should be carried out under highly inert conditions.

3.2.4 Intermetallic Compounds

They are the compounds formed between metals. The main difference between an alloy and an intermetallic compound is that the alloy can have variable composition and the intermetallic compound should have a fixed composition. Like alloys they have very good thermal and electrical conductivity, but their ductility is very poor. The ductility can be improved by forming glassy intermetallics through rapid cooling or by adding elements like boron. Another way of improving toughness is to form composites. The intermetallics can retain the strength at high temperatures and in some cases an improvement of strength at high temperature is also observed. Some of the intermetallics used as matrices are NiAl, TiAl, etc.

3.3 Ceramic Matrix

Ceramic materials are the compounds formed between metals and non-metals. However, only those compounds, which have better mechanical properties and high temperature resistance, are considered as ceramic materials. Generally, they are the oxides, carbides and nitrides of metals. The melting points of ceramic materials are generally high and they can retain the mechanical properties at high temperatures. They have very good oxidation and chemical resistance. Since the modulus and strength values of ceramic materials are high, the main purpose of forming composites is to improve the fracture toughness.

Unlike the metallic materials, the ceramic materials are iono-covalent compounds, i.e. the ions or atoms are bonded with strong ionic and covalent bonds. Hence, the number of slip systems is restricted, and that is responsible for the low ductility of ceramic materials. Since the ceramic materials are processed at high temperatures, the formation of flaws is unavoidable. During loading those cracks propagate and lead to catastrophic failure. The presence of reinforcements in a ceramic material can prevent the propagation of cracks in many ways and thus increases the fracture toughness. Some of the toughening mechanisms operate in CMCs are crack deflection, crack bridging, fibre pull-out and transformation toughening. When the reinforcements have higher fracture toughness, they will not allow the crack to propagate through them. Either the crack bows out or is deflected. In this way, the crack propagation is delayed. When fibrous reinforcements are present in a ceramic matrix, they can bridge the crack faces and thus preventing the easy crack propagation. A tailored interface will allow the pull-out of fibrous reinforcements. Hence, a part of energy utilised for this process and the crack propagation is delayed. The transformation toughening mechanism operates in zirconia toughened ceramics. Zirconia exists in three crystalline forms, viz., cubic, tetragonal and monoclinic forms. The transformation from tetragonal to monoclinic form involves a volume expansion of about 4 %. When the tetragonal zirconia particles are present in a ceramic matrix, they can transform to monoclinic form during loading. This generally happens near the crack tip, since the stress concentration is high in the region. The transformation associated with volume expansion will try to close the crack, thus preventing easy propagation.

The interface engineering is very important in ceramic matrix composites. The interface should not be very strong or very weak. To have a tailored interface, many surface modification procedures are adopted. Some of the matrix materials used in CMCs are alumina, silicon carbide, silicon nitride, glass and cement, and the details about these materials are given in the following sections.

3.3.1 Alumina

Alumina or aluminium oxide is one of the most widely used advanced ceramic materials. It exists in various forms like γ, θ, δ and α. The α-alumina is the stable form and the other forms are transitional aluminas. The other forms of alumina can be transformed into α–alumina by heating at high temperature. Alumina has a melting point of 2020 °C. The α-form has hexagonal structure and the other forms have cubic structure. It also has high hardness and strength. It is generally produced from bauxite ore. It has very good chemical resistance even at high temperature. The fracture toughness of this material is around 3 $\mathrm{MPa}\sqrt{\mathrm{m}}$. Silicon carbide fibres and whiskers and zirconia particles are generally used to improve the fracture toughness of this material.

3.3.2 Silicon Carbide

SiC exists in two crystalline forms. The α–SiC is hexagonal, whereas the β-SiC is cubic. This material also has high hardness and strength. The thermal conductivity of SiC is also high. Depending on the processing conditions, it exists in either α-form or β-form. Bulk quantity of SiC is produced by the carbothermal reduction of silica using carbon in an arc furnace. This is one of the common abrasive materials used in grinding wheels and abrasive papers. This material also has low fracture toughness. SiC fibres and whiskers are generally used as reinforcements for this material.

3.3.3 Silicon Nitride

Apart from high hardness and strength, this material also has low thermal expansion coefficient. It also has good oxidation resistance at high temperatures. Because of its high thermal stability, many engine components are made with this material. SiC fibres and whiskers are generally used as reinforcements. Various methods like compaction and sintering, hot pressing, hot isostatic pressing are used to product silicon nitride ceramic components. Reaction bonding technique using silicon is another attractive method to prepare ceramic parts with this material.

3.3.4 Glass

Glass matrix can also be used to form CMCs. The brittleness of glass can be reduced by forming a composite. Carbon, SiC, alumina fibres are generally used as reinforcements to glass. The low temperature requirement for the processing of composite is the main attraction for glass matrix. Various glasses can be prepared by varying the composition of oxides.

3.3.5 Cements

The main advantage of cement matrix is that the composite can be formed at room temperature. Hence, glass fibres, organic fibres and plant fibres can be used as reinforcements. After the ban of asbestos fibres, cement sheets are currently produced using natural fibres in many countries.

4 Types of Reinforcement

There are a variety of reinforcements available for the fabrication of composites. Depending on the application and cost, one can select a suitable reinforcement. The reinforcements can be broadly classified into natural and synthetic reinforcements. The natural reinforcements can be further divided into inorganic and organic reinforcements. Many mineral fibres come under the category of inorganic reinforcements. The plant and animal based fibres are organic reinforcements. The natural reinforcements are relatively cheap. The plant based fibres are also environmental friendly. However, there are many disadvantages with natural fibres. Some of the mineral fibres are carcinogenic. The plant fibres absorb moisture and degrade over a period of time. Natural fibres are not available as continuous fibres. The mechanical properties of natural fibres are generally inferior to the synthetic fibres and also there is wide variation. Some of the inorganic fibrous materials are asbestos and wollastonite. The usage of asbestos is banned in many countries. The other mineral fibres are not effective as the synthetic fibres.

Animal hair is another category of natural fibres. Although they are used in protective clothing, they are not commonly used in composites. There are a variety of plant fibres available throughout the world. Some of the common plant fibres are jute, coir, sisal, cotton, etc.

The plant based natural fibres are one among the fastest growing types of reinforcement for polymeric materials. They are finding increasing use in composites for automotive applications, since the cost is 30 % less than glass fibres. Moreover, the natural fibres weigh only about 50 % of glass fibres for the same volume and the composites made with natural fibres are easier to dispose. The interior parts of automobiles, furnitures, doors and flower pots are some of the common products made with natural fibre composites.

Among the plant based natural fibres, wood fibres are widely used in North America. The cost of wood fibre is less than that of widely used fillers, such as calcium carbonate. Natural fibres can also be obtained from the stem, leaf or seed of certain plants. The fibres obtained from stem are called ‘bast’ fibres and a few examples of bast fibres are flax, hemp and jute. Flax fibre is produced largely in Canada and China, hemp is mainly produced in Philippines and the largest producers of jute are India, China and Bangladesh. Sisal and abaca are the common leaf fibres. Brazil and Tanzania are the two largest producers of sisal. Abaca fibre is also produced in large quantities by Philippines. The commonly used seed fibres are cotton and coir. China, India and USA are the leading producers of cotton. The major producers of coir fibre are India and Sri Lanka. More information on the natural fibres can be found in the Chap. 5.

The synthetic fibres are high performance fibres with very high mechanical properties. They’re available in various forms for the fabrication of composites. Some of the forms are continuous fibre rovings, chopped strand mat and woven rovings. There are a variety of synthetic fibres available in the market. Depending on the property requirement one can select the appropriate fibre. The commonly used synthetic fibres are glass, carbon, aramid, polyethylene, alumina and silicon carbide. Among the synthetic fibres, the glass fibre is widely used in composites because of its relatively lower cost.

4.1 Glass Fibres

Glass is an amorphous material. It is normally based on silica. Other oxides are added to silica to modify the properties. Depending on the composition, the properties will vary. The common glass fibre types are E-glass, S-glass, C-glass, A-glass and Z-glass. The E–glass is electrically insulating glass and originally used for electrical insulation. This is the very commonly used glass fibre in composites. The S-glass is high strength glass fibre. The C-glass has high chemical resistance and A-glass has higher alkali resistance.

The chemical compositions of these glass fibres are given in Table 1. Glass fibres are available in various forms for the fabrication of composites [6]. They are continuous roving, woven roving, chopped strand mat, chopped strand, yarn and fabrics. During the production of glass fibres, the fibres are collected as strands consisting of around 200 individual filaments with size coating. The rovings are a collection of continuous strands. Woven roving mats are produced by weaving the rovings.

Table 1 Composition of various glass fibres

Constituents	Composition (wt%)				
	E glass	S glass	C glass	A glass	Z glass
SiO_2	52.0–53.0	64.0–65.0	65.0	72.5	60.0
Al_2O_3	14.0–15.0	25.0–26.0	4.0	0.7–1.5	–
B_2O_3	8.0–10.0	–	6.0	–	–
MgO	4.5	10.0	3.0	2.5	–
CaO	17.5	–	14.0	10.0	–
Na_2O/K_2O	0.5	–	8.0	13.5–14.0	20.0
Fe_2O_3	0.4	–	–	–	–
SO_3	–	–	–	0.7	–
TiO_2	–	–	–	–	5.0
ZrO_2	–	–	–	–	15.0

Chopped strands are produced by cutting the strands to 5–50 mm length and the chopped strand mats are produced by spraying these short strands with a binder over a flat conveyor. Yarns are twisted fibres with better integrity and the fabrics are made by the conventional weaving of these yarns.

4.2 Carbon Fibres

Carbon is a light element with the density of 2.2 g/cm^3. It exists in three crystalline forms, viz. diamond, graphite and fullerene. The diamond form has cubic structure with strong covalent bonds in all three directions. This is the hardest material on earth. Graphite has hexagonal structure with covalent bonds in the plane and weak van der Waals forces between the planes. Because of these different kinds of bonding, it has anisotropic properties. The modulus value along the plane is about 1000 GPa, whereas it is only 35 GPa in the perpendicular direction. Fullerene has bulky ball structure with 60 or 70 carbon atoms. The graphitic form of carbon is present in carbon fibre. Hence, it is necessary to align all the planes along the fibre direction to achieve better properties. Carbon fibre is prepared from polymeric precursor fibres, which are special textile fibres that can be carbonised without melting. A commonly used precursor fibre is polyacrylonitrile fibre and the other precursor fibres are rayon and the fibres obtained from pitch and phenolics. After spinning the precursor fibre, it is stabilised by heating in air at 250 °C. The stabilised fibres are carbonised at 1000–1400 °C under inert atmosphere. During carbonisation all other elements, except carbon leave the fibre. The resulting carbon fibre may not have good mechanical properties. To achieve better mechanical properties, a graphitization treatment is carried out, which involves heating at 2000–2200 °C with stress under argon atmosphere. The regular arrangement of lamellar planes along the fibre direction happens during this treatment.

Although the preparation of carbon fibre looks simple, each and every parameter during each step of processing should be controlled to the optimum level. The processing details are kept as closely guarded secret and only a few companies mastered the art of preparation of carbon fibres. However, the properties of carbon fibre vary from one manufacturer to another. Hence, a variety of carbon fibres with different properties is available in the market. Like glass fibres, carbon fibres are also available in various forms for the fabrication of composites. Carbon fibres have very high modulus value compared to glass fibres. Instead of converting to carbon fibre, some people tried to improve the properties of polymeric fibre itself by playing with the molecular structure. The result is the birth of polyethylene and aramid fibres.

4.3 Polyethylene Fibre

Polymer molecules in a polymeric material are neither aligned nor stretched. They assume random coil configuration. Although the atoms in a polymer molecule are covalently bonded, the individual molecules are held together only by weak van der Waals forces. This is responsible for the poor mechanical properties of polymeric materials. A small force is enough to overcome the intermolecular bonding forces, thus leading to stretching and alignment of polymer molecules. Once the polymer molecules are completely stretched and aligned, it is very difficult to deform further. This is the basis for the development of high performance polymeric fibres.

The stretching and orientation of polymer molecules depend on the draw ratio (the ratio of original diameter to final diameter). It may not be possible to apply any draw ratio to polymeric materials. The maximum draw ratio depends on molecular structure and drawing conditions, like temperature and strain rate. The polymer molecules should stretch and align without the formation of defects during the drawing process.

Polyethylene is a very common polymer with poor mechanical properties. The modulus value is less than 10 GPa and the strength hardly exceeds 50 MPa. Very high mechanical properties can be realized in this polymer by stretching and aligning. Polyethylene fibres with the modulus value of 120 GPa and strength of more than 2000 MPa are available in the market. High performance polyethylene fibres are prepared by gel-spinning process. Gels are swollen network, in which the crystalline regions present at the junctions. Polyethylene gel fibre is prepared from a dilute solution of polyethylene using the appropriate spinning process. This gel fibre is subjected to drawing at high temperature to form the polyethylene fibre. The crystalline regions present at the junction facilitate the full stretching of polymer chains. The specific gravity of polyethylene fibre is less than 1. Apart from very high modulus and strength, this fibre also has very good damping properties, which is useful for shock absorption.

4.4 Aramid Fibre

This is also a polymeric fibre. Aramid is the short form of aromatic polyamide. These aromatic polyamides form rigid rod like structure. Stretching may not be needed for these molecules, but molecular alignment is needed to achieve better mechanical properties. Under certain conditions these aramids form liquid crystals in an appropriate solvent. In the liquid crystal state, a group of polymer rods align in the same direction. However, different groups are oriented in different directions. The formation of liquid crystal state can be observed using polarised light microscope.

Because of the rigid rod like structure, these polymers are very difficult to deform and also difficult to dissolve in common solvents. The solvent suitable for dissolving aramid is 100 % sulphuric acid. The viscosity of this solution shows an abnormal behaviour after certain concentration. The viscosity of this solution initially increases with increasing concentration of aramid. After certain concentration, there is a sudden drop in viscosity. This is due to the formation of liquid crystal state. The liquid crystal regions act like a dispersoid. The solution at the liquid crystal state is used for the preparation of fibres, by dry-jet wet spinning process. It is necessary to maintain the liquid bath at low temperatures (−4 °C). It is a well-known fact the concentration of solution increases with temperature. Hence, by keeping the spinneret 1 cm above the liquid bath a higher temperature can be maintained in the solution. The higher the concentration, the higher will be the yield. Because of the air gap, this process is called dry-jet wet spinning process. The aramid fibres are also produced by a few companies and commercially available in the name of Kevlar, Technora, Nomex, etc. Apart from high modulus and strength, these fibres also have good vibration damping properties. Bullet proof clothes for low enforcing agencies throughout the world are made using these fibres. The major disadvantage of these polymeric fibres is their poor high temperature stability. It is not possible to use these fibres in composites intended for high temperature applications.

4.5 Ceramic Fibres

For the composites used above 1000 °C, only ceramic fibres are suitable. They have high temperature stability and can retain their mechanical properties at high temperatures. The commonly used ceramic fibres are silicon carbide and alumina based fibres. Silicon carbide fibres are prepared by chemical vapour deposition (CVD) and polymer pyrolysis processes. The chemical vapour deposition of SiC is carried out on carbon or tungsten substrate fibres in a CVD reactor. Methyl tricholorosilane (MTS) is an ideal raw material to deposit SiC, since it contains only one carbon and one silicon in its structure. This MTS undergoes reduction reaction in the presence of hydrogen gas. The flow of hydrogen should be optimum for the formation of stoichiometric SiC. The fibres produced by CVD process have less flexibility because of large diameter (~ 150 μm). However, these fibres have good oxidation and creep resistance. The SiC fibres having good flexibility are produced by polymer pyrolysis of polymeric precursor fibres. The process is almost similar to that used for carbon fibre production and the major difference is in the precursor fibre. A polymer containing silicon in its backbone structure is used as the starting material. This polymer on pyrolysis at 1400 °C forms SiC. The oxidation resistance of this fibre is poor compared to CVD derived fibre. This is due to oxygen pick-up during stabilisation treatment and the presence of residual carbon and silicon. The oxidation resistance of present SiC fibres is significantly high because of the better control of processing parameters.

Alumina based ceramic fibres are generally produced by sol-gel process. Sol is one of the colloidal systems, in which fine solid particles are dispersed in a liquid medium. A gel is the interpenetrating network of solid particles with the liquid present within the network. The processes involving sol and gel stages are called sol-gel process. A sol can be converted to gel by the evaporation of liquid or by controlling the pH. Metallo-organic compounds are used as the starting materials to prepare these oxide fibres. For example, aluminium isopropoxide or secondary butoxide is the starting material for alumina and tetraethyl orthosilicate is the starting material for silica. The required amount of the respective metallo-organic compounds are dissolved in the appropriate solvents separately and hydrolysed in the presence of catalysts to form sols. The required quantities of sols are mixed depending on the final composition. Alumina based fibres are prepared from 100 % alumina to 40 % alumina with other oxides like silica. Either the sol or the gel can be used to prepare the fibre. The gel fibre is converted to ceramic fibre by controlled drying and calcination. Since the solid content of sol/gel is very less, there is very large shrinkage during the conversion. Hence, it is essential to heat the gel fibre at a very slow heating rate to avoid fibre breakage. These oxide fibres are mainly used in metal matrix composites. More information on the synthetic fibres can be found in Chap. 4.

4.6 Whiskers

Whiskers are elongated single crystals. They are available as short fibres. Since the whiskers are almost defect free, it is possible to realise the mechanical properties close to theoretical values. Although carbon and silicon nitride whiskers are available, silicon carbide whiskers are the commonly used reinforcements in composites. The SiC whiskers are generally prepared by the carbothermal reduction of rice husk or by vapour-liquid-solid (VLS) process. Rice husk is the waste material obtained during polishing of rice grains. It contains an intimate mixture of silica and organic compounds. The cleaned rice husk is coked at 700 °C under inert conditions to convert the organic compounds into carbon. The temperature is then raised to 1400 °C. At this temperature, the carbon reacts with silica and form SiC particulates and whiskers. The residual carbon and silicon carbide particles are removed from the SiC whiskers by various treatments. The aspect ratio of whiskers formed by this process is low and also there is wide variation in properties.

Good quality SiC whiskers with high aspect ratio are prepared by the VLS process. The VLS stands for the vapour feed gases, liquid catalyst and solid whiskers. Transition metal particles of size ~30 μm are used as catalyst. These metallic particles are taken on a carbon substrate and heated to 1400 °C in a reaction chamber. SiO and carbonaceous gases are fed into the chamber in a controlled flow rate. The catalyst particles melt at this temperature and absorb SiO and C gases. These react and form SiC. Once it is supersaturated, SiC is precipitated out as whiskers. These whiskers can have strength as high as 20 GPa.

SiC whiskers can be used as reinforcements in MMCs and CMCs. However there are many problems in using whiskers. High mechanical properties in the composites can be realised only when the whiskers are aligned in the loading direction. The alignment of whiskers is a major problem. Another problem is the wide variation of properties. Since the whisker diameter is at the submicron level, they have the tendency to form agglomerates. The uniform dispersion is another major hurdle. SiC whiskers are carcinogenic in nature. Since they are very fine, whiskers can go into the lungs and deposit there, which can cause cancer. Hence, it is necessary to take appropriate precautions while handling the whiskers.

4.7 Nanofibres

When the diameter of a fibre is less than 100 nm, then it is called nanofibre. Nanofibres based on alumina, silicon carbide and carbon are available now. Even the carbon nanotubes (CNT) can be considered as nanofibrous materials. A method commonly used in the recent years to produce nanofibres is electrospinning process. An appropriate solution coming out of a nozzle is drawn into nanofibre by applying very high voltage between the nozzle and a metallic substrate. To prepare ceramic nanofibres, the corresponding polymeric precursor fibres are produced first and then they are converted to ceramic fibres by pyrolysis. CNTs are prepared by arc discharge and chemical vapour deposition methods. Although the yield is high in arc discharge method, CVD process is preferred to get high quality CNTs. There is no doubt that the nanofibres are better than micron size fibres, but there are many challenges with the nanofibres. At present the nanofibres are more expensive. The commercial production of nanofibres is yet to start. Although long nano fibres can be produced, continuous nanofibres are a distant dream. There are many issues on the uniform distribution of nanofibres in the matrix material, since the nanofibres have high tendency to form agglomerates. The compatibility between the nanofibre and matrix material is another issue to be addressed. More information on the nanofibres is available in Chap. 7.

Plant based natural fibres in general are suitable for plastics to improve their mechanical properties. Nevertheless, the wide variation in properties of natural fibres is a major drawback. The variation is mainly due to the fibre structure, which depends on the overall environmental conditions during growth. Hence, the natural fibres are preferred only for uncritical applications. Synthetic fibres are produced to specific

Table 2 Mechanical properties of natural fibres and synthetic fibres [7]

Fibre	Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Cotton	1.5–1.6	7.0–8.0	287–597	5.5–12.6
Jute	1.3	1.5–1.8	393–773	26.5
Flax	1.5	2.7–3.2	345–1035	27.6
Hemp	–	1.6	690	–
Ramie	–	3.6–3.8	400–938	61.4–128.0
Sisal	1.5	2.0–2.5	511–635	9.4–22.0
Coir	1.2	30.0	175	4.0–6.0
Viscose (cord)	–	11.4	593	11.0
Soft wood kraft	1.5	–	1000	40.0
E-glass	2.5	2.5	2000–3500	70.0
S-glass	2.5	2.8	4570	86.0
Aramid (normal)	1.4	3.3–3.7	3000–3150	63.0–67.0
Carbon (standard)	1.4	1.4–1.8	4000	230.0–240.0

properties and also the variation is very less. The advanced composites, for which the properties are very critical, are only made with synthetic fibres. The properties of common plant based natural fibres and synthetic fibres are given in Table 2.

5 Manufacturing Techniques

There are a variety of techniques available to produce composites and some of the techniques are amenable for mass production. It may not be possible to produce complex shapes by using some techniques. Some of the techniques are more expensive to use. Depending on the application, cost and properties, an appropriate method can be selected. Generally, the MMCs and CMCs need higher temperatures for processing. Hence, the methods used to produce PMCs may not be suitable for MMCs and CMCs. The commonly used manufacturing methods for these three types of composites are explained briefly in the following sections.

5.1 Manufacturing of PMCs

The manufacturing methods of PMCs can be broadly classified into thermoset resin based and thermoplastics based methods. In the thermoset resin based methods, the composites are fabricated using the liquid resin. Hence, the fabrication can be carried out at room temperature. Thermoplastic composites are fabricated above the melting temperature of matrix material. The commonly used manufacturing methods with thermoset resins are hand lay-up, resin transfer moulding (RTM), resin infusion, autoclave processing, compression molding, filament winding and pultrusion. Injection moulding, reinforced reaction injection moulding, and thermoforming are the common methods used with thermoplastics. These manufacturing methods are briefly explained below.

5.1.1 Hand Lay-up

This is the most widely used method for the manufacturing of composites because of its simplicity. No expensive equipment is needed for this process. Even the mould will not cost much, since it can be made from wood, plastics and fibre reinforced plastics. Any complex shape can be made easily with this process. In this process, a mould is made according to the final shape of product. It can be a single piece mould or multi-segment mould depending on the complexity of the product. The mould surface should have good surface finish, since the surface finish on the product depends on this. Moreover, the release of the product after curing will be easy, when the surface finish is good. After that a thin release film is applied over the mould surface. Polyvinyl alcohol solution can be used to form the release film. A water solution of polyvinyl alcohol (PVA) forms a solid film over the surface on drying at room temperature. It may stick to the product, but it can be easily removed by putting the product in hot water for some time.

Once the release film is formed, a gel-coat layer is generally applied first. The gel-coat is made with the same resin used for the fabrication of composite. Some inert fillers, colouring agents and other special additives are added to the resin to prepare the gel-coat. The gel-coat layer is about 0.5 mm thick. Before the gel-coat is completely solidified (thumb impression should form while touching), the reinforcement mat is placed over the gel-coat. The resin with the curing agent is applied over the reinforcement using a paint brush. To ensure complete wetting of the reinforcement and to remove entrapped air a roller is rolled over the surface. Special kind of rollers for the fabrication of composites is available in the market. The required number of layers is laid one by one like this. The schematic of this process is shown in Fig. 7. This is a manual process. Hence, the quality of the product

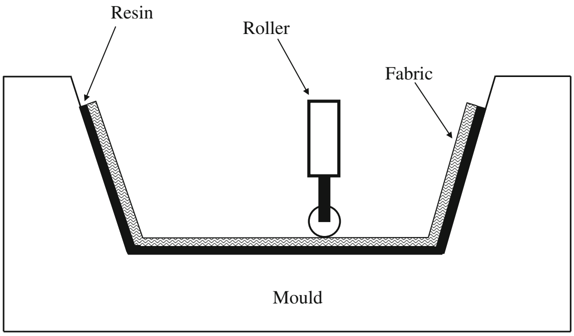

Fig. 7 Schematic of hand lay-up process [8]

depends on the skill of the fabricator. A product with good surface finish, uniform distribution and thickness of resin and, negligible pores is considered as a good quality product. There are certain disadvantages with this process. The product can have good surface finish only on one side, i.e. the surface in contact with the mould during fabrication. It is very difficult to produce products with consistent quality. It is a time-consuming and labour-intensive process.

5.1.2 Resin Transfer Moulding (RTM)

This is a semi-automated process. Some of the short-comings of hand lay-up process are overcome in this process. Consistent quality products with good surface finish on both the sides can be produced by this process. For this process, the moulds are made with fibre reinforced plastics or metals. The required amount of reinforcement is stacked over the female mould and then closed with the male mould. The resin is mixed with curing agent in a mixing head and then pumped into the mould cavity. Vents are provided at the farther ends of mould. After completely filling the mould cavity, the resin starts coming out through the vents. The resin injection is stopped at this stage and the resin is allowed to cure. The mould is opened to remove the product after curing. This is a faster process than hand lay-up. When the size of the product is large, multiple injection parts should be provided. The fibre wash-out can happen near the injection parts, if chopped strand mat is used. The stitching of the mat can reduce this problem to some extent. The mould design is a critical element for this process to achieve complete filling of the mould. A variant of this process is vacuum assisted RTM, in which vacuum is applied through the vents to remove entrapped air and to facilitate easy flow of resin.

5.1.3 Resin Infusion/Vacuum Bag Moulding

This process is similar to RTM, but the resin is flowing into the mould cavity by the application of vacuum. The top mould can be rigid mould or flexible. Resin trap should be provided in the vacuum line; otherwise the resin can enter the vacuum pump after filling the mould. Very large products such as boat hulls are made with this process.

5.1.4 Autoclave Process

Autoclave is a high temperature pressure vessel. The composites fabricated using prepregs are generally cured in autoclave. A high quality composite product can be produced by this process. A composite product fabricated over a mould is covered with a vacuum bag. By applying vacuum, the air entrapped within the product is removed. The pressure and temperature within the autoclave are then increased slowly. The temperature initiates the curing reaction and the pressure facilitates better consolidation. By introducing bleeder fabric layers the resin content can be accurately controlled. By theoretical analysis, one can determine the orientation of fibres and its content to meet the required properties. The same properties can be achieved by this process. The composites fabricated by the hand lay-up process can also be consolidated by this process.

5.1.5 Compression Moulding

Moulding compounds are generally used in the compression moulding process. The moulding compounds are prepared by mixing the fibres and fillers in a thermoset resin. Hot curing catalysts are used in the moulding compounds. Hence, the curing reaction will not start after mixing. Further, to avoid any chance of curing, the moulding compounds are generally stored at 18 °C. The moulding compounds can be made in the form of sheet or bulk. Very large products are generally made using sheet moulding compounds and small products are made using bulk moulding compounds. The required quantity of moulding compound is placed on a compression moulding die. The die and the platens of the press are heated to the molding temperature. Pressure is applied to the moulding compound by moving the top or bottom platen. The moulding compound flows and completely fills the die cavity. The curing reaction will be over in a few minutes. The die is opened by moving the platens apart and then the product is removed from the die. The die is now ready for another cycle. The pressure applied during the compression moulding process is very high. The moulding temperature is also of the order of 120 °C. Hence, metallic dies are used in this process. The products with good surface finish can be made by this process. Thermoplastic composites can also be fabricated by compression moulding using thermoplastic composite sheets.

5.1.6 Filament Winding

This process is generally used to produce axisymmetric parts such as, cylinders, spheres, etc. It is possible to incorporate very high quantity of fibres in this process. A fibre content of more than 70 vol % is very common in this process. Fibre rovings and prepreg tapes are generally used. A collection of rovings impregnated with resin is wound on rotating mandrel. The winding angle is controlled by the rotating speed of mandrel and the speed of movement of fibre feeder. The schematic of this process is shown in Fig. 8. The final properties of the composite can be controlled by the fibre winding angle and it is possible to fabricate the composite with the required fibre angle in this process. Very long pipes for the transportation of different liquids can be made by this process.

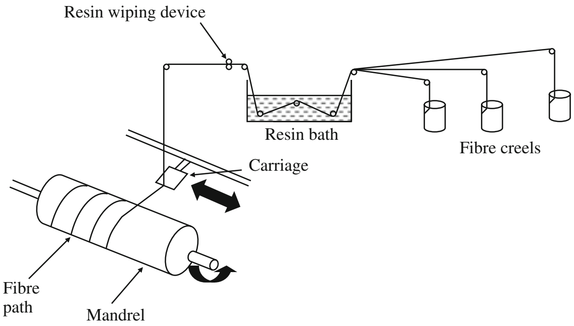

Fig. 8 Schematic of a filament-winding process [5]

5.1.7 Pultrusion

Very long products with constant cross-section are made by this process. Very high fibre content can be realised in this process also. Long tubes and rods are some of the products. These regular shapes are used for the construction of walk-ways, side grills, ladders, etc. These pultruded polymer composite products are more preferred for off-shore structures because of their good corrosion resistance. In this process resin impregnated fibres are allowed to pass through a hot die, where consolidation and curing of resin take place. The cured composite product is pulled through the other end of the die. A cut-off saw cuts the product to the required length. Metallic dies with hard surfaces are used in this process to withstand the high temperature and abrasion. Improper wetting and fibre breakage are some of the problems with this process.

5.1.8 Injection Moulding

It is one of the common processing methods for thermoplastics. The same equipment can be used to produce thermoplastic composites with short fibres or particulates. Since hard reinforcements are used, the dies should have high abrasion resistance. A thermoplastic material is mixed with the reinforcement in an extruder above the melting temperature of the thermoplastics. The molten matrix with reinforcement is injected into the die. After sufficient cooling, the die is opened to remove the product. Only fibres with low aspect ratio are used in this process, since the long fibres will increase the viscosity and affect the flow.

5.1.9 Reinforced Reaction Injection Moulding (RRIM)

It is similar to the RTM process used with thermoset resin. Instead of liquid thermoset resin, liquid monomer is injected into the mould cavity containing fibre reinforcement. The monomer undergoes polymerisation reaction within the mould and forms the final thermoplastic matrix. Since the melt viscosity of thermoplastics is high, it is very difficult to get easy flow. This problem is overcome by the use of monomer, which has lower viscosity. There is a limitation with this process, i.e. the monomer should be selected in such a way that it should not produce a by-product during the polymerisation reaction. This restricts the number of thermoplastic matrices suitable for this process.

5.1.10 Thermoforming

Metal forming process is used to produce metallic parts by the deformation of metal sheets. In the thermoforming process, thermoplastic composite sheets are used to produce composite products. The thermoplastic composite sheet is heated with infrared lamp above the glass transition temperature of the thermoplastic matrix. It is then transferred to a die kept in a press. The hot thermoplastic composite sheet undergoes deformation within the die and forms the product according to the shape of die.

5.2 Manufacturing of MMCs

Metal matrix composites are being produced by melt processing and powder metallurgy techniques. Deposition techniques like electrodeposition, physical vapour deposition and chemical vapour deposition can also be used. Although the product quality is good with these methods, they are time-consuming and expensive methods. Recently, MMCs are also produced by in situ processing methods.

5.2.1 Stir Casting

This is the simplest method to produce MMCs. In this process, the required alloy is melted above its melting temperature. The reinforcements in the form of particulates or short fibres are slowly added to the melt. To ensure the uniform distribution of reinforcements, the melt is stirred well during the reinforcement addition. Even then the segregation and settling of reinforcements are the major problems with this process. The chemical nature and size of reinforcements play a major role for the uniform distribution. Sometimes the reinforcements are chemically modified to improve wetting. When the size of reinforcement is very small, it will drastically increase the viscosity of melt. Moreover, the fine reinforcements stay at the surface of melt. Larger reinforcements try to settle at the bottom of melt, when their density is higher than melt density. Since this processing is carried out above the melting temperature of metal matrix, there is a possibility of unwanted reactions between reinforcement and matrix materials. These reactions may lead to the formation of detrimental compounds, which can affect the properties of MMC. Once the required amount of reinforcement is added, the melt is stirred for a few minutes and then poured into a mould. A better control of processing parameter is needed to get a good quality composite with this process.

5.2.2 Melt Infiltration

A porous preform is made with particulates or short fibres. This preform is infiltrated with molten metal. Generally, it is difficult to get complete infiltration without the application of pressure. The pressure is applied to the melt by mechanical means on by using high pressure gas. The former is called squeeze infiltration process and its schematic is shown in Fig. 9. In this process, the preform is kept in a pre-heated die, the required quantity of molten metal is poured over that and then pressure is applied to the melt by lowering the top punch. The precise quantity of reinforcement is ensured in this process. The probability of reactions is also less due to the shorter duration of the process. Even without any chemical modification, complete wetting of reinforcement can be achieved in this process. The only condition is that the preform should have continuous porous network.

5.2.3 Powder Metallurgy Technique

Reinforcements in the form of particulates or short-fibres are generally used in this process. The reinforcement is thoroughly mixed with the matrix powder in a mixer. The mixture is compacted in a die and then sintered at high temperature. The sintering temperature is generally 0.7–0.8 of the melting point of matrix material.

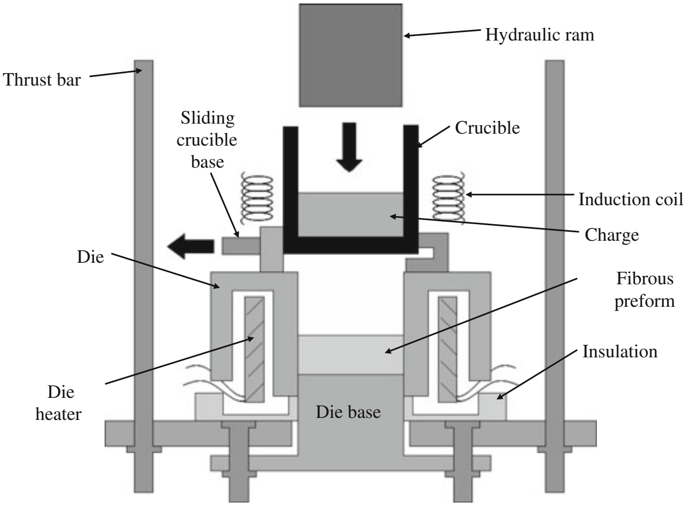

Fig. 9 Schematic of squeeze infiltration process [9]

Since the metallic materials undergo rapid oxidation reactions at high temperature, the sintering process should be carried out under inert atmospheric conditions. Most of the times, a thin oxide layer is already present over the metallic particles. Hence, it is necessary to use a reducing atmosphere during the initial periods of sintering. The densification of composite during sintering occurs by the diffusion of metallic atoms. The presence of reinforcements may prevent the diffusion. Hence, it is very difficult to achieve good density by normal sintering process. It is necessary to use sintering additives or high pressure to facilitate easy diffusion.

5.3 Manufacturing of CMCs

The manufacturing of CMCs needs still higher temperatures. Hence, the melt processing routes are not generally preferred. The powder based methods are widely used to produce CMCs. Apart from these methods; the deposition methods are also common with CMCs. Some special techniques, such as reaction bonding, directed oxidation and polymer infiltration and pyrolysis are also used. In any case, the manufacturing of CMC is more expensive than that of PMC and MMC.

5.3.1 Compaction and Sintering

The reinforcements in the form of short-fibres or particulates are thoroughly mixed with matrix powder. This mixture is compacted in a die using a press and then sintered at high temperature. As in MMC, the composite is densified by the diffusion process, which is affected by the presence of reinforcements. Hence, hot pressing or hot isostatic pressing (HIP) is necessary to achieve good density. Hot pressing is generally carried out using graphite dies with a typical pressure of 50 MPa. The final composite produced by hot pressing may have anisotropic properties due to directional pressing during this process. The complexity of product shape is also restricted for the hot pressing process. CMCs with complex shapes and isotropic properties can be produced with hot isostatic pressing. There are two variants in HIP; in one of the variants, a disposable can material is used during the process. The reinforcement and matrix powder mixture is taken in a can, evacuated and sealed. The sealed can is placed inside the hot isostatic press and then pressure and heat are simultaneously applied. Inert gases at high pressure are used to apply pressure to the can. After the required duration, the pressure and temperature are reduced. The densified CMC part is taken out from the can. Either glass or stainless steel is used as can material depending on the HIPing temperature. In another variant, a presintered CMC is placed inside hot isostatic press to achieve further densification. A presintered CMC with a density of more than 92 % of theoretical density will have only closed pores. This will not allow the pressurising gases to enter the composite; hence further densification can be achieved.

5.3.2 Reaction Bonding

This is a relatively low temperature process. In this process, silicon based composites are first made by the powder metallurgy technique. These composites are subjected to nitridation at 1300°–1400 °C. The silicon particles react with nitrogen and form silicon nitride matrix. This reaction closes the pores. The main advantage of this process is that the composite will not undergo any shrinkage during the CMC formation. However, the presence of unreacted silicon and residual pores are unavoidable.

5.3.3 Directed Oxidation

This process was invented by the Lanxide Corporation. A reinforcement preform is placed over molten metal. The molten metal infiltrates into the preform by capillary action. During the infiltration, the metal reacts with the surrounding gases and forms the respective ceramic matrix. For example, alumina based composites can be produced by the infiltration of aluminium metal and subsequent oxidation using oxygen. In this case, the CMCs are formed at the processing temperatures of MMC. Hence, the cost of production of CMC will be low. However, the presence of residual metal is a major problem, especially for the composites used at high temperatures. The presence of residual metal may be beneficial for the CMCs used at room temperature, since it will increase the toughness.

5.3.4 Polymer Infiltration and Pyrolysis (PIP)

In this process, a reinforcement preform is infiltrated with liquid/molten polymer and then the polymer is converted to a ceramic material by high temperature pyrolysis. Since the polymer to ceramic conversion takes place with the liberation of volatile materials from the polymer, it may not be possible to get a dense ceramic matrix in a single cycle. The infiltration and pyrolysis cycle should be repeated for 3–4 times, to get appreciable amount of ceramic matrix. Even after 3–4 cycles, the presence of pores is unavoidable. Hence, the mechanical properties of the CMC may not be high. SiC and Si_3N_4 based composites are generally produced by this method.

5.3.5 Chemical Vapour Infiltration

When the chemical vapour deposition happens inside a porous preform, then the process is called chemical vapour infiltration. Although this process is more expensive, it is justified by the high performance of CMCs. In this process, the appropriate gases react at high temperature and form the ceramic material, which is deposited over the reinforcement surface within the pores. The schematic of this

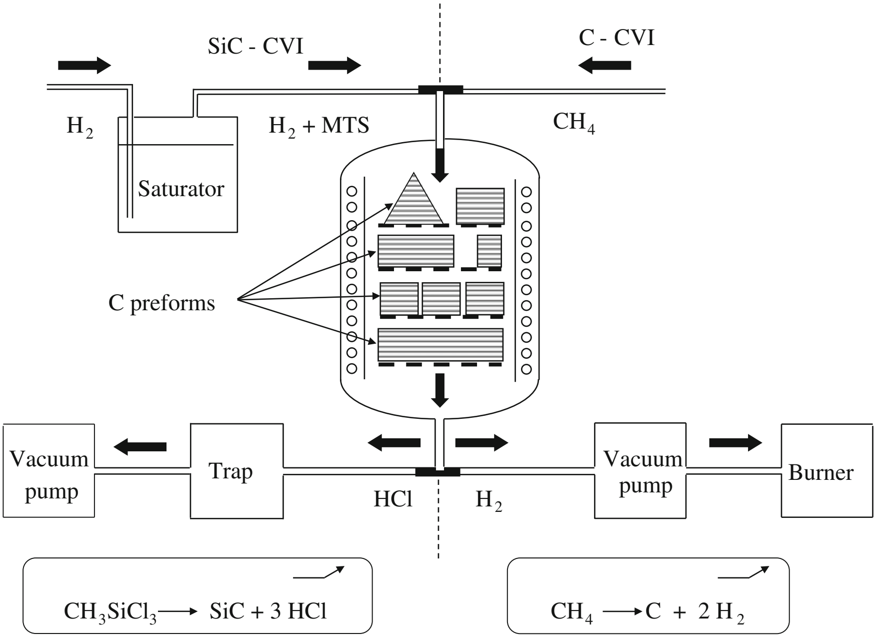

Fig. 10 Schematic of isothermal CVI process [10]

process is shown in Fig. 10. Under normal heating process in a furnace, the surface of preform will be at a higher temperature than inside. Hence, the deposition is more predominate at the surface, which will close the surface pores. Once the surface pores are closed, the interior surfaces of the preform may not have access to the gases for the formation of ceramic matrix. Hence, the preform is removed from the reactor frequently and the surface layer is removed by grinding. Instead of this, a temperature gradient can be maintained from top to the bottom of preform which can facilitate the directional deposition. However, this will restricts the number of products formed at the same time and also the complexity of product shape. For example, SiC_f/SiC composites are produced by chemical vapour infiltration of SiC_f preform with methyl trichlorosilane (MTS) and hydrogen gases. As mentioned earlier, this is a very time-consuming process.

6 Applications

At present composites are finding applications in all engineering fields. A study by DuPont indicates that about 50 % of the engineering materials used in the year 2020 will be made-up of composite materials. The composites are finding applications from the house-hold items to aerospace parts. The main driving force for the usage of composite material is weight reduction. Apart from this, a tailorable property is another major advantage of composites. The polymer composites are the most widely used composite materials, followed by MMCs and then CMCs. Some of the important applications of these three types of composites are given in the following sections.

6.1 Applications of PMCs

The applications of PMCs started with aerospace applications during the Second World War. After the war, people started using PMCs for making boat hulls. During this time, many glass fibre production facilities have been started all over the world. This has driven the expansion of application of composites to many areas. Most of the structural parts of military aircrafts are currently being made with PMCs. Rotor blades of all helicopters are made with PMCs because of their extremely high fatigue resistance. The usage of PMCs in commercial aircrafts is also increasing steadily. The recently developed Boeing 787 aircraft has 50 % PMCs on its total weight. In the ground transport also PMCs are widely used. Bus bodies, car bodies, bumpers, doors, seat-rest, brake-pad are some of the applications of PMCs in automobiles. Truck-cabin, elliptical spring and containers are other applications.

Even now the cost of PMCs is higher than that of cement based building materials. However, the wood based parts, such as window frames and doors, bath room doors, partitions and furnitures can be replaced with PMCs. The PMC parts will have better performance than wooden parts. The roofing for parking areas, domes and translucent roofs are also made with PMCs. Repairing of concrete structures is another important application of PMCs. The damaged part of bridges and multi-storey buildings can be strengthened with fibre reinforced plastics. Very large pipes for the transportation of gases and liquids are being made with PMCs (Fig. 11).

Fig. 11 HOBAS 3 m FRP pipes (*Courtesy*: HOBAS Engineering GmbH, Pischeldorferstraße 128, 9020 Klagenfurt)

Because of their high electrical insulating properties, PMCs are the preferred choice for electrical and electronics applications. High voltage insulators, printed circuit boards, etc. are currently being made with PMCs. In the energy sector, wind mill blades are the important applications of PMCs. Antenna dishes, which will not undergo any dimensional change due to the variation in temperature are being made with carbon fibre reinforced epoxy.

Many sporting goods are currently being made with PMCs. Tennis rackets, Golf clubs, fishing rods, ski boards and sports cycle frames are some of the applications of PMCs. Light weight, good impact properties, and high strength of PMCs are attractive properties for these applications.

6.2 Applications of MMCs

Many PMCs and metallic parts are currently being replaced by MMCs. The abrasion/scratch resistance of MMCs is better than PMCs. With improved strength and modulus, the MMC part can perform better than the metallic parts. In some applications the high wear resistance of MMCs is utilized. In aerospace applications, fan exit guide vans, stator vans, fuel tank covers are some of the parts made with MMCs. Either the short fibres or the particulates are generally used in MMCs.

Automobile pistons with selective reinforcement in the regions, where high wear resistance required, can be made with MMCs. The critical speed of drive shaft depends on the stiffness. High stiffness, hence high critical speed can be achieved with MMC shafts. Brake pads/discs for many transport vehicles are being made with MMCs (Fig. 12). They have high wear resistance coupled with good thermal conductivity. Roller coaster brake fins are another interesting application of MMCs.

Cemented carbides are the commonly used cutting tool materials now. They are made with tungsten carbide particles and cobalt. Substrate carriers of electronic circuit boards need very high thermal conductivity. The carbon fibre reinforced aluminium composite is a suitable choice for this application.

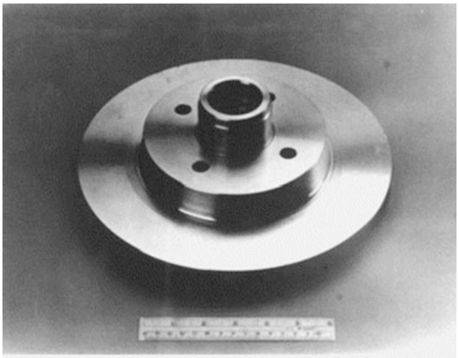

Fig. 12 An air-cooled brake disc made of A359 Al alloy reinforced with 20 vol % of SiC particles [11]

6.3 Applications of CMCs

The CMCs are generally preferred for high temperature applications. Many engine components can be made with CMCs. Gas turbine engines with CMCs are under development. Automobile engines made with CMCs can give high fuel efficiency. These engines are adiabatic engines, since there is no need of cooling system to control the temperature of engine. Already the prototype has been made in Japan.

Another important application is cutting tools. Ceramics are generally hard, but they are very brittle. By forming a ceramic composite, the fracture toughness of ceramics can be improved. A CMC cutting tool will have high hardness and appreciable toughness. High speed machining is possible with these CMC cutting tools.

Brake systems for aircrafts are made with CMCs. Carbon fibre reinforced carbon composites are used because of their high wear resistance and good thermal conductivity. These composites are also used in re-entry vehicles. Since these composites are biocompatible, many medical implants can be made.

Cement based CMCs can be used in building applications. The natural fibre reinforced cement sheets are used for roofing in many developing countries. The incorporation of glass or polymeric fibres can improve the performance of concrete.

7 Conclusion

The composite materials have many advantages and the important advantage is high specific strength/stiffness. Hence, it is possible to make light-weight and high performance components with composite materials. The properties of composites are controlled by the type and quantity of reinforcement and matrix, and size, shape and the nature of distribution of reinforcement. The composites can be classified into various types based on the matrix, the type and arrangement of reinforcement and the size of reinforcement. The fibre reinforced composites are very common because of the many advantages of fibres compared to particulates. There are natural fibres as well as synthetic fibres. Although the natural fibres are inexpensive and environmental friendly, their mechanical properties may not be suitable to produce high performance composites. The synthetic fibres are high performance fibres and there are a variety of fibres available to meet the requirements for various applications. Similarly, a variety of matrix materials is also available. Depending on the service temperature, a suitable matrix material can be selected. The processing of polymer composites is matured enough and there are plenty of methods like, hand lay-up, filament winding, pultrusion, etc. available to make the composites of any shape and size. The processing methods of metal and ceramic matrix composites are evolving and there are a few methods available to fabricate these composites on a commercial scale. Wherever possible, the components made with conventional materials are being replaced with composite materials because of weight advantage and high performance.

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