Material Science

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Chapter 12. Composites

Learning objectives:

- To know the different class of materials called composites
- To study different composites and their strengthening mechanisms with examples.
- To understand the importance and application of composites.

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Highlights, Motivation and Critical Concepts:

With the invention and continued progress of modern technology, need for materials with special properties are growing. Basic conventional engineering materials are not able to serve the purpose. New class of materials, known as composites, is thus emerged to serve the specific needs of modern technology. A composite is made artificially and it contains at least two chemically distinct constituents, which are insoluble in each other. Thus it achieves properties of both the constituents, which are otherwise does not exist together. An engineer needs to have a very good knowledge about these materials for efficient use of composites, and also to develop a new category of composites. This module is constructed with aim to explain the different composites and their strengthening mechanisms with examples.

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There is a great need for materials with special properties with emergence of new technologies. However, conventional engineering materials are unable to meet this requirement of special properties like high strength and low density materials for aircraft applications. Thus, emerged new class of engineering materials – *composites*. Unfortunately, there is no widely accepted definition for a composite material. For the purpose of this module, the following definition is adopted: any multiphase material that is artificially made and exhibits a significant proportion of the properties of the constituent phases. The constituent phases of a composite are usually of macro sized portions, differ in form and chemical composition and essentially insoluble in each other.

Composites are, thus, made by combining two distinct engineering materials in most cases; one is called *matrix* that is continuous and surrounds the other phase – *dispersed phase*. The properties of composites are a function of the properties of the constituent phases, their relative amounts, and size-and-shape of dispersed phase.

Millions of combinations of materials are possible and thus so number of composite materials. For ease of recognition, composite materials are classified based on different criteria like: (1) type of matrix material – metal matrix composites, polymer matrix composites and ceramic matrix composites (2) size-and-shape of dispersed phase – particle-reinforced composites, fiber-reinforced composites and structural composites. It is understandable that properties of composite materials are nothing but improved version of properties of matrix materials due to presence of dispersed phase. However, engineers need to understand the mechanics involved in achieving the better properties. Hence the following sections highlight the mechanics of composites, which depend on size-and-shape of dispersed phase.

12.1 Particle-reinforced composites

This class of composites is most widely used composites mainly because they are widely available and cheap. They are again two kinds: dispersion-strengthened and particulate-

reinforced composites. These two classes are distinguishable based upon strengthening mechanism – dispersion-strengthened composites and particulate composites.

In *dispersion-strengthened composites*, particles are comparatively smaller, and are of 0.01-0.1µm in size. Here the strengthening occurs at atomic/molecular level i.e. mechanism of strengthening is similar to that for precipitation hardening in metals where matrix bears the major portion of an applied load, while *dispersoids* hinder/impede the motion of dislocations. Examples: thoria (ThO_2) dispersed Ni-alloys (TD Ni-alloys) with high-temperature strength; SAP (sintered aluminium powder) – where aluminium matrix is dispersed with extremely small flakes of alumina (Al_2O_3).
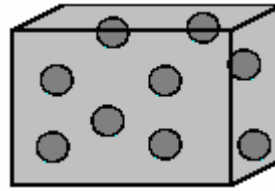

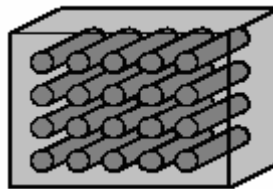Figure 12.1. Particulate reinforced composite

Figure 12.2. Particulate reinforced composite

Particulate composites are other class of particle-reinforced composites. These contain large amounts of comparatively coarse particles. These composites are designed to produce unusual combinations of properties rather than to improve the strength. Mechanical properties, such as elastic modulus, of particulate composites achievable are in the range defined by *rule of mixtures* as follows:

Upper bound is represented by: $E_c(u) = E_m V_m + E_p V_p$

And lower bound is represented by: $E_c(l) = \dfrac{E_m E_p}{E_p V_m + E_m V_p}$

where E and V denote elastic modulus and volume fractions respectively while c, m, and p represent composite, matrix and particulate phases. A schematic diagram of these bounds is shown in the *figure*-12.1.
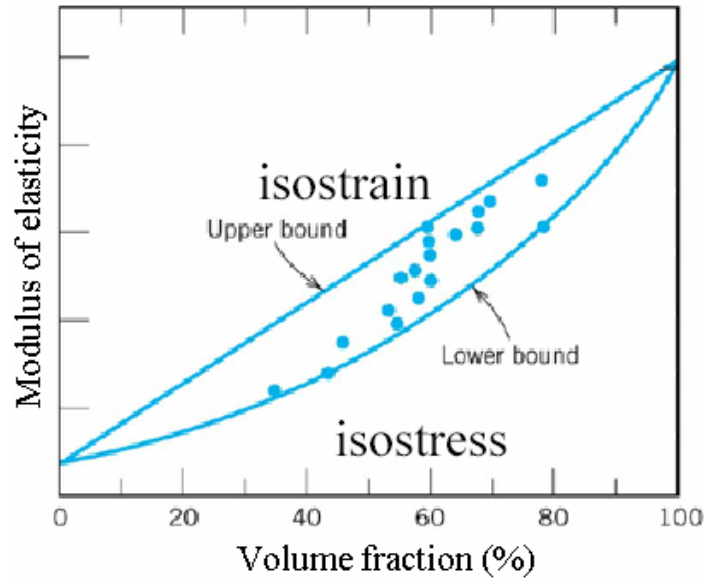
Figure-12.3: *Schematic presentation of rule-of-mixture bounds*.

Particulate composites are used with all three material types – metals, polymers and ceramics. Cermets contain hard ceramic particles dispersed in a metallic matrix. Eg.: tungsten carbide (WC) or titanium carbide (TiC) embedded cobalt or nickel used to make cutting tools. Polymers are frequently reinforced with various particulate materials such as carbon black. When added to vulcanized rubber, carbon black enhances toughness and abrasion resistance of the rubber. Aluminium alloy castings containing dispersed SiC particles are widely used for automotive applications including pistons and brake applications.

Concrete is most commonly used particulate composite. It consists of cement as binding medium and finely dispersed particulates of gravel in addition to fine aggregate (sand) and water. It is also known as Portland cement concrete. Its strength can be increased by additional reinforcement such as steel rods/mesh.

12.2 Fiber-reinforced composites

Most fiber-reinforced composites provide improved strength and other mechanical properties and strength-to-weight ratio by incorporating strong, stiff but brittle fibers into a softer, more ductile matrix. The matrix material acts as a medium to transfer the load to the fibers, which carry most off the applied load. The matrix also provides protection to fibers from external loads and atmosphere.

These composites are classified as either continuous or discontinuous. Generally, the highest strength and stiffness are obtained with continuous reinforcement. Discontinuous fibers are used only when manufacturing economics dictate the use of a process where the fibers must be in this form.

The mechanical properties of fiber-reinforced composites depend not only on the properties of the fiber but also on the degree of which an applied load is transmitted to the fibers by the matrix phase. Length of fibers, their orientation and volume fraction in addition to direction of external load application affects the mechanical properties of these composites.

Effect of fiber length: Some critical length (l_c) is necessary for effective strengthening and stiffening of the composite material, which is defined as:

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

σ_f^* – ultimate/tensile strength of the fiber, d – diameter of the fiber, τ_c – interface bond strength. Fibers for which $l \gg l_c$ (normally $l > 15\ l_c$) are termed as continuous, discontinuous or short fibers on the other hand.

Effect of fiber orientation and concentration: with respect to orientation, two extremes possibilities are – parallel alignment and random alignment. Continuous fibers are normally aligned, whereas discontinuous fibers are randomly or partially orientated. Two instants of loading are: longitudinal loading and transverse loading.

(a) Continuous fiber composites:

Under *longitudinal loading*, by assuming that deformation of both matrix and fiber is the same i.e. isostrain condition, rule-of-mixtures results in the following:

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

where A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases respectively. In the composite, if matrix and fiber are all of equal length, area fractions will be equal to volume fractions. Thus,

$$\sigma_c = \sigma_m V_m + \sigma_f V_f$$

When the isostrain assumption is taken into account, the above equation transforms into

$$E_{cl} = E_m V_m + E_f V_f = E_m (1 - V_f) + E_f V_f$$

The ratio of the load carried by the fibers to that carried by the matrix is given by

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

In case of *transverse loading*, it is assumed that both matrix and fiber will experience the equal stress i.e. isostress condition. Then the modulus of the composite is given by:

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

Longitudinal tensile strength: as mentioned earlier, matrix material is softer i.e. fibers strain less and fail before the matrix. And once the fibers have fractured, majority of the load that was borne by fibers is now transferred to the matrix. Based on this criterion the following equation can be developed for longitudinal strength of the composite:

$$\sigma_{cl}^* = \sigma_m' (1 - V_f) + \sigma_f^* V_f$$

where σ'_m – stress in the matrix at fiber failure, σ_f^* – fiber tensile strength.

Whereas longitudinal strength is dominated by fiber strength, a variety of factors will have a significant influence on the transverse strength. These include properties of both the fiber and matrix, interface bond strength, and the presence of voids.

(b) Discontinuous and aligned fiber composites:

Even though reinforcement efficiency is lower for discontinuous fiber composites than continuous fiber composites, discontinuous and aligned fiber composites are commercially gaining an important place. The longitudinal strength of these composites is given by:

$$\sigma_{cd}^* = \sigma_f^* V_f (1 - \frac{l_c}{2l}) + \sigma_m' (1 - V_f) \text{ when } l > l_c \text{ and}$$

$$\sigma_{cd'}^* = \frac{l \tau_c}{d} V_f + \sigma_m' (1 - V_f) \text{ when } l < l_c$$

where τ_c – smaller of either the fiber-matrix bond strength or the matrix shear yield strength.

(c) Discontinuous and randomly orientated fiber composites:

Reinforcement efficiency of these fiber composites is difficult to calculate, and is usually characterized by a parameter known as fiber efficiency parameter, K. K depends on V_f and the E_f/E_m ratio. If rule-of-mixtures can be applied, elastic modulus of these composites is given by:

$$E_{cl} = K(E_m V_m + E_f V_f)$$

12. 3 Structural composites

These are special class of composites, usually consists of both homogeneous and composite materials. Properties of these composites depend not only on the properties of the constituents but also on geometrical design of various structural elements. Two classes of these composites widely used are: laminar composites and sandwich structures.

Laminar composites: there are composed of two-dimensional sheets/layers that have a preferred strength direction. These layers are stacked and cemented together according to the requirement. Materials used in their fabrication include: metal sheets, cotton, paper, woven glass fibers embedded in plastic matrix, etc. Examples: thin coatings, thicker protective coatings, claddings, bimetallics, laminates. Many laminar composites are designed to increase corrosion resistance while retaining low cost, high strength or light weight.

Sandwich structures: these consist of thin layers of a facing material joined to a light weight filler material. Neither the filler material nor the facing material is strong or rigid, but the composite possesses both properties. Example: corrugated cardboard. The faces bear most of the in-plane loading and also any transverse bending stresses. Typical face materials include Al-alloys, fiber-reinforced plastics, titanium, steel and plywood. The core serves two functions – it separates the faces and resists deformations perpendicular to the face plane; provides a certain degree of shear rigidity along planes that are perpendicular to the faces. Typical materials for core are: foamed polymers, synthetic rubbers, inorganic cements, balsa wood. Sandwich structures are found in many applications like roofs, floors, walls of buildings, and in aircraft for wings, fuselage and tailplane skins.

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What are composites?
Why do we need composites?
How the composites are made?
How the presence of dispersed phase improves the properties?
What are structural composites?
Want to know how good you are in this chapter?

What are composites?
Composites are the multiphase materials, which can be defined as any multiphase material that is artificially made and exhibits a significant proportion of the properties of the constituent phases. The constituent phases of a composite are usually of macro sized portions, differ in form and chemical composition and essentially insoluble in each other.

Why do we need composites?
Composites are the class of materials with special properties. Properties of the composite can be tailored to meet the required purpose. So, it is important to have composite materials for the technologies which demand special properties.

How the composites are made and classified?
Composites are made by combining two distinct engineering materials in most cases; one is called *matrix* that is continuous and surrounds the other phase – *dispersed phase*. The properties of composites are a function of the properties of the constituent phases, their relative amounts, and size-and-shape of dispersed phase.

Millions of combinations of materials are possible and thus so number of composite materials. For ease of recognition, composite materials are classified based on different criteria like: (1) type of matrix material – metal matrix composites, polymer matrix composites and ceramic matrix composites (2) size-and-shape of dispersed phase – particle-reinforced composites, fiber-reinforced composites and structural composites.

How the presence of dispersed phase improves the properties?

Particle-reinforced composites

They are again two kinds: dispersion-strengthened and particulate-reinforced composites. These two classes are distinguishable based upon strengthening mechanism – dispersion-strengthened composites and particulate composites.

In *dispersion-strengthened composites*, particles are comparatively smaller, and are of 0.01-0.1µm in size. Here the strengthening occurs at atomic/molecular level i.e. mechanism of strengthening is similar to that for precipitation hardening in metals where matrix bears the major portion of an applied load, while *dispersoids* hinder/impede the motion of dislocations. Examples: thoria (ThO$_2$) dispersed Ni-alloys (TD Ni-alloys) with high-temperature strength; SAP (sintered aluminia powder) – where aluminium matrix is dispersed with extremely small flakes of alumina (Al$_2$O$_3$).

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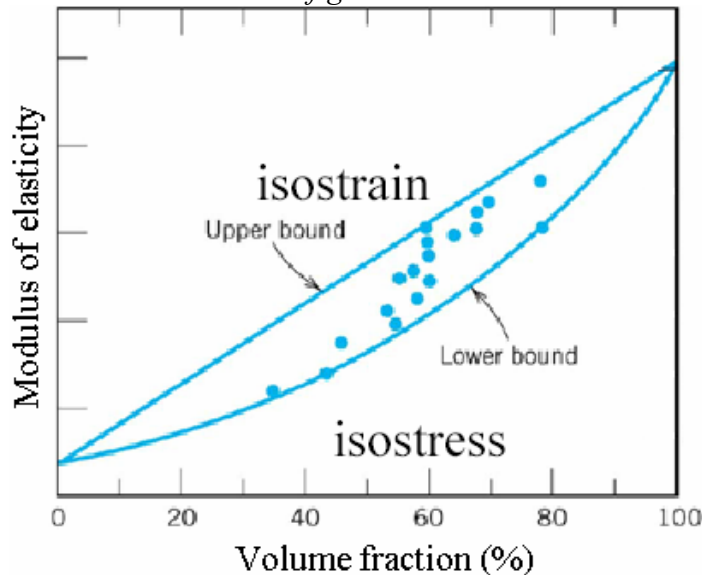

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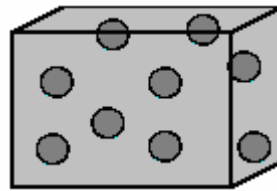

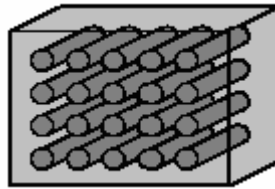Figure 12.2. Particulate reinforced composite

Figure 12.3. Particulate reinforced composite

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What are structural composites?

Structural composites are special class of composites, usually consists of both homogeneous and composite materials. Properties of these composites depend not only on the properties of the constituents but also on geometrical design of various structural elements. Two classes of these composites widely used are: laminar composites and sandwich structures.

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Want to know how good you are in this chapter?

1. Composite materials are classified based on:

(a) Type of matrix   (b) Size-and-shape of reinforcement (c) Both   (d) None

2. Major load carrier in dispersion-strengthened composites

(a) Matrix   (b) Fiber   (c) Both   (d) Can't define

3. Usually softer constituent of a composite is

(a) Matrix   (b) Reinforcement   (c) Both are of equal strength   (d) Can't define

4. Usually stronger constituent of a composite is

(a) Matrix   (b) Reinforcement   (c) Both are of equal strength   (d) Can't define

5. Last constituent to fail in fiber reinforced composites

(a) Matrix   (b) Fiber   (c) Both fails at same time   (d) Can't define

6. Size range of dispersoids used in dispersion strengthened composites

(a) 0.01-0.1 μm   (b) 0.01-0.1 nm   (c) 0.01-0.1 mm   (d) None

7. Rule-of-mixture provides _____ bounds for mechanical properties of particulate composites.

(a) Lower   (b) Upper   (c) Both   (d) None

8. Al-alloys for engine/automobile parts are reinforced to increase their

(a) Strength   (b) Wear resistance   (c) Elastic modulus   (d) Density

9. Mechanical properties of fiber-reinforced composites depend on

(a) Properties of constituents
(b) Interface strength
(c) Fiber length, orientation, and volume fraction
(d) All the above

10. Longitudinal strength of fiber reinforced composite is mainly influenced by

(a) Fiber strength   (b) Fiber orientation   (c) Fiber volume fraction   (d) Fiber length

11. The following material can be used for filling in sandwich structures

(a) Polymers   (b) Cement   (c) Wood   (d) All

12. Not an example for laminar composite

(a) Wood   (b) Bimetallic   (c) Coatings/Paints   (d) Claddings

Answers:

1. c
2. a
3. a
4. b
5. a

6. a
7. c
8. b
9. d
10. a
11. d
12. a