

Composite Materials

"We never reach our ideals, whether of mental or moral improvement, but the thought of them shows us our deficiencies and spurs us on to higher and better things"

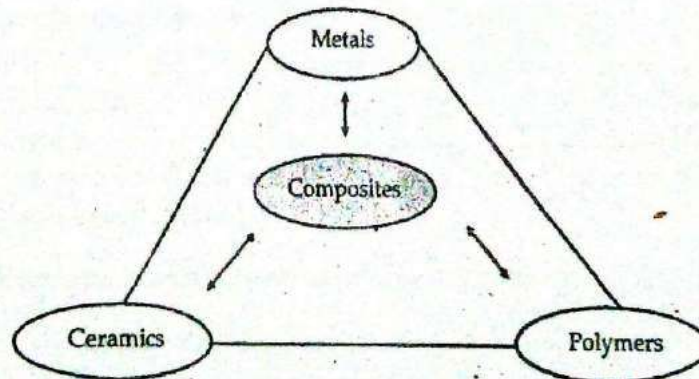
1 INTRODUCTION

For better overall performance we require unusual combinations of properties that cannot be provided by conventional materials like metals, ceramics or polymers. For example, structural materials required for aircraft must have high specific strength, stiffness and excellent resistance to corrosion, abrasion, impact and heat. This is rather unusual combination of properties since strong materials are generally dense and also increase in strength and stiffness usually results in decrease in impact strength.

The great and diverse demands made on materials for better overall performance led to the concept of composite materials.

A *composite* may be defined as any multiphase material which consists of two or more physically and/or chemically distinct phases with an interface separating them.

(As per this definition most of the metallic alloys, ceramic materials etc., are not considered as composite materials.)



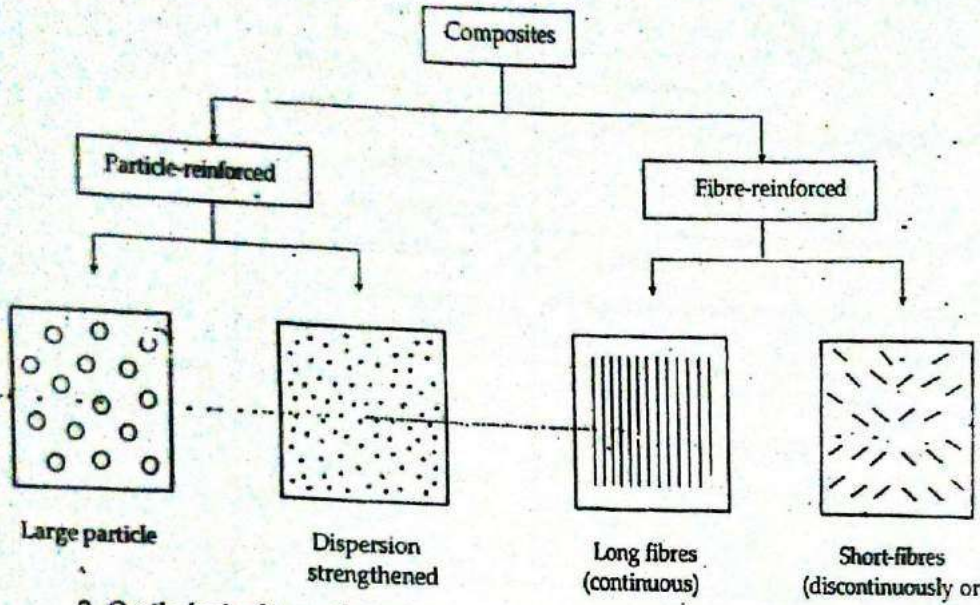
Newer materials "composites" are obtained from conventional materials like Metals, Ceramics & Polymers by adding fibers, particles etc. to them.

The composite materials shows properties distinctively different from those of the individual materials of the composite. In fact, composites show extraordinary combination of properties like toughness and strength with low weights and high temperature resistance. For instance, compared to steel and aluminium, composites are lighter, have low coefficient of thermal expansion and have superior strength, stiffness and fatigue resistance.

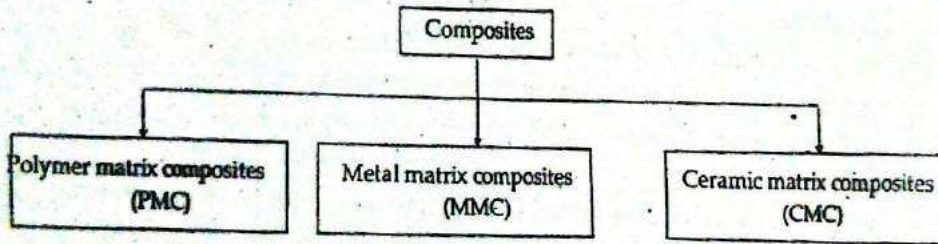
2 CLASSIFICATION OF COMPOSITE MATERIALS

Composite materials can be broadly classified into following types :

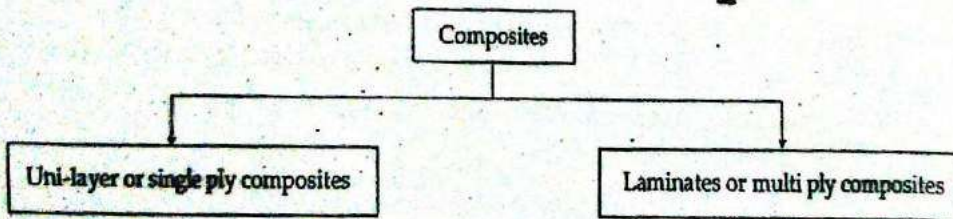
1. On the basis of type of reinforcement used in the matrix



2. On the basis of type of matrix



3. On the basis of number of ply or lamina's or layers



3 CONSTITUENTS OF COMPOSITES

Composites, in general, consist of body constituents and structural constituents. The *body constituent* enclose the composite and give it its bulk form. The continuous *matrix phase* is the body constituent. The *structural constituents* determine the internal structure of the composite. This is also known as *dispersed phase*.

The surface forming the common boundary between the matrix and dispersed phase is known as *interphase*.

Properties of the composites depends upon :

- (i) The properties of the constituent materials ;

- (ii) Their relative amounts (*i.e.*, concentration of constituents);
- (iii) Their distribution and orientation; and
- (iv) The geometry of the dispersed phase namely the shape, size and size distribution

These constituents are briefly discussed below :

(A) The Matrix phase

Matrix phase may be metal, ceramics or polymer. Depending on the type of matrix we have three broad categories of composites *viz.*

- (i) Polymer matrix composites (PMC);
- (ii) Metal matrix composites (MMC); and
- (iii) Ceramic matrix composites (CMC)

The matrix phase has several important functions *viz.* :

- (i) It binds the fibers together by virtue of its cohesive and adhesive characteristics;
- (ii) It acts as a medium by which an externally applied load is transmitted and distributed to the dispersed phase (generally a fiber);
- (iii) It protects the individual fibers from chemical reaction with the environment and from surface damage due to mechanical abrasion. Otherwise surface flaws may result which lead to failure at low levels of tensile stress.
- (iv) It keeps the reinforcing fibers in the proper position and orientation so that they can carry the intended loads;
- (v) It prevents the propagation of brittle cracks by virtue of its relative softness and plasticity. It provides interlaminar shear strength to the composite. Even if some of the individual fibers fail, total failure of the composite will not occur until large number of adjacent fibers fail and form a cluster of critical size.

The essential requirements of a good matrix materials are :

- (a) It should be ductile;
- (b) The bonding strength between the matrix and fibre must be high. This is essential to maximise the stress transmittance from the weak matrix to the strong fibers. Moreover, the ultimate strength of the composite depends on the strength of this bond;
- (c) It should have good corrosion resistance.

The properties governed by matrix phase :

Generally matrix determines the overall service temperature limitations of the composite. It also controls the environmental resistance of the composite. For example, composites based on polymers are limited to service temperatures below 300°C.

The pros and cons of different matrix phases are summarized below :

| Matrix Phase | Pros | Cons |
|--------------|---|--|
| 1. Metals | <ul style="list-style-type: none"> • Ductile • High moduli, • Resist thermal shock, • Easy to manufacture. | <ul style="list-style-type: none"> • High density, • Costly manufacturing & materials costs. |
| 2. Ceramics | <ul style="list-style-type: none"> • Thermal stability, • Load bearing capacity, • Stiffness. | <ul style="list-style-type: none"> • Brittle, • Costly manufacturing & material costs, • Not stable against mechanical shock. |
| 3. Polymers | <ul style="list-style-type: none"> • Low cost, • Light weight, • Corrosion resistant, • Tough, • Easily processible. | <ul style="list-style-type: none"> • Lower strength & Stiffness, • Low thermal stability, • Low load bearing capacity |

In polymer matrix composites (PMC), both thermoplastic and thermosetting resins can be used. *Advantages of thermoplastic resins over thermosets are listed below :*

- (i) They are tougher and have high strains to failure ;
- (ii) They offer the potential of improved hot/wet resistance ; and
- (iii) No chemical reactions are involved causing release of gaseous products or exothermal heat.

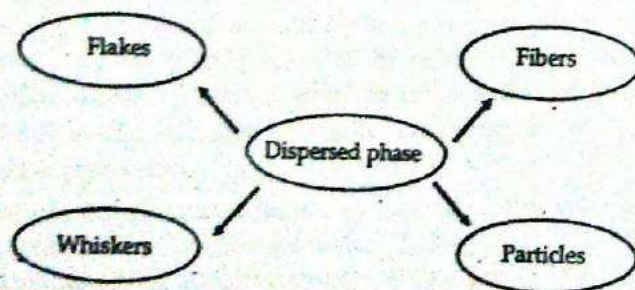
Examples of some representative polymeric matrix materials are :

Epoxy, polyetherether ketone, polyimide, polysulfone and phenolics.

(B) The Dispersed phase

The dispersed phase can be fiber, particle etc. On this basis we have fibre and particle reinforced composites.

The following figure shows types of reinforcement in composites :



The important characteristics of these structural constituents of composites are summarized below :

I. Fibers. Any polymer, metal or ceramic that has been drawn into long and thin filament, is termed as fiber. It is characterized by high *aspect ratio* (length to diameter ratio) and near crystal-sized diameter. They have high strength and

stiffness. This is due to the fact that the probability of the existence of a critical surface flaw that can lead to fracture diminishes with increasing aspect ratio. Effective transfer of load from one fiber to another requires the maintenance of characteristic aspect ratio. Orientation of fibers determine the property of fibrous composite. For example, in one dimensional fibrous composite, strength and modulus of the composite is maximum in the direction of fiber axis. The mechanical properties in any one direction are proportional to the amount of fibers by volume oriented in that direction.

Some of the fibers (used as reinforcements) are glass fibers, carbon fibers, aramide fibers, boron fibers and ceramic fibers.

The principal reinforcing fibers are briefly discussed below :

(i) **Glass fibers.** They are produced by extruding a glass melt through small orifices, rapidly pulling and subsequently cooling the emerging filaments. Individual fibers are called monofilaments and have diameter around 10 μm . Generally "size" is applied in liquid form (it contains chemical coupling agent, a binder and a lubricant) to glass monofilaments to help in the handling of strands, to protect them from detrimental abrasion and to promote subsequent adhesion of glass fibers to matrix.

Glass is popular as a fiber reinforcement material for several reasons :

- (a) High strength glass fibers can be easily drawn from the molten state,
- (b) It is readily available and is low in cost,
- (c) Commonly available manufacturing techniques can be employed for the economic production of glass fiber-reinforced polymer composites,
- (d) Composites, so produced, can be used in variety of corrosive environments since glass fibers when coupled with a plastic matrix exhibits chemical inertness, and
- (e) Glass fiber-reinforced polymer composites have very high specific strength since glass fibers are relatively very strong.

Glass fibers have found very extensive use in plastics. Most commonly (1) in continuous form in catalyst activated thermo-setting resins and (2) in short form in thermoplastics.

(ii) **Carbon fibers.** They are prepared by preoxidation in the temperature range of 200–250° C under tension and controlled carbonisation (upto 1000° C) of an already formed organic carbon rich filamentary material. They are usually subjected to controlled surface treatments including oxidative etching, vapour deposition and polymer coating.

The monofilaments of carbon fibers have diameter in the range of 5 to 10 microns.

Carbon fibers are used as reinforcement in advanced polymer matrix composites due to :

- (a) Their high specific strength and stiffness which is retained even at elevated temperatures ;
- (b) Good resistance to moisture, acids, bases and wide variety of solvents ;
- (c) Availability of relatively inexpensive and cost effective manufacturing processes for both fibers and composites.

COMPOSITE MATERIALS

(iii) **Aramid fibers.** They are basically aromatic polyamides (aramides) like Nomex and Kevlar. For instance, Kevlar is p-phenylene terephthalamide. It is spun from a nematic liquid crystalline solution using a dry jet wet spinning technique using sulphuric acid as the solvent and cold water as coagulant.

The characteristic properties of Kevlar fibers are :

- Higher tensile strengths and tensile moduli compared to other polymeric fiber materials.
- Excellent toughness, impact resistance and resistance to creep and fatigue failure.
- Resistant to combustion and stability even at relatively high temperatures.
- Retain mechanical properties over a temperature range of :
- 200 to + 200° C.

Limitations

- Weak in compression and
- Susceptible to degradation by strong bases and acids

Aramide fibers are commonly used in PMC 's. The common matrix materials are polyesters and epoxies.

Specific strength and specific stiffness of few selected fiber materials are given in Table 1 below :

Table 1

| Fiber | Specific Strength (Tensile strength/density) (kN.m) | Specific stiffness (Tensile stiffness/density) (kN.m) |
|-----------|---|---|
| Glass | 136 | 2.9 |
| Carbon | 123 | 14 |
| Aluminium | 24 | 2.8 |

II) Particles. Dispersed phase in particulate composites consist of particles. These particles can be metallic or non-metallic. Distribution of particles in a given matrix is generally random rather than controlled. Resulting composites are therefore usually isotropic. Because of their inherent hardness relative to the matrix material, the particles in a particulate composite place constraints on the plastic deformation of the plastic material. In essence the matrix transfers some of the applied stress to the particles, which bear a fraction of the load. There should be a good bond at the interface of matrix and particle for desired reinforcement in mechanical properties.

Particle-matrix interactions that lead to strengthening may or may not occur on the atomic or molecular level depending on size of the particles. Particulate fillers are accordingly classified as *large particle* and *dispersion strengthened* respectively.

The properties of matrix materials which are modified by adding particulate fillers are :

- Improved performance at elevated temperatures,
- Improved wear and abrasion resistance,
- Increase in surface hardness,
- Reduction in (cost, shrinkage and friction) and
- Modification in thermal and electrical conductivities.

(III) **Flakes.** Thin flakes primarily have a two-dimensional geometry. They impart equal strength in all directions in their plane compared to fibers that are unidirectional reinforcements. Flakes can be packed more efficiently than fibers or spherical particles.

For example, mica flakes are used in electrical and heat insulating applications.

(IV) **Whiskers.** Whiskers are primarily very thin single crystals with high aspect ratio. They exhibit a high degree of crystalline perfection. They are associated with exceptionally high strengths because they are free from surface defects (flaws). Because of their high cost and difficulty in incorporating them in matrix, their extensive use is limited.

Important whisker materials are graphite, aluminium oxide, silicon carbide and silicon nitride.

4 ROLE OF INTERFACE IN COMPOSITE PERFORMANCE AND DURABILITY

The transmission of stress from matrix phase to reinforcement depends on the strength of interfacial bond. A strong interfacial bond resists failure.

For composites that have a good interfacial bond, the fracture mode is generally a sharp well-defined break.

For composites that have a poor interfacial bond, the fracture will be a progressive one-bond failure, followed by matrix failure and finally fibre failure.

The interface can act as a locus of chemical reaction, it can also serve as a nucleation site and a preferential adsorption site. It is because of (i) The difference between thermal expansion coefficients of the reinforcement and the matrix phases and (ii) Cure shrinkage in thermosets and crystallization in thermoplastics.

5 FIBER-REINFORCED COMPOSITES

When fibers are used as dispersed phase for the reinforcement of matrices, the resultant composites are known as fiber reinforced composites.

Fiber-reinforced composites are characterized by:

- (i) high specific strength (i.e. tensile strength/specific gravity)
- (ii) high specific modulus (i.e. modulus of elasticity/specific gravity)

The properties of fiber-reinforced composites depend on

- (a) Nature and properties of fibre and matrix materials;
- (b) Their relative volume fractions;
- (c) Orientation and distribution of fibers in matrix phase (superior properties are observed in the direction where fibers are oriented);
- (d) Strength of the interfacial bond between the fiber and the matrix phases (high strength is generally desired);
- (e) Length of the fibers or more appropriately aspect ratio (length : diameter ratio) of fibers.

For number of fiber-reinforced composites, aspect ratio has value in between 20 and 150. In fact, for effective strengthening and stiffening of the composite, some critical fibre length is must.

Critical fibre length (l_c) is defined as:

$$l_c = \sigma_f d / T_c$$

where σ_f is ultimate fibre strength of the fibers.

d is diameter of fibers, and

T_c is shear yield strength or fibre-matrix bond strength.

Long (or continuous) fibers have their lengths which are about 15 times greater than the critical length but in short (or discontinuous) fibers, the lengths of the fibers are considerably lower than their critical length. That's why the reinforcement efficiency of continuous fibers is higher than that for discontinuous fibers.

Some Important Types of Fiber-Reinforced Composites :

(A) **Glass-fiber reinforced composites :** Glass fibers (both long and short) are generally used for improving the properties of polymeric matrices like polyesters, nylon etc.

These composites have the following characteristics :

- (i) Lower densities,
- (ii) Higher tensile strengths,
- (iii) High impact resistance,
- (iv) Excellent chemical and corrosion resistance.

But, these composites also have the following *limitations :*

- (i) Limited service temperatures, because most polymeric matrices begin to deteriorate or flow at high temperatures.
- (ii) These materials do not possess the desired stiffness and rigidity, particularly in their applications as structural components.

Some typical applications of these materials are in

Automotive parts, storage tanks, industrial floorings, plastic pipes and in transportation industries to reduce vehicle weight and boost fuel efficiency.

(B) **Carbon Fiber-Reinforced Polymer Composites :** High performance carbon fibers are now-a-days used as reinforcement in advanced polymer matrix composites, which requires retention of desired properties even at higher temperatures and excellent resistance to corrosion along with lighter weights.

Some typical applications of these materials are :

- (i) Military and commercial aircraft structural components such as wing,
- (ii) Wing, body and stabilizer components of helicopters,
- (iii) Sports and recreational equipments like fishing rods, golf clubs.

The uses of these materials are limited because of their higher costs.

(C) **Aramid Fiber-Reinforced Polymer Composites :** These materials can be broadly classified into following categories :

(i) *Short fibre reinforced composites.* The short fibers of *p*-aramid have high aspect ratio and high surface area and hence they give effective reinforcement. Moreover, they have inherent toughness, strength and heat stability. They also have high wear resistance and are used in automotive brakes and clutches. In fact these composites perform better than asbestos at less than one-tenth the amount in brakes and clutches. Because asbestos causes serious health problems so its use is now-a-days restricted.

(ii) **Long fibre reinforced composites.** These composites are metal-like in ductile energy absorption and respond to compressive stresses non-catastrophically. This is due to the fact that aramid fibres absorb energy in its accordion like compressive collapse. They are excellent advanced engineering and structural materials. The latest commercial aircrafts Boeing 767 and Airbus 320 contain about 3-5% of composites, much of which is *p*-aramid or hybrids of *p*-aramid and carbon.

The helicopter industry also utilises composites based on *p*-aramid in fuselage parts, motor housing and rotor blades. Even primary structures of small business air crafts are being made by using these composites.

These materials are also used for manufacturing protective apparel (thermal, cuts, ballistics).

(D) **Alumina and/or carbon fibers reinforced metal-matrix composites :** Fibre reinforcement in ductile metal matrix may improve specific strength & stiffness, resistance to abrasion & creep and dimensional stability.

The properties and application of two such composites are summarized below :

| Matrix | Reinforcement | Characteristic properties | Applications |
|--------------------------------|---|---|----------------------------------|
| Aluminium alloy | Alumina or Carbon fibres | Light in weight, Resists wear and thermal distortion | Engine component of Automobiles. |
| Nickel and Cobalt based alloys | Alumina or refractory metals such as tungsten | Excellent high-temperature, creep and rupture resistance, Excellent impact strength | Turbine engines |

8 SHORT FIBRE REINFORCED COMPOSITES

Introduction. When the composites are used in applications where the state of stress can be accurately determined then unidirectional composites either as such or in the form of laminates are used having strength matched to the design needs. This is due to the fact that unidirectional composites have higher strength and modulus in the direction of the fiber axis and are generally very weak in the transverse direction.

It is improper to use unidirectional composites in those applications where isotropic stresses (*i.e.*, stresses equal in all directions) are imposed or where stresses may not be predictable. Multilayered composites constructed from layers of unidirectional laminae having different fiber orientations are essentially isotropic in a plane but the surface layers are still very weak in the transverse direction. Since failure is often initiated from surface layers, hence in applications where protection from a corrosive environment is an important factor (*e.g.* storage tanks in the chemical industry), multilayered composites cannot be used.

This problem can be solved by using those laminates in which each layer or lamina is isotropic. When randomly oriented short fibers are used as the reinforcement, an isotropic layer is obtained. There is another advantage of short fiber reinforced composites. These can be easily and economically molded into desired shapes by injection or compression molding.

Properties of short fiber reinforced composites

The strengthening in short fiber reinforced composites is achieved partly by restraining the deformation of the matrix between the fibers and partly by sharing of load between the fibers and the matrix. Strength and orientation of short fibers, their V_f , interfacial bond strength and kind of matrix govern the properties of these composites.

(i) **Fatigue.** As the weaker matrix is required to sustain a much greater proportion of the cyclic load, short-fiber reinforced composites are much less resistance to fatigue damage. This damage is generally initiated by debonding of those fibers that lie perpendicular to the loading direction, in randomly oriented short fiber composites. But in aligned short-fiber composites the fiber ends and weak interfaces can become sites for fatigue crack initiation.

Thus, an important aspect of fatigue of short-fiber composites is that local failures in the matrix and at the weak interface can destroy the integrity of the composite even though the fibers remain undamaged.

(ii) **Impact strength.** When brittle matrices (*e.g.*, polystyrene) and ductile matrices (*e.g.*, polyethylene) are reinforced incorporating short glass fibers, the tensile impact energy of former increases but for later materials, it decreases.

This can be explained as follows :

In ductile matrices, the triaxial restraint of the matrix between fibers limits the elongation of the matrix, and thus addition of rigid fibers greatly reduces the toughness.

But in brittle matrices addition of fibers increase toughness because of crack blunting, branching and arrest effects.

9 PARTICLE-REINFORCED COMPOSITES

In the particle-reinforced composites, the dispersed phase is a particle which generally has nearly same dimensions in all the directions (i.e., it is equi-axed).

The behaviour of these composites is governed by :

- (i) Distribution of particles throughout the matrix.
(For effective reinforcement, distribution should be uniform).
- (ii) Relative volume fraction of the constituents (Greater the volume fraction of particulate reinforcement, more will be the improvement in the mechanical properties).
- (iii) Strength of the bond at the interface of particles and matrix (stronger the bond, better will be the properties of composites).

Generally particulate phase can be divided into two categories viz. large particle and Dispersion-strengthened. The corresponding composites are briefly described below :

(i) *Large-Particle Composites*. In these composites the interactions between particle and matrix phases are not on the atomic or molecular level.

Elastic modulus of particle reinforced composite fall between

$$E_c(u) = E_m (1 - V_p) + E_l V_p$$

and

$$E_c(l) = \frac{E_m E_p}{(1 - V_p) E_p + V_p E_m}$$

where $E_c(u)$ and $E_c(l)$ represent upper and lower elastic modulus of composite.

E_m and E_p represents elastic modulus of matrix and particle phases and V_p represents volume fraction of particle phase.

Examples of large particle reinforced composites :

1. A composite in which vulcanized rubber (matrix) is reinforced by adding 15-30% by volume of carbon-black particles with 20-50 μm diameter.

The resulting composite has excellent tensile strength, toughness and abrasion resistance and is used for making *automobile tyres*.

2. *Cermets* (or ceramic-metal composite) in which ceramics like titanium carbide (TiC) and tungsten carbide (WC) are embedded in metals such as nickel or cobalt.

Cermets are used extensively as cutting tools. The cutting surface is being provided by hard ceramic carbide particles. They are not capable of withstanding the cutting stresses as they are brittle so they are not used alone. For enhancing the toughness, these particles need to be incorporated in ductile metal-matrix which

prevents particle to particle crack propagation by isolating them. As the cutting action generate high temperatures hence both the components (of composite used for cutting tools) should be refractory materials. In this case they are ceramics and metals.

(ii) **Dispersion-Strengthened composites.** Here reinforcement is done by the uniform dispersion of fine particles of very hard and inert material. These particles may be metallic or non-metallic. But because of their fine dimensions, interactions between them and matrix phase is on the atomic or molecular level. Generally, inert particles are chosen for reinforcement which do not react with the matrix phase hence strengthening is retained at elevated temperatures. Moreover, the resulting composites are durable.

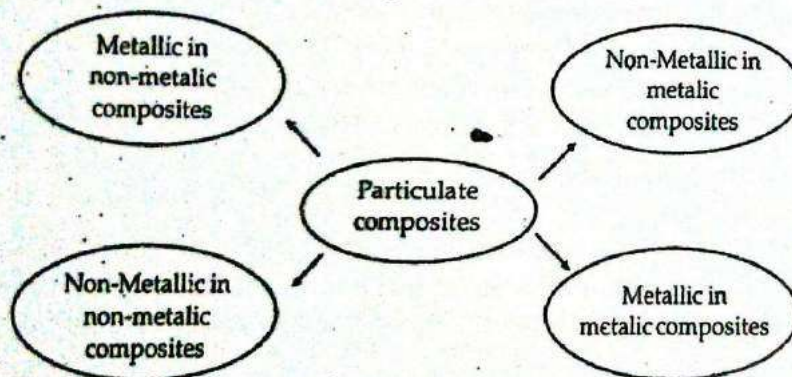
Examples of Dispersion strengthened composites : (1) Thoria-dispersed (or TD) nickel. In this composite, about 3 volume % of thoria (ThO_2) in the form of fine particles are uniformly dispersed in nickel matrix for improving the high-temperature strength of nickel alloys.

(2) Sintered aluminium powder : here aluminium metal matrix is reinforced by incorporating extremely fine (0.1 to $0.2 \mu\text{m}$ thick) particles of aluminium oxide. The resulting composites have excellent high temperature strength.

The four broad categories of particle reinforced composites are summarized below :

10 PARTICULATE COMPOSITES

Particulate composites are broadly classified as :



Types of Particulate composites

(i) **Non-metallic in metallic composites.** Examples of Non-metallic in metallic composites are :

- Ceramics particles suspended in a metal-matrix.
- Such composites are known as *cerments* and are of two types :
 - (a) **Oxide based cerments.** For example, Al_2O_3 with 72 vol. % dispersed in chromium matrix has strength 30 GPa and also has very good thermal shock-resistance.

(b) Carbide based cements

| Carbide | Matrix | Applications |
|---------|--------|---|
| WC | Co | Wire-drawing die, valves and other machine parts requiring very high hardness |
| CrC | Co | Valves, pump-parts & spray nozzle as it has very high resistance to corrosion and abrasion. |

(ii) *Metallic in non-metallic composites.* Examples of metallic in non-metallic are:

Aluminium paint in which aluminium flakes suspended in paint.

(iii) *Metallic in metallic-composites.* Examples of metallic in metallic-composites are:

- (a) Lead particles in copper alloys & steel, improves the machineability of the latter.
- (b) Bearings made from Cu alloys utilize lead as a natural lubricant.

(iv) *Non-metallic in non-metallic composites.* Examples of non-metallic in non-metallic composites are:

- (a) Flakes of mica or glass in glass or plastic matrix respectively.
- (b) Concrete is another example of this class in which particles of sand and rock are dispersed in cement which then chemically react with water for hardening.