Mechanical Properties of Solids

These include those characteristics of material that describe its behaviour (response) under the action of external forces (loads) Can be determined by conducting experimental tests on the material specimen. Strength, Hardness, Toughness, Brittleness, Ductility, Malleability, Elasticity Plasticity, Rigidity, Resilience, Fatigue, Creep

1) STRENGTH: It is the ability of a material to resist deformation under the action of tensile, compressive or shear force. The strength of a component is usually based on the maximum load that can be borne before failure is apparent. The most common measure of strength is the yield strength.

2) HARDNESS: It is the ability of a material to offer resistance to penetration or indentation. It is also the ability to resist wear, abrasion, scratch or cutting.

3) TOUGHNESS: It describes a material's resistance to fracture under impact loading. It is often expressed in terms of the amount of energy a material can absorb before fracture. Toughness is not a single property but rather a combination of strength and ductility.

4) BRITTLENESS: It is that property by virtue of which a material breaks easily under action of shock loads without appreciable amount. It indicates the lack of ductility. For example glass, ceramics and cast iron are brittle materials.

5) DUCTILITY: It is a measure of the amount of deformation of a material can withstand before breaking. It is also the ability of a material by which it can be drawn into wires.

6) MALLEABILITY: It is the ability of a material by which it can be rolled into sheets. Malleability is the ability of a material to exhibit large deformation subjected to compressive force whereas ductility is the ability of a material to deform upon the application of tensile force. Aluminum, Copper and gold have good malleability.

7) ELASTICITY: It is the property of a material to regain its original shape after the removal of load. When a material is subjected to an external load of such magnitude that deformation continues only with increase in load, and on removing the load it regains its original shape, then the material is said to have elasticity.

8) PLASTICITY: It is the property of a material by virtue of which it undergoes permanent deformation. When a material is subjected to an external load of such magnitude that deformation continues with no apparent further increase in load, the material is said to have become plastic. In this region the material experiences permanent deformation and does not return to its original shape when the load is removed.

9) RIGIDITY: It is also known as stiffness. It is the property of a material by virtue of which the material resists elastic or plastic deformation under applied loads.

10) MACHINABILITY: It refers to the ease with which a material can be removed during various machining operations. It describes the property of a material when it is cut. Materials with good machinability require less power to cut, resulting in good surface finish and longer cutting tool life.

11) HARDENABILITY: It indicates the degree of hardness that a material can acquire through a hardening process. It is the capability of a material to get hardened by heat treatment. It determines the depth and distribution of hardness induced by quenching.

12) RESILIENCE: It is the property of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. In other words, it is the maximum energy per volume that can be elastically stored.

13) FATIGUE: It is the strength of the materials when subjected to cyclic or rapid fluctuating load conditions. Owing to fatigue a material fails at a stress level much below that under static loads. The maximum stress to which the material can be subjected without fatigue failure is known as the endurance limit.

14) CREEP: It is the progressive deformation of a material under a constant static load maintained for a long period of time. It is a slow, temperature-aided, time-dependent deformation. It occurs in three stages known as primary, secondary and tertiary stage.

Stress

Stress is defined as force per unit area within materials that arises from externally applied forces, uneven heating, or permanent deformation and that permits an accurate description and prediction of elastic, plastic, and fluid behaviour.

Stress is given by the following formula:

σ=FA

where, σ is the stress applied, ***F*** is the force applied and ***A*** is the area of the force application.

The unit of stress is N/m^2.

Types of Stress

Stress applied to a material can be of two types as follows:

Tensile Stress

The external force per unit area of the material resulting in the stretch of the material is known as tensile stress.

Compressive Stress

Compressive stress is the force that is responsible for the deformation of the material, such that the volume of the material reduces.

Strain

Strain is the amount of deformation experienced by the body in the direction of force applied, divided by the initial dimensions of the body.

The following equation gives the relation for deformation in terms of the length of a solid:

ϵ=δlL

where ε is the strain due to the stress applied, δl is the change in length and **L** is the original length of the material.

The strain is a dimensionless quantity as it just defines the relative change in shape.

Types of Strain

Strain experienced by a body can be of two types depending on stress application as follows:

Tensile Strain

The deformation or elongation of a solid body due to applying a tensile force or stress is known as Tensile strain. In other words, tensile strain is produced when a body increases in length as applied forces try to stretch it.

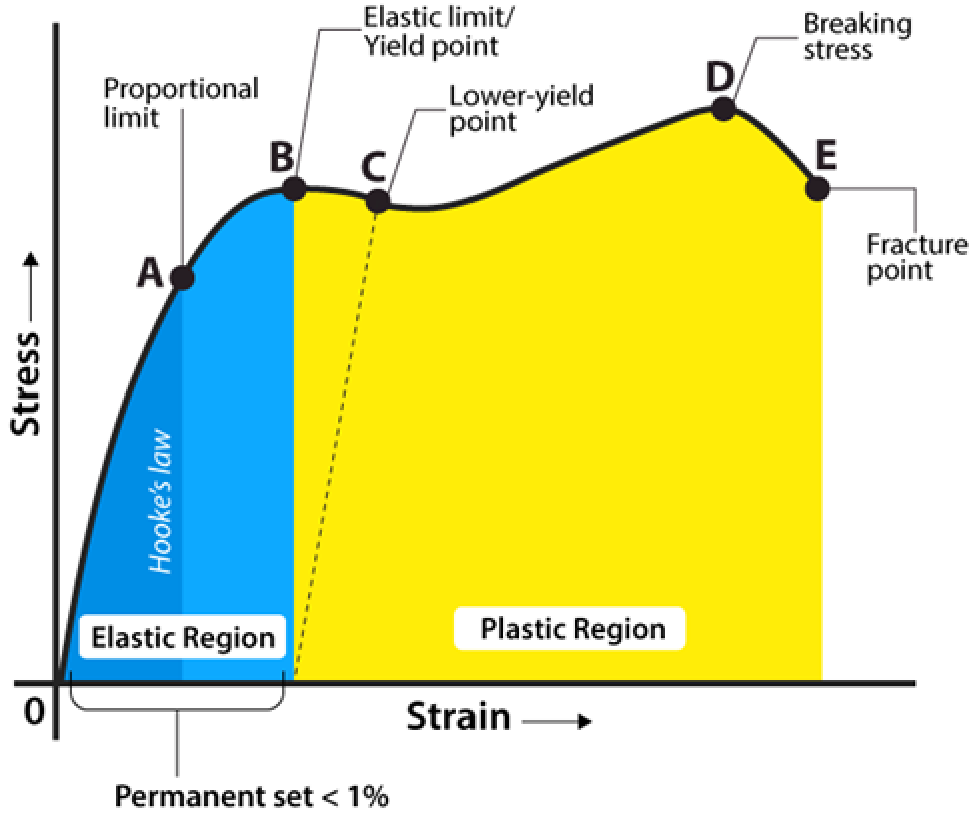
Compressive Strain

Compressive strain is the deformation in a solid due to the application of compressive stress. In other words, compressive strain is produced when a body decreases in length when equal and opposite forces try to compress it.

Stress-Strain Curve

When we study solids and their mechanical properties, information regarding their elastic properties is most important. We can learn about the elastic properties of materials by studying the stress-strain relationships, under different loads, in these materials.

The material's stress-strain curve gives its stress-strain relationship. In a stress-strain curve, the stress and its corresponding strain values are plotted. An example of a stress-strain curve is given below.



Explaining Stress-Strain Graph

The different regions in the stress-strain diagram are:

(i) Proportional Limit

It is the region in the stress-strain curve that obeys Hooke's Law. In this limit, the stress-strain ratio gives us a proportionality constant known as Young's modulus. The point OA in the graph represents the proportional limit.

(ii) Elastic Limit

It is the point in the graph up to which the material returns to its original position when the load acting on it is completely removed. Beyond this limit, the material doesn't return to its original position, and a plastic deformation starts to appear in it.

(iii) Yield Point

The yield point is defined as the point at which the material starts to deform plastically. After the yield point is passed, permanent plastic deformation occurs. There are two yield points (i) upper yield point (ii) lower yield point.

(iv) Ultimate Stress Point

It is a point that represents the maximum stress that a material can endure before failure. Beyond this point, failure occurs.

(v) Fracture or Breaking Point

It is the point in the stress-strain curve at which the failure of the material takes place.

Hooke's Law

In the 19th-century, while studying springs and elasticity, English scientist Robert Hooke noticed that many materials exhibited a similar property when the stress-strain relationship was studied. There was a linear region where the force required to stretch the material was proportional to the extension of the material, known as Hooke's Law.

Hooke's Law states that the strain of the material is proportional to the applied stress within the elastic limit of that material.

Mathematically, Hooke's law is commonly expressed as:

$F = -k.x$

Where F is the force, x is the extension in length, and k is the constant of proportionality known as the spring constant in N/m.

Elastic Moduli of Materials

The following table lists Young’s modulus, shear modulus and bulk modulus for common materials.

Material	**Young’s modulus (E) in GPa**	**Shear modulus (G) in GPa**	**Bulk modulus (K) in GPa**
Glass	55	23	37
Steel	200	84	160
Iron	91	70	100
Lead	16	5.6	7.7
Aluminium	70	24	70

POLYMER COMPOSITES

The polymer composites have another name called Polymer Matrix Composites (PMC).

• A polymer matrix composite (PMC) is a composite material composed of a variety of short or continuous fibers bound together by an organic polymer matrix. PMCs are designed to transfer loads between fibers of a matrix.

• Another Definition: A composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components

PROPERTIES OF POLYMER COMPOSITES

- Lightweight
- High stiffness
- High strength along the direction of their reinforcements
- Good abrasion resistance
- Good corrosion resistance.

STRUCTURE OF POLYMER COMPOSITE

- A polymer composite is a multi-phase material in which reinforcing fillers are integrated with a polymer matrix, resulting in synergistic mechanical properties that cannot be achieved from either component alone
- Fiber
- Matrix

FIBER

- The fiber is most often glass, but sometimes Kevlar, carbon fiber, or polyethylene.
- The fiber is embedded in the matrix in order to make the matrix stronger. Fiber-reinforced composites have two things going for them. They are strong and light. They're often stronger than steel, but weigh much less. This means that composites can be used to make automobiles lighter, and thus much more fuel efficient.

MATRIX

- The matrix is usually a thermoset like an epoxy resin, polydicyclopentadiene, or a polyimide. The properties of the matrix determines the resistance of the PMC to processes that includes impact damage, water absorption, chemical attack, and high-temperature creep.

TYPES OF COMPOSITES

Metal Matrix Composite

- To make metal matrix composites, engineers bind carbon fibers with aluminum. They can also use iron metal, but it's denser than aluminum. This makes iron composites less favorable for the aerospace industry
- Besides, aluminum has added advantages. It has a lower density which doesn't affect its tensile nature. It is also resistant to corrosive agents.

Polymer Matrix Composite

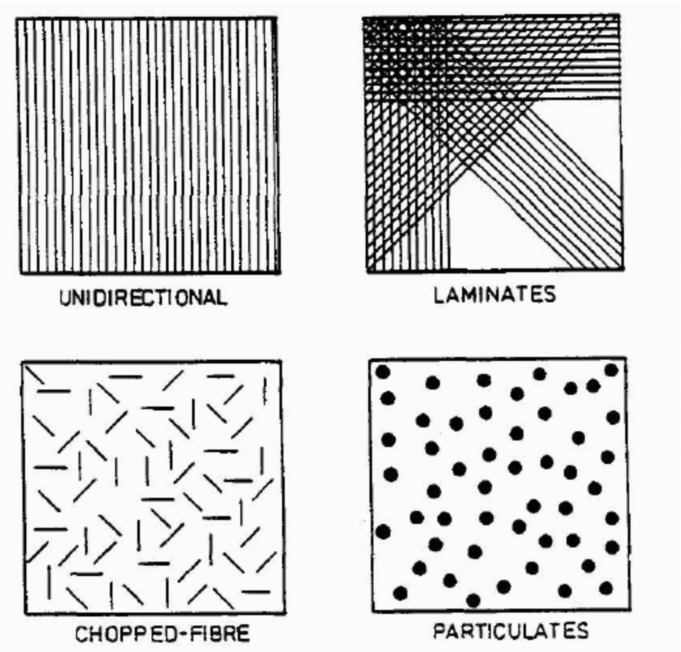
- Industrials bind carbon fibers with polymers to form a polymer matrix composite mold. These two components have high resistance to corrosion and abrasion.
- Besides, their lightweight is an added advantage in the aerospace industry. We use them to transmit loads between the carbon fibers.

Particulate Reinforced Composites

- They are carbon fiber composites that have a ceramic matrix. Composites with gravel in cement paste are particulate-reinforced composites.
- These composite molds have scattered components. For instance, metallic pieces of gravel are dispersed in the mold.

Fibrous Composites

- Fibrous composites are popular for their regenerative strength. Instead of using a strand of fiber, it pays off to merge them in a matrix to form a fibrous composite.
- In this case, if a strand breaks, the load is transmitted to the next fibers. This quality makes them desirable in industrial setups.
- Besides, they have a low density which translates to less bulkiness. They also exhibit high tensile properties. Fiber-reinforced matrices also have high thermal-resistant qualities.



Particle Reinforcing Composites

- Particle reinforcing in composites is a less effective means of strengthening than fibre reinforcement. Particulate reinforced composites achieve gains in stiffness primarily, but also can achieve increases in strength and toughness. In all cases the improvements are less than would be achieved in a fibre reinforced composite.
- Particulate reinforced composites find applications where high levels of wear resistance are required such as road surfaces. The hardness of cement is increased significantly by adding gravel as a reinforcing filler.
- The principal advantage of particle reinforced composites is their low cost and ease of production and forming.

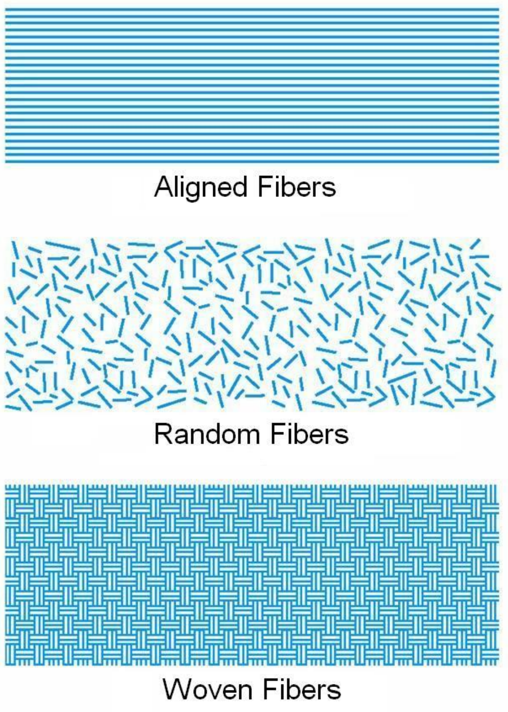
Fiber-Reinforced Composites

Fiber-reinforced composites are composed of axial particulates embedded in a matrix material. The objective of fiber-reinforced composites it to obtain a material with high specific strength and high specific modulus. (i.e. high strength and high elastic modulus for its weight.) The strength is obtained by having the applied load transmitted from the matrix to the fibers. Hence, interfacial bonding is important. Classic examples of fiber-reinforced composites include fiberglass and wood.

Fiber Geometry

Some common geometries for fiber-reinforced composites:

- **Aligned**
  The properties of aligned fiber-reinforced composite materials are highly anisotropic. The longitudinal tensile strength will be high whereas the transverse tensile strength can be much less than even the matrix tensile strength. It will depend on the properties of the fibers and the matrix, the interfacial bond between them, and the presence of voids.



- There are 2 different geometries for aligned fibers:
    1. **Continuous & Aligned**

       The fibers are longer than a critical length which is the minimum length necessary such that the entire load is transmitted from the matrix to the fibers. If they are shorter than this critical length, only some of the load is transmitted. Fiber lengths greater that 15 times the critical length are considered optimal. Aligned and continuous fibers give the most effective strengthening for fiber composites.

    2. **Discontinuous & Aligned**

       The fibers are shorter than the critical length. Hence discontinuous fibers are less effective in strengthening the material, however, their composite modulus and tensile strengths can approach 50-90% of their continuous and aligned counterparts. And they are cheaper, faster and easier to fabricate into complicated shapes.

- **Random**
  This is also called discrete, (or chopped) fibers. The strength will not be as high as with aligned fibers, however, the advantage is that the material will be istropic and cheaper.

- **Woven**
  The fibers are woven into a fabric which is layered with the matrix material to make a laminated structure**.**

Fiber Cross Section

Of course, the fiber cross sectional shape and size is also important.

Here are some examples of the cross-sectional areas and shapes for a wide variety of reinforing fibers:

Some general catagories of fibers based on cross section:

Whiskers

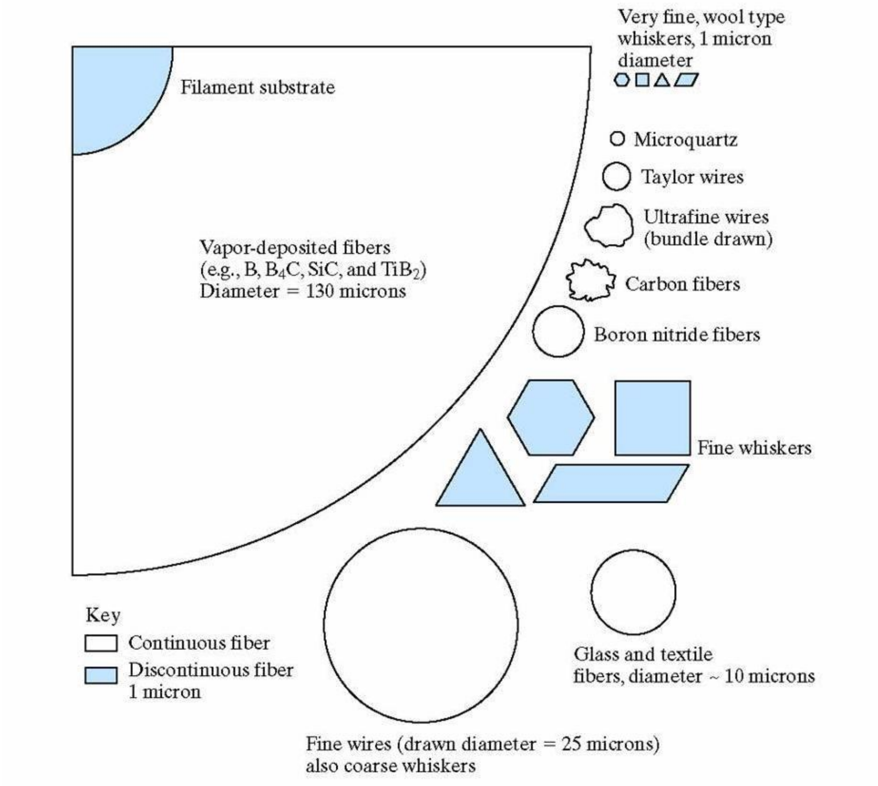
- very small diameter (~1 micron) single crystals
- strong because they are virtually flaw free
- expensive
- difficult to put in a matrix
- examples include graphite (C), SiN, Al_2O_3, SiC

Fibers

- small diameters (~10 microns)
- can be polycrystalline or amorphous

Wires

- large diameters (~25 microns)
- made from metals such as steel, Mo, W



Fiber Materials for Fiberglass

And of course, the fiber material is important too.

A commonly used glass fiber composition for structural composites is E-glass, in which E stands for "electrical type". It is a lime-aluminum-borosilicate glass with zero or low sodium and potassium levels. It is popular because it has chemical durability.

A more advanced and expensive fiber is S-glass, a magnesia-alumina-silicate glass that is used for high-strength applications.

The composition of these and other common glass fiber materials are listed here:

Designation	Characteristic	Composition								
		SiO_2	Al_2O_3 + Fe_2O_3	CaO	MgO	Na_2O	K_2O	B_2O_3	TiO_2	ZrO_2
A-glass	common soda-lime silica	72	<1	10		14				
AR-glass	alkali resistnat (for concrete reinforcement)	61	<1	5	<1	14	3		7	10

C-glass	chemical corrosion resistant	65	4	13	3	8	2	5		
E-glass	electrical composition	54	15	17	5	<1	<1	8		
S-glass	high strength and modulus	65	25		10					

Matrix Materials for Fiberglass

Some common thermosetting polymeric matrix materials for fiberglass include epoxies, polyesters, phenolics and silicones.

Some of the common thermoplastic polymeric matrix materials for fiberglass include nylon 66, polycarbonate and polystyrene.

Advanced Fiber-Reinforced Composite Systems Other Than Fiberglass

Advanced composites include those systems in which reinforcing fibers have moduli higher than that of E-glass.

Here is a list of a variety of advanced composite systems.

Class	**Fiber**	**Matrix**
Polymer matrix	Para-aramid (Kevlar)[1]	Epoxy
	Para-aramid (Kevlar)	Polyester
	C (graphite)[2]	Epoxy
	C (graphite)	Polyester
	C (graphite)	polyetheretherketone (PEEK)
	C (graphite)	polyphenylene sulfide (PPS)
Metal matrix	B	Al
	C	Al
	Al_2O_3	Al
	Al_2O_3	Mg
	SiC	Al
	SiC	Ti (alloys)
Ceramic matrix	Nb	$MoSi_2$
	C	C
	C	SiC

	SiC	Al_2O_3
	SiC	SiC
	SiC	Si_3N_4
	SiC	Li-Al-silicate (glass-ceramic)

Kevlar

Kevlar is a polyamide, a type of synthetic polymer, in which the amide groups are separated by para phenylene groups, meaning that the amide groups are attached to each other on opposite sides of the phenyl group (i.e. carbons 1 and 4).

Kevlar is a type of aramid fiber. It is woven into textile materials and is extremely strong and lightweight, with resistance toward corrosion and heat. It is used in vast applications such as aerospace engineering (such as the body of the aircraft), body armor, bulletproof vests, car brakes, and boats.

Kevlar is a Du Pont trade name for poly p-phenyleneterephthalamide (PPD-T). It is an aramid, i.e. an aromatic (benzene ring type) polyamide polymer fiber with a very rigid molecular structure. It is used for high-performance composite applications where light weight, high strength and stiffness, damage resistance, and resistance to fatigue, creep, and stress rupture are important.

Kevlar 29 is a low-density high-strength aramid fiber designed for such applications as ballistic protection, ropes, and cables.

Kevlar 49 is characterized by a low density and high strength and modulus. It is used as reinforcement for plastics in composites for aerospace, marine, automotive, and other industrial applications.

Carbon fibers are made of graphitic and noncrystalline regions. It has the highest specific strength and specific modulus of all fiber materials. It retains tensile strength at high temperatures and is not affected by moisture, solvents, acids or bases at room temperatures. However, at high temperatures it is subject to oxidation.

Polyamide

A polyamide is a polymer that contains recurring amide groups (R—CO—NH—R′) as integral parts of the main polymer chain. Synthetic polyamides are produced by a condensaton reaction between monomers, in which the linkage of the molecules occurs through the formation of the amide groups. They may be produced by the interaction of a diamine (a compound containing two amino [NH2] groups)

Some important types of Fiber reinforced composites are

1. Glass fiber reinforced polymer composite

Fiber glass reinforced composites can be produced by properly incorporating the continuous or discontinuous glass fibers with in a plastic matrix. Polyesters are most commonly used matrix material. most recently nylons are

It is the most popular fiber reinforcement material due to Easily available, easily fabricated, highly economical and which provides stiffness, strength, impact resistance and resistance to corrosion and chemicals.
limitations: they can fuse or melt at high temperatures
Applications: Automobile parts, storage tanks, floorings and plastic pipes etc

2. Carbon fiber reinforced polymer composites

Carbon fibers like (graphite, Graphenes or carbon nano tubes) dispersed in the polymer matrix.
They provide excellent resistance to corrosion, lighter density, retention of desired properties even at elevated temperatures.
limitations: High cost
Applications: Structural components of air craft like wings and bodies, sport equipment, fishing rods etc.

3. Alumina oxide/ carbon fiber reinforced metal composites:

Fibers of alumina or carbon dispersed in metal or metal alloy matrix which possess improved specific strength. stiffness, wear resistance**,** creep resistance and resistance to thermal distortion etc
Ex:1. Fiber Al_2O_3 / carbon in a matrix metal alloy find applications in the preparation of components of automobile engines.
2 . Fiber Al_2O_3 /W_2O_3 in a matrix of Ni or Co based alloy find applications in the preparation of components of turbine engines.

Particulate Reinforced Composite

The solid particulates of metal oxides or carbides of varying size and form dispersed in metal, metal alloy, ceramic or polymer liquid matrix.
Particle reinforced composites are further classified into the following two types
1) Large -particulate composites 2) Dispersion strengthened composites

1) Large -particulate composites

Large particle composite used with all the three major types of materials, namely metals, polymer and ceramics.
Example: 1. concrete which is composed of cement matrix and particulates of sand and gravel.
2. Automobile tire in which Carbon black particles dispersed in rubber matrix
3. Ceramic - metal composites which are known as cermets. The most commonly used cermets are
Ex: 1. Al_2O_3 dispersed in Cr matrix possess good strength and good thermal shock resistance.
2. Tungsten carbide(WC) dispersed in Co matrix finds application in preparation of Valves, Spray nozzles and machine parts which require high surface hardness.

2) Dispersion strengthened composites

Very small particles of the range 10-100nm size are used in this which improve strength and hardness.

Metals and Metal alloys may be hardened and strengthened by the uniform dispersion of high volume percent of very hard and inert materials, the strength is achieved due to interactions between particle and dislocations within the matrix. example Thoria-dispersed Nickel Precipitation hardening: The strength and hardness of some metal alloys may be improved by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix with the help of appropriate heat treatment. This process called Precipitate hardening or Age hardening.

Structural composites

Structural composites are prepared by Compressing the stacking of layers of fiber reinforce composites

These are of two types 1. Laminated composites 2. Sandwich composites.

1. Laminated Composites.

A Laminar composite consists of two-dimensional sheets or panels that have preferred high strength direction, successive oriented fiber reinforced layers of these are stacked and then cemented together in such a way that the orientation of the high strength varies with each successive layer

Example: Plywood, Copper bottom steel articles

2, Sandwich panels

These usually consist of two strong outer sheets called faces, separated by a layer of less dense material called core which is of lower strength and lower stiffness.

face materials: ply wood, titanium, steel, and aluminum alloy

Core materials: Synthetic rubber, Foamed polymer

Metal Matrix Composites

Metal Matrix Composites (MMCs) are materials produced by adding reinforcement in the form of particles (ceramic or metal), fibers, whiskers or even a sheet metal to a metal or alloy matrix

MMCs are made by dispersing a reinforcing material into a metal matrix. The reinforcement surface can be coated to prevent a chemical reaction with the matrix. For example, carbon fibers are commonly used in aluminium matrix to synthesize composites showing low density and high strength. However, carbon reacts with aluminium to generate a brittle and water-soluble compound Al_4C_3 on the surface of the fiber. To prevent this reaction, the carbon fibers are coated with nickel or titanium boride.

Matrix

The matrix is the monolithic material into which the reinforcement is embedded, and is completely continuous. This means that there is a path through the matrix to any point in the material, unlike two materials sandwiched together. In structural applications, the matrix is usually a lighter metal such as aluminum, magnesium, or titanium, and provides a complete support for the reinforcement. In high-temperature applications, cobalt and cobalt–nickel alloy matrices are common.

Reinforcement

The reinforcement material is embedded into a matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties such as wear resistance, friction coefficient, or thermal conductivity. The reinforcement can be either continuous or discontinuous. Discontinuous MMCs can be isotropic and can be worked with standard metalworking techniques, such as extrusion, forging, or rolling. In addition, they may be machined using conventional techniques, but commonly would need the use of polycrystalline diamond tooling (PCD).

Continuous reinforcement uses monofilament wires or fibers such as carbon fiber or silicon carbide. Because the fibers are embedded into the matrix in a certain direction, the result is an anisotropic structure in which the alignment of the material affects its strength. One of the first MMCs used boron filament as reinforcement. Discontinuous reinforcement uses "whiskers", short fibers, or particles. The most common reinforcing materials in this category are alumina and silicon carbide.

Applications

- High performance tungsten carbide cutting tools are made from a tough cobalt matrix cementing the hard tungsten carbide particles; lower performance tools can use other metals such as bronze as the matrix.
- Some tank armors may be made from metal matrix composites, probably steel reinforced with boron nitride, which is a good reinforcement for steel because it is very stiff and it does not dissolve in molten steel.
- Some automotive disc brakes use MMCs. Early Lotus Elise models used aluminum MMC rotors, but they have less than optimal heat properties, and Lotus has since switched back to cast iron. Modern high-performance sport cars, such as those built by Porsche, use rotors made of carbon fiber within a silicon carbide matrix because of its high specific heat and thermal conductivity. 3M developed a preformed aluminum matrix insert for strengthening cast aluminum disc brake calipers, reducing weight by half compared to cast iron while retaining similar stiffness. 3M has also used alumina preforms for AMC pushrods.
- Ford offers a Metal Matrix Composite (MMC) driveshaft upgrade. The MMC driveshaft is made of an aluminum matrix reinforced with boron carbide, allowing the critical speed of the driveshaft to be raised by reducing inertia. The MMC driveshaft has become a common modification for racers, allowing the top speed to be increased far beyond the safe operating speeds of a standard aluminum driveshaft.
- Honda has used aluminum metal matrix composite cylinder liners in some of their engines, including the B21A1, H22A and H23A, F20C and F22C, and the C32B used in the NSX.
- Toyota has since used metal matrix composites in the Yamaha-designed 2ZZ-GE engine which is used in the later Lotus Lotus Elise S2 versions as well as Toyota car models, including the eponymous Toyota Matrix. Porsche also uses MMCs to reinforce the engine's cylinder sleeves in the Boxster and 911.
- The F-16 Fighting Falcon uses monofilament silicon carbide fibers in a titanium matrix for a structural component of the jet's landing gear.
- Specialized Bicycles has used aluminum MMC compounds for its top of the range bicycle frames for several years. Griffen Bicycles also made boron carbide-aluminum MMC bike frames, and Univega briefly did so as well.
- Some equipment in particle accelerators such as Radio Frequency Quadrupoles (RFQs) or electron targets use copper MMC compounds such as Glidcop to retain the material properties of copper at high temperatures and radiation levels.[11][12]
- Copper-silver alloy matrix containing 55% by volume diamond particles, known as Dymalloy, is used as a substrate for high-power, high-density multi-chip modules in electronics for its very high thermal conductivity. AlSiC is an aluminium-silicon carbide composite for similar applications.
- Aluminium-Graphite composites are used in power electronic modules because of their high thermal conductivity, the adjustable coefficient of thermal expansion and the low density.

MMCs are nearly always more expensive than the more conventional materials they are replacing. As a result, they are found where improved properties and performance can justify the added cost. Today these applications are found most often in aircraft components, space systems and high-end or "boutique" sports equipment. The scope of applications will certainly increase as manufacturing costs are reduced.

In comparison with conventional polymer matrix composites, MMCs are resistant to fire, can operate in wider range of temperatures, do not absorb moisture, have better electrical and thermal conductivity, are resistant to radiation damage, and do not display outgassing. On the other hand, MMCs tend to be more expensive, the fiber-reinforced materials may be difficult to fabricate, and the available experience in use is limited.

Ceramic matrix composites

Ceramic matrix composites (CMCs) are a special type of composite material in which both the reinforcement (refractory fibers) and matrix material are ceramics. In some cases, the same kind of ceramic is used for both parts of the structure, and additional secondary fibers may also be included.

Corrosion behaviour of CMCs are scarce except for oxidation at temperatures above 1000 °C. These properties are determined by the constituents, namely the fibers and matrix. Ceramic materials, in general, are very stable to corrosion. The broad spectrum of manufacturing techniques with different sintering additives, mixtures, glass phases, and porosities are crucial for the results of corrosion tests. Less impurities and exact stoichiometry lead to less corrosion. Amorphous structures and non-ceramic chemicals frequently used as sintering aids are starting points of corrosive attack.

Alumina

Pure alumina shows excellent corrosion resistance against most chemicals. Amorphous glass and silica phases at the grain boundaries determine the speed of corrosion in concentrated acids and bases and result in creep at high temperatures. These characteristics limit the use of alumina. For molten metals, alumina is used only with gold and platinum.

Alumina fibers

These fibers demonstrate corrosion properties similar to alumina, but commercially available fibers are not very pure and therefore less resistant. Because of creep at temperatures above 1000 °C, there are only a few applications for oxide CMCs.

Carbon

The most significant corrosion of carbon occurs in the presence of oxygen above about 500 °C (932 °F). It burns to form carbon dioxide and/or carbon monoxide. It also oxidizes in strong oxidizing agents like concentrated nitric acid. In molten metals, it dissolves and forms metal carbides. Carbon fibers do not differ from carbon in their corrosion behavior.

Silicon carbide

Pure silicon carbide is one of the most corrosion-resistant materials. Only strong bases, oxygen above about 800 °C (1,470 °F), and molten metals react with it to form carbides and silicides. The reaction with oxygen forms SiO_2 and CO_2, whereby a surface layer of SiO_2 slows down subsequent oxidation (*passive oxidation*). Temperatures above about 1,600 °C (2,910 °F) and a low partial pressure of oxygen result in so-called *active oxidation*, in which CO, CO_2 and gaseous SiO are formed causing rapid loss of SiC. If the SiC matrix is produced other than by CVI, corrosion-resistance is not as good. This is a consequence of porosity in the amorphous LPI, and residual silicon in the LSI-matrix.

Silicon carbide fibers

Silicon carbide fibers are produced via pyrolysis of organic polymers, and therefore their corrosion properties are similar to those of the silicon carbide found in LPI-matrices. These fibers are thus more sensitive to bases and oxidizing media than pure silicon carbide.

Applications

CMC materials overcome the major disadvantages of conventional technical ceramics, namely brittle failure and low fracture toughness, and limited thermal shock resistance. Therefore, their applications are in fields requiring reliability at high-temperatures (beyond the capability of metals) and resistance to corrosion and wear.

- Heat shield systems for space vehicles, which are needed during the re-entry phase, where high temperatures, thermal shock conditions and heavy vibration loads take place.
- Components for high-temperature gas turbines such as combustion chambers, stator vanes, exhaust mixers and turbine blades.
- Components for burners, flame holders, and hot gas ducts, where the use of oxide CMCs has found its way.
- Brake disks and brake system components, which experience extreme thermal shock (greater than throwing a glowing part of any material into water).
- Components for slide bearings under heavy loads requiring high corrosion and wear resistance.

In addition to the foregoing, CMCs can be used in applications which employ conventional ceramics or in which metal components have limited lifetimes due to corrosion or high temperatures.