

Module 5

Mechanical Properties of Solids and Composite Materials

What is 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 $(\sigma) = F/A$
- 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

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.

What is 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.
- Strain $\epsilon = \delta l / L$
- 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

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.

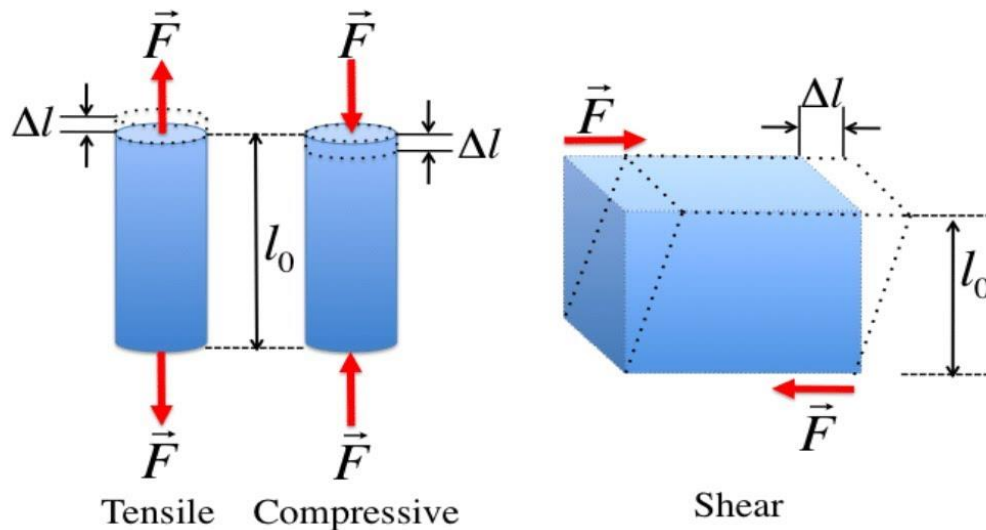
Compressive Strain

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.

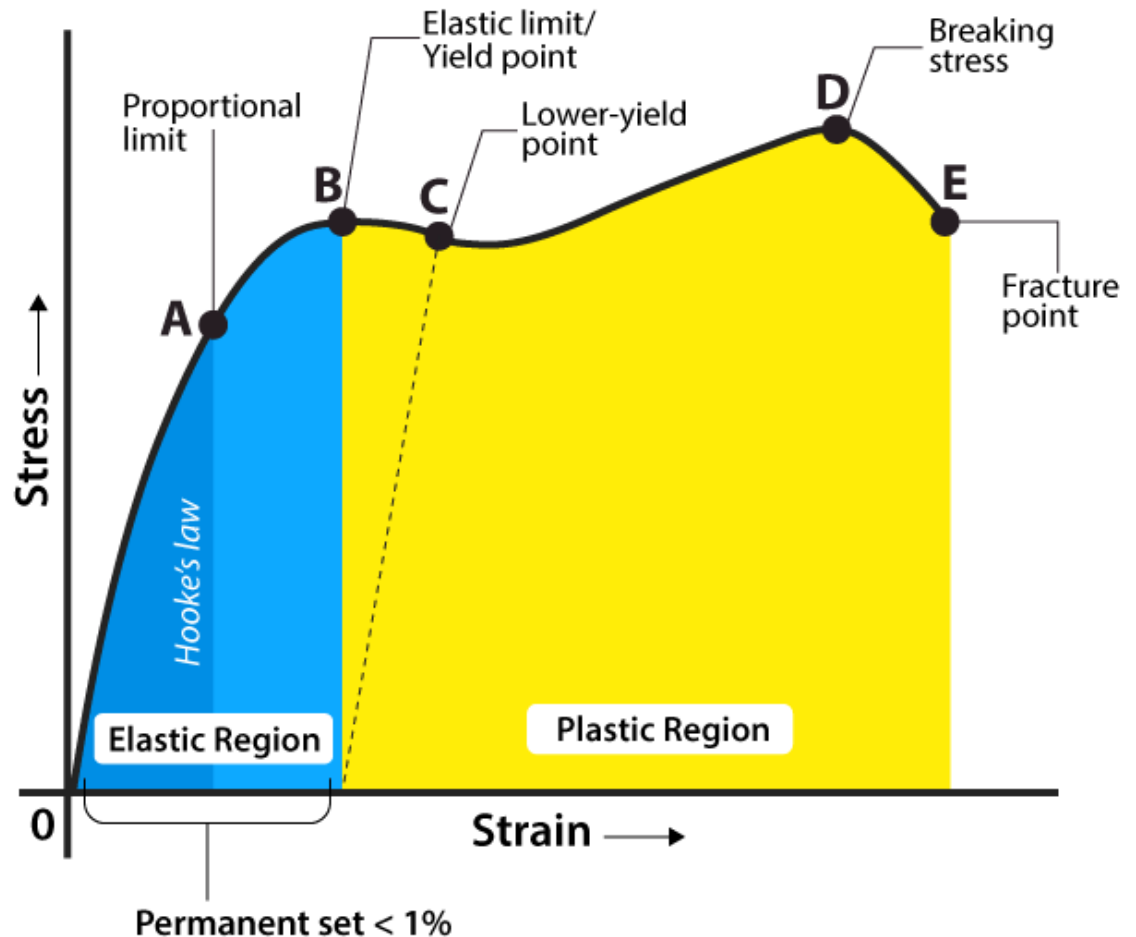
Difference between stress and strain

Stress	Strain
Stress is the restoring or deforming force per unit area.	The strain is the change in shape per original shape.
Its formula is $\sigma = F/A$	Its formula is $\epsilon = \Delta L/L$
Its unit is N/m^2	It has no unit

Stress & Strain



Stress-strain relationship, plc⁴



- 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.

Explaining Stress-Strain Graph

The different regions in the stress-strain diagram are:

(i) Proportional Limit

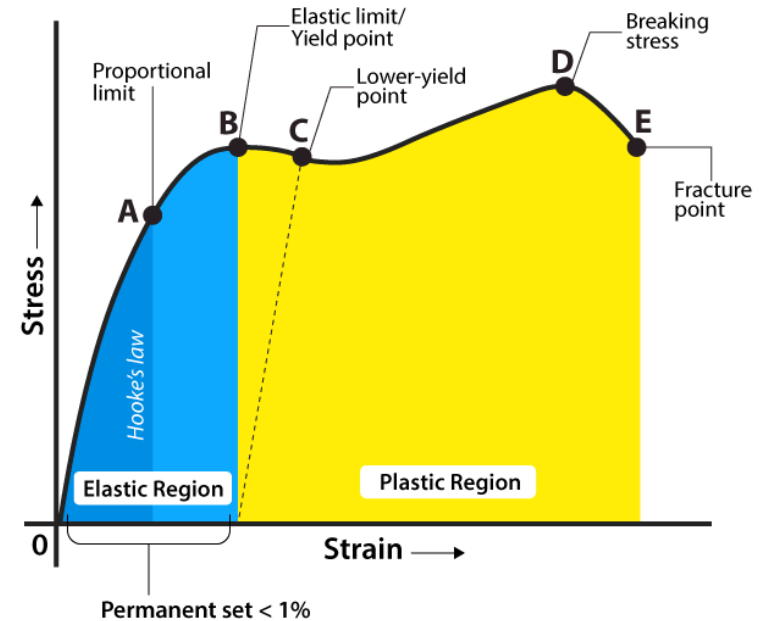
It is the region in the stress-strain curve that obeys **Hooke's Law**. In this limit, the stress-strain ratio gives us a proportionality constant known as Young's modulus. The point **OA** in the graph represents the proportional limit.

(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

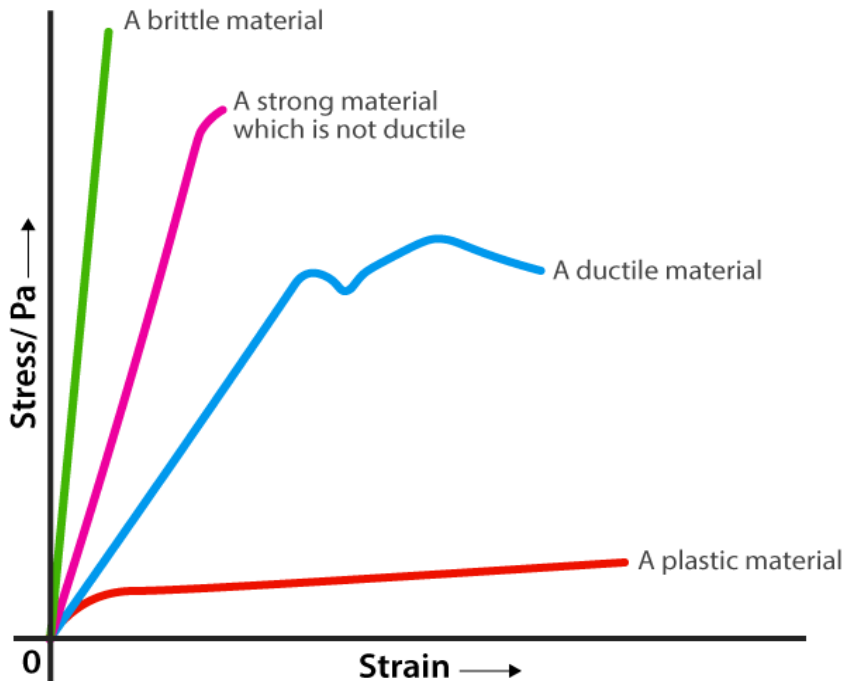
It is the point in the stress-strain curve at which the **failure** of the material takes place.

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:
$$\mathbf{F = -k.x}$$
- 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.

Yield Strength Graph

- Each and every material possess a characteristic stress-strain curve that allows us to determine what application they are best suited for.
- Each material curve possesses different transition points, i.e. from elasticity to plasticity and finally to breakage.
- The point at which the material transforms from elastic to plastic is known as the **yield point**.



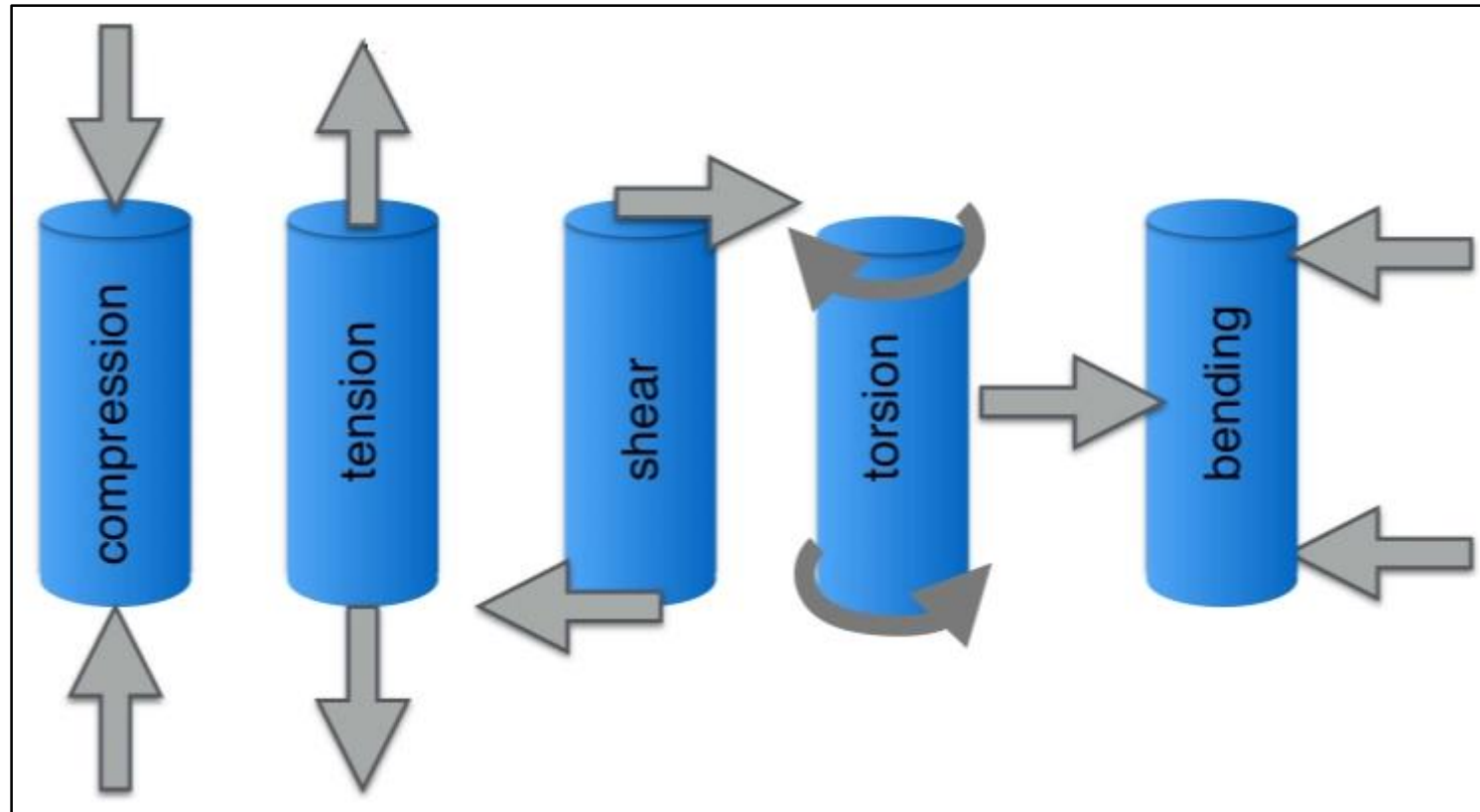
- The magnitude of the stress at which the transition from elastic to plastic occurs is known as the **yield strength**.
- **Yield strength is a constant that represents the maximum limit of elastic behaviour.**
- Ductile materials like metals have higher yield strength values than plastics.

The yield strength of steel and various metals

Material	Yield Strength (megapascal MPa)
Steel	448
Stainless Steel	520
Copper	70
Brass	200+
Aluminium Alloy	414
Cast Iron	130

- The yield strength of materials can be increased by adding impurities to the material.
- The intensified density causes the material to grow more tolerant to deformations, as the impurities fill the voids left after crystalline dislocations.

Types of stress and strain



	<i>a</i>	<i>b</i>	<i>c</i>
Deformation			
Strain	$\varepsilon = -\frac{\Delta L}{L_0}$	$\gamma = \frac{\Delta x}{L_0} = \tan \alpha$	$\varepsilon = -\frac{\Delta V}{V_0}$
Stress	$\sigma = -\frac{F}{A}$	$\tau = \frac{F}{A}$	$-p$ (hydrostatic pressure)
Elastic modulus	E (Young's modulus)	G (shear modulus)	K (bulk modulus)
Elastic stress-strain relationship	$\sigma = E\varepsilon$	$\tau = G\gamma$	$p = K\varepsilon$

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

Mechanical Properties Of Solids

Stress And Strain

$$\text{Stress} = \frac{\text{Restoring force}}{\text{Area}} = \frac{F}{A}$$

$$\text{Strain} = \frac{\text{Change in configuration}}{\text{Original configuration}}$$

Young's Modulus

$$Y = \frac{\text{Normal Stress}}{\text{Longitudinal Strain}}$$

Bulk Modulus

$$B = \frac{\text{Normal Stress}}{\text{Volumetric Strain}}$$

$$\text{Compressibility, } K = \frac{1}{B}$$

Modulus Of Rigidity

$$G = \frac{\text{Shearing Stress}}{\text{Shearing Strain}}$$

Poisson's Ratio

$$\sigma = \frac{\text{Shearing Stress}}{\text{Longitudinal Strain}}$$

Relation Between Y, B, G and σ

$$\bullet Y = 3B(1 - 2\sigma)$$

$$\bullet Y = 2G(1 + \sigma)$$

$$\bullet \sigma = \frac{3B - 2G}{2G + 3B}$$

$$\bullet \frac{9}{Y} = \frac{1}{B} + \frac{3}{G}$$

Hooke's Law

Stress \propto Strain
or Stress = E x Strain
(E = modulus of elasticity)

Elasticity And Plasticity

Elasticity: Ability of a body to regain its original shape, on removing deforming force.

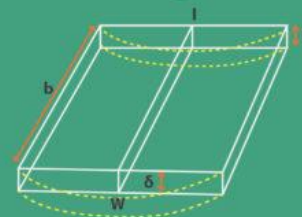
Plasticity: The inability of a body to regain its original size and shape on the removal of the deforming force.

Application Of Elasticity

Designing beams for bridges:

The depression in rectangular beam,

$$\delta = \frac{WL^3}{4YBd^3}$$



Elastic Potential Energy

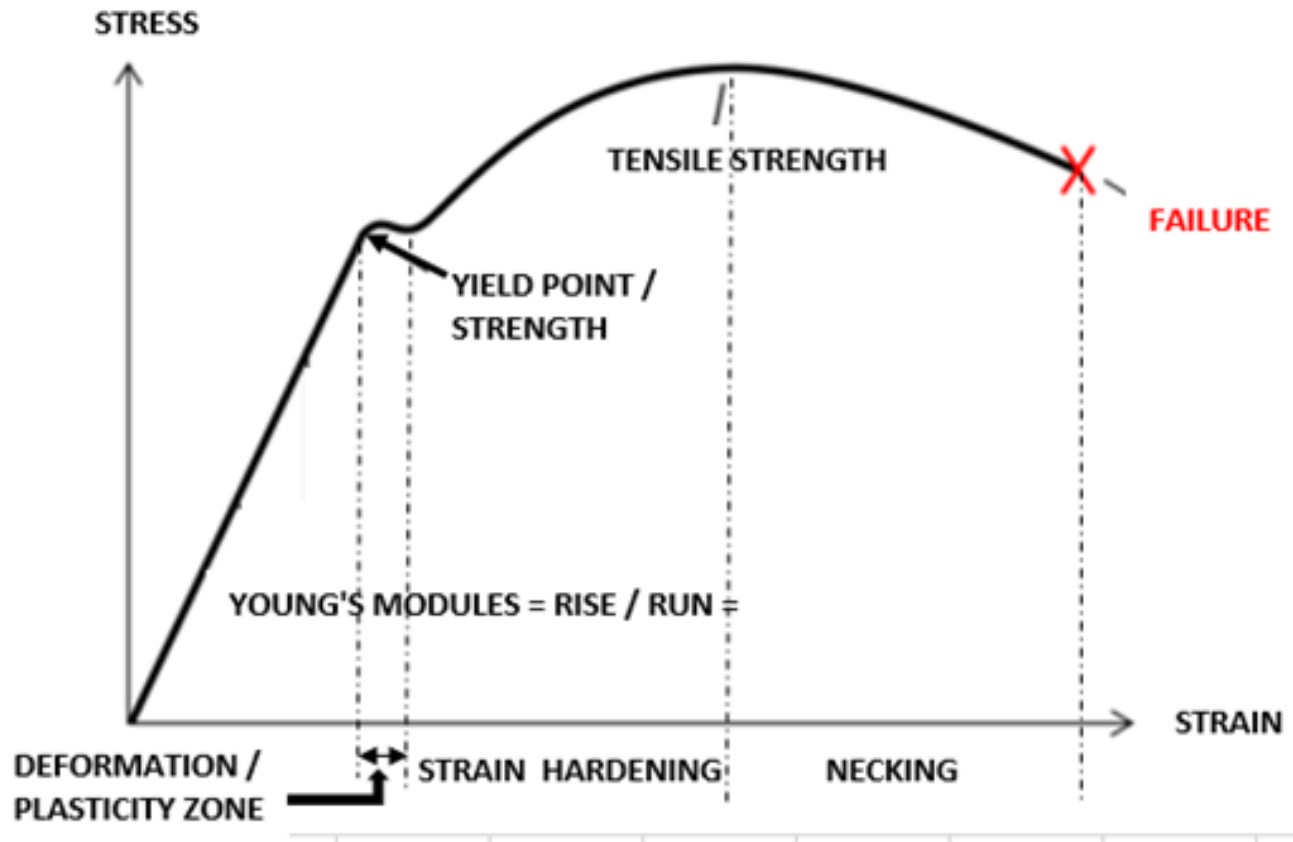
$$U = \frac{1}{2} F \times \Delta L$$
$$= \frac{1}{2} \text{ Stress} \times \text{Strain} \times \text{Volume}$$

P.E. stored per unit volume of stretched wire,

$$U = \frac{1}{2} \times \text{Stress} \times \text{Strain}$$
$$= \frac{1}{2} \times Y \times (\text{Strain})^2$$

Tensile strength:

- Tensile strength is the **maximum load** that a material can support without fracture when being stretched, divided by the original cross-sectional area of the material.
- Tensile strengths have dimensions of **force per unit area**.
- It **measures the strength** of the materials.



Mechanical Properties

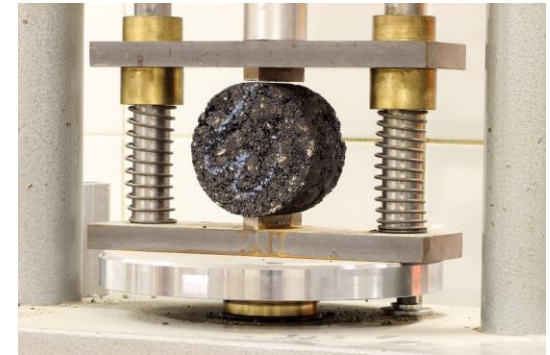
- Elasticity
 - non permanent deformation
- Plasticity - permanent deformation
- Strength - ability to withstand load
- Ductility - ability to be drawn into wire
- Malleability - ability to deform under compression
- Hardness - resistance to abrasion, wear, scratch, cut
- Brittleness - fracture without warning
- Toughness - amt of energy absorbed before rupture
- Stiffness - to resist deformation Al v/s steel beam (sag)
- Resilience - resist impact/ shock, absorb energy upto elastic limits
- Fatigue - under alternating stresses
- Creep - slow & progressive deform.. at const stress & at high temp

Creep and Creep strength

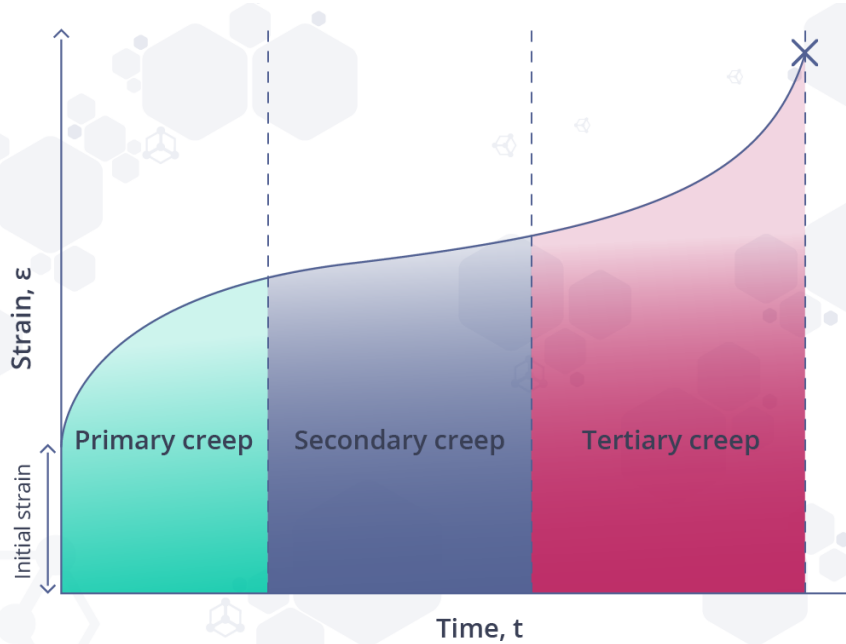
- A material **behaves differently** when subjected to an instantaneous high stress or a constant stress for a certain amount of time.
- When under continuous mechanical stress, a material tends to **move gradually** or deform in a permanent manner. This natural tendency is called **creep**.
- Several **factors** play in the initiation and progression of creep in a material, including **temperature, time, stress, and alloy composition**.
- The rate of deformation due to creep is called **creep rate**.
- It is very important to study creep in various **engineering applications**, especially those where high temperature and stress are involved. Discs and blades in turbines, spaceship bodies, and steam lines are a few examples of where creep effects may take place.
- **Creep strength**, also known as *creep limit*, is a measurement of a material's **resistance to creep**. It is also described as the stress at particular environmental conditions that produces a constant creep rate.
- In other words, **creep strength is the maximum stress endured by a material for a specific period of time without extreme deformation**.

What is creep?

- **Creep is defined as a time-dependent material deformation under continuous stress below the material's yield strength.**
- It is commonly observed to be quite impactful under elevated temperatures, especially with metals. Yet, it can still take place at room temperature, like with glass and lead, at a much slower rate.
- Other names for creep include *material creep* and *cold flow*.
- When materials are subjected to increasingly high-stress levels over a long period, creep can become severe. This especially applies to materials that are frequently exposed to high heat and can even permanently deform as temperatures reach the melting point.
- Without exceeding the material's [yield strength](#), creep can result in plastic strain, which is a unique aspect of this phenomenon, as plastic deformation generally happens when the yield strength is exceeded.



A typical creep curve showing the different stages of creep deformation.



1. Primary Creep

This initial stage is when elastic deformation **begins to occur**. Afterwards, plastic deformation takes over, as the creep slows down from its initial fast rate due to a process called strain hardening (or work hardening), where the material is strengthened by plastic deformation.

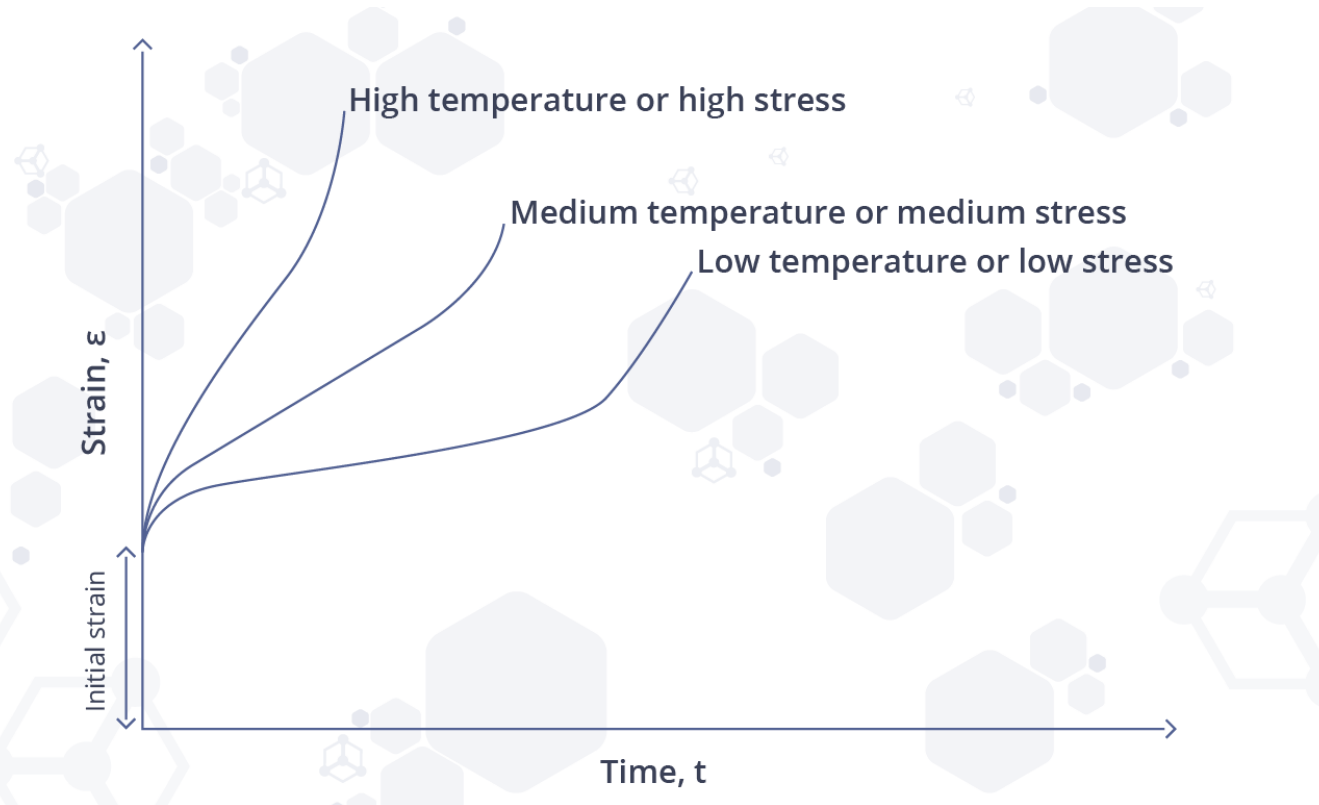
2. Secondary Creep

This stage is also called the **steady-state creep**. It takes place as the strain rate starts to settle into a constant state. Strain is comparatively slow, as microstructural damage has not been reached yet.

3. Tertiary Creep

This is the final stage in a material's creep deformation, where deterioration in the material's microstructure comes about. This continuous damage causes the strain to pick up speed and worsen until sufficient voids in the microstructure are generated, resulting in the **material failing in a fracture**.

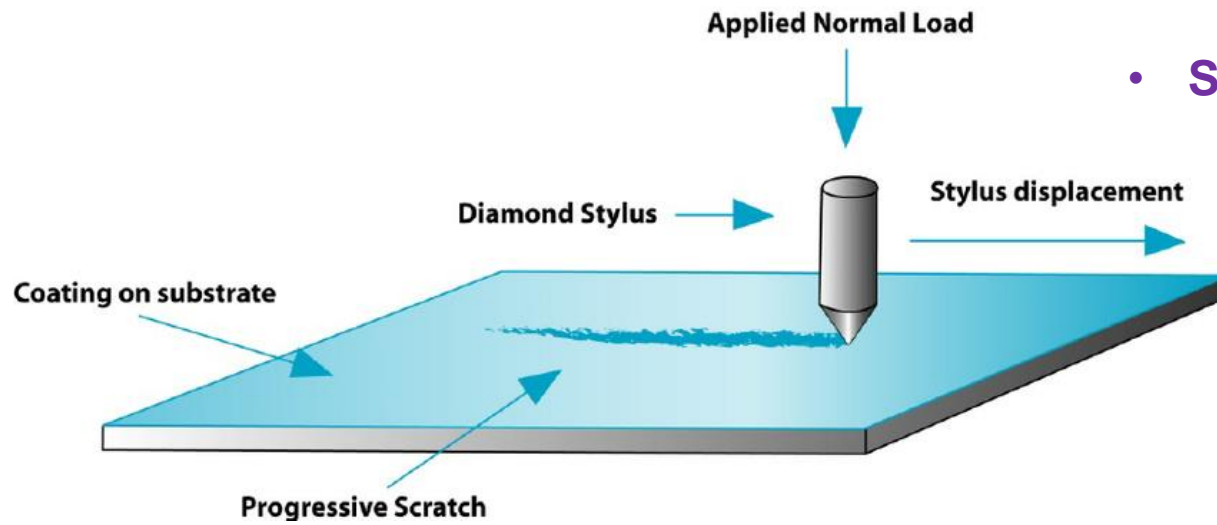
A graph showing the effects of temperature and stress on creep deformation.



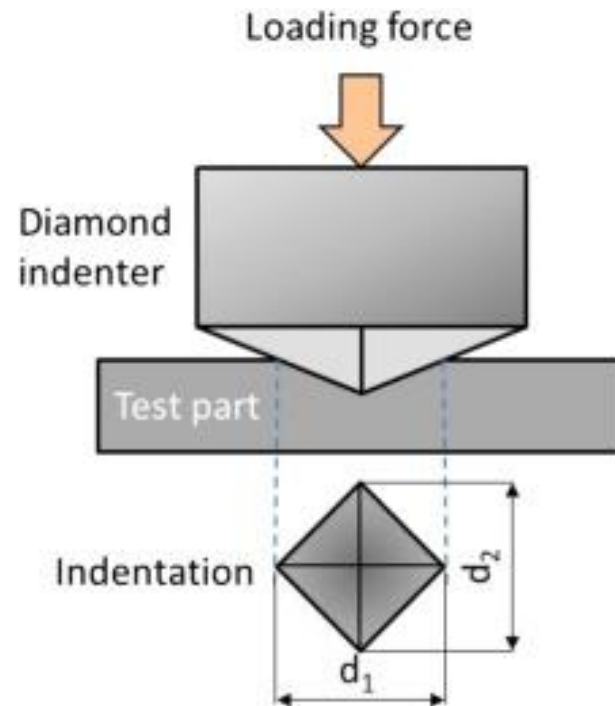
Hardness

- **Hardness is a metric that measures how resistant a material is to localised plastic deformation caused by mechanical indentation or abrasion.** It has important diagnostic properties in mineral identification or abrasion.
- Hardness describes the resistance that a material exhibits to permanent indentation or marking by scratches. Hardness is not a material property, rather a value ascribed to a material as a result of empirical testing. There are six main hardness tests that can be carried out: Vickers, Rockwell, Brinell, Mohs, Shore and Knoop. Which one to apply depends on the type of material to be tested and the equipment available. Most hardness tests involve using machinery that indents the material over a certain time period, applying a predetermined force or loading.
- There is a general bounding between hardness and chemical composition, thus most hydrous minerals like halides, carbonates, sulfates, and phosphates are relatively soft. Sulfides are relatively most soft (two exceptions being marcasite and pyrite) and silicates are hard and most anhydrous oxides. In general, the different materials have different hardness.
- For example, hard metals like titanium and beryllium are harder than soft metals like sodium and metallic tin, or wood and normal plastics.
- Powerful intermolecular bonds are commonly used to identify macroscopic hardness, but the structure of solid materials under stress is more complicated.
- In addition, there are different measurements of hardness such as scratch hardness, indentation hardness, and rebound hardness
- **Hardness is based on** plasticity, ductility, elastic stiffness, strain, strength, toughness, [viscosity](#), and viscoelasticity. For example, polymers and elastomers, it is defined as the resistance to elastic distortion of the surface.
- **Scratch Hardness**
- Scratch hardness is a measurement of a sample's resistance to fracture or permanent plastic deformation caused by pressure from a sharp edge. An object made by a tougher material will scratch an object made by a softer material, according to the theory. Scratch hardness refers to the force used to break through the film to the substrate when examining coatings. Sclerometer is a tool that is used for the measurement of scratch hardness.
- **Indentation Hardness**
- The resistance of a sample to material deformation caused by a steady compression load from a sharp object is measured by indentation hardness. Indentation hardness test is primarily used in engineering fields and metallurgy fields. Indentation tests are based on the principle of calculating the essential dimensions of an indentation created by special dimensions and loaded indenter.

- **Scratch Hardness**



- **Indentation Hardness**



Fatigue

- Materials have been known to fail in service under **repetitive stresses** that are much lower than their tensile strength. It's estimated that about 90% of mechanical failures of materials in service are caused by or at least contributed to by fatigue.
- Therefore, fatigue is an **important parameter to consider for moving mechanical components** that are expected to last for long periods.

What is fatigue strength?

- **Mechanical fatigue:** from fluctuating stresses and strains
- **Creep fatigue:** as a result of cyclic stresses at elevated temperatures
- **Thermal fatigue:** from repeated changes in temperature
- **Thermo-mechanical fatigue:** a combination of thermal and mechanical fatigue
- **Fretting fatigue:** fatigue due to frictional wear
- **Corrosion fatigue:** resulting from cyclic stresses under corrosive conditions
- Fatigue strength, however, generally refers to mechanical fatigue, and it is defined as **the stress level below which there would be no fatigue failure** even if there were to be a certain very high number of stress cycles applied to a material. This mechanical stress can be either axial stress, torsional stress or flexural stress. Fatigue strength is often used interchangeably with *fatigue limit* or *endurance limit*, but they are not strictly the same thing.
- Fatigue limit is a stress level below which there would be no fatigue failure no matter the number of load cycles the material is subjected to. But since it is impossible to test a material for an infinite number of cycles, the fatigue limit is an assumption deduced from testing results. It should be noted that some materials, such as aluminium and copper, do not have an endurance limit because they will always eventually fail from fatigue when subjected to a certain number of cyclic loading regardless of how small the load is. Therefore, the fatigue strengths of such materials are usually calculated as the stress levels they can endure without failing at a large total number of cycles, usually 5×10^8 cycles
- A material that is operating under cyclic loads below its fatigue strength will be expected never to fail as a result of fatigue alone for a certain number of specified loading cycles.

Calculation of Young's modulus simple exercises

1. A wire with a radius of 5mm is hung freely from the ceiling. A load of 5N is applied to its free end. Find the elongation in the wire if its volume is $7.85 \times 10^{-5} \text{m}^3$ & young's modulus is 10^{11}N/m^2 .
- a) $6.21 \times 10^{-7} \text{m}$
 - b) $7.00 \times 10^{-7} \text{m}$
 - c) $6.36 \times 10^{-7} \text{m}$
 - d) $8.00 \times 10^{-9} \text{m}$

The initial length of wire is

$$\text{Vol} / \pi r^2 = 7.85 \times 10^{-5} / \pi \times 0.005^2 = 1 \text{m}.$$

Stress = Y*strain.

$$F/A = Y \cdot \Delta l / l.$$

$$\begin{aligned} \Delta l &= F/A \cdot l/Y = (5/\pi r^2) \cdot (1/10^{11}) \\ &= 6.37 \times 10^{-7} \text{m} \end{aligned}$$

1. A wire has a young's modulus of 10^5N/m^2 , length 1m & radius 3mm. Assuming a uniform cross sectional area, find the radius of wire after it is under a force of 1N from both ends.
- a) 2.58m
 - b) 2.30m
 - c) 3.54m
 - d) 2.24m

Explanation: Force = 1N. Initial area = $\pi r^2 = 2.82 \times 10^{-5} \text{m}^2$.

Stress = $Y \times \text{Strain}$

$$\Delta l = F/A \times 1/Y = (1/2.82 \times 10^{-5}) \times (1/10^5) = 0.35 \text{m}$$

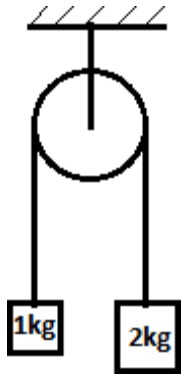
As volume will remain same (we can also say that product of l & r^2 will be constant as other terms in expression of volume are constants).

$$1 \times 3^2 = 1.35 \times R^2$$

$$\Rightarrow R = 2.58 \text{m}.$$

In the given system, masses are released from rest. The young's modulus of wire is 10^{11}N/m^2 , length = 1m & radius = 2mm. Find elongation in wire when masses are moving.

Assume pulley to be frictionless.



- a) $1.05 \times 10^{-5} \text{m}$
- b) $2 \times 10^{-5} \text{m}$
- c) $3 \times 10^{-5} \text{m}$
- d) $0.5 \times 10^{-5} \text{m}$

Let the tension in rope be 'T' & acceleration of masses be 'a'.

$$2g - T = 2a \quad \& \quad T - 1g = 1a.$$

On solving these equations we get, $T = 4g/3 = 1.33g$.

For rope, Stress = Y * Strain.

$$\therefore T/A = Y \cdot \Delta l / l \quad (\text{where } A \text{ is area of rope } \& \text{ } l \text{ is initial length})$$

$$\therefore \Delta l = (1.33g/\pi r^2) \cdot (1/10^{11}) = 1.05 \times 10^{-5} \text{ m}.$$

Composite materials

Composites consist of:

1. Combination of two or more materials – Composite = matrix + fiber (filler):

- **Matrix:**

- material component that surrounds the fiber.
- Usually a **ductile, or tough, material w/ low density**
- **Strength usually = 1/10 (or less) than that of fiber**
- Examples include: thermoplastic or thermoset
 - Thermoset most common (epoxy, phenolic)
- Serves to hold the fiber (filler) in a favorable orientation.

- **Fiber aka reinforcing material aka Filler:**

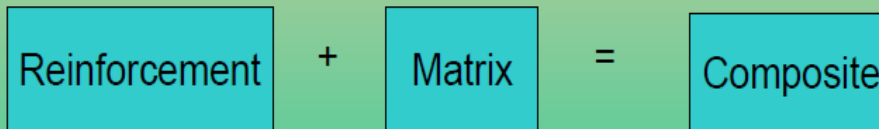
- **Materials that are strong with low densities**
- Examples include glass, carbon or particles.

2. Designed to display a combination of the best characteristics of each material i.e. fiberglass acquires strength from glass and flexibility from the polymer.

3. Matrix and filler bonded together (adhesive) or mechanically locked together!

Composite Material

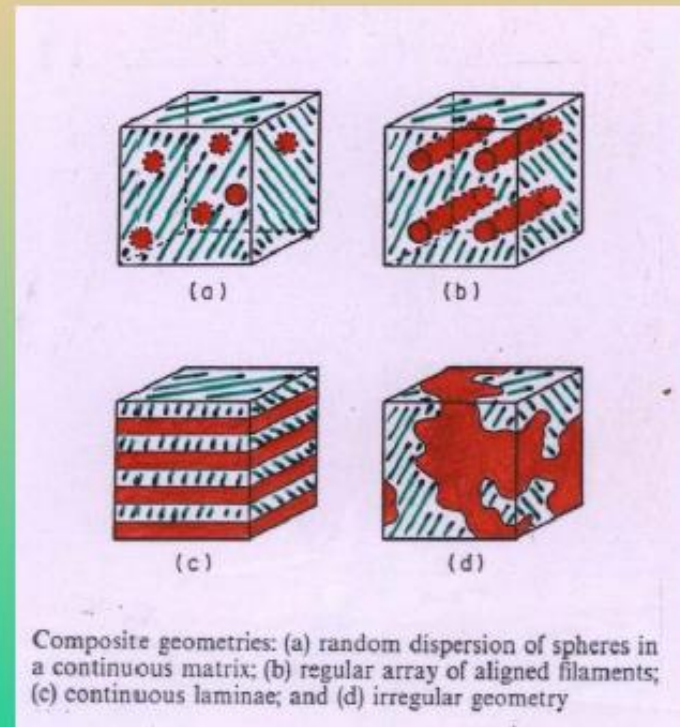
A combination of two or more materials to form a new material system with enhanced material properties



- In their broadest form, **composites are materials consist of two or more constituents. The constituents are combined in such a way that they keep their individual physical phases and are not soluble in each other or not to form a new chemical compound.**

Definition: An advanced composite material comprises at least two chemically different materials (heterogeneity): a *reinforcement*, and a *matrix* that binds the reinforcement and is separated from it by a sharp interface.

Dispersed phase
within **continuous phase**



Polymer composite is a material made of two or more types of polymers, but the polymer composites are **not chemically joined** the way that copolymers are, instead, polymer composites have a defined interface between the polymers

Materials for Composites

- **Matrices:** – **Metals** (Cu, Al, Ti, Ni...); **Polymers** (Thermosets, thermoplastics, Elastomers); **Ceramics** (SiC...)
- **Reinforcements:** **Fibers** (B, C, Glass, Aramids, PE,...); **Particles, flakes, ribbons...**

Definitions:

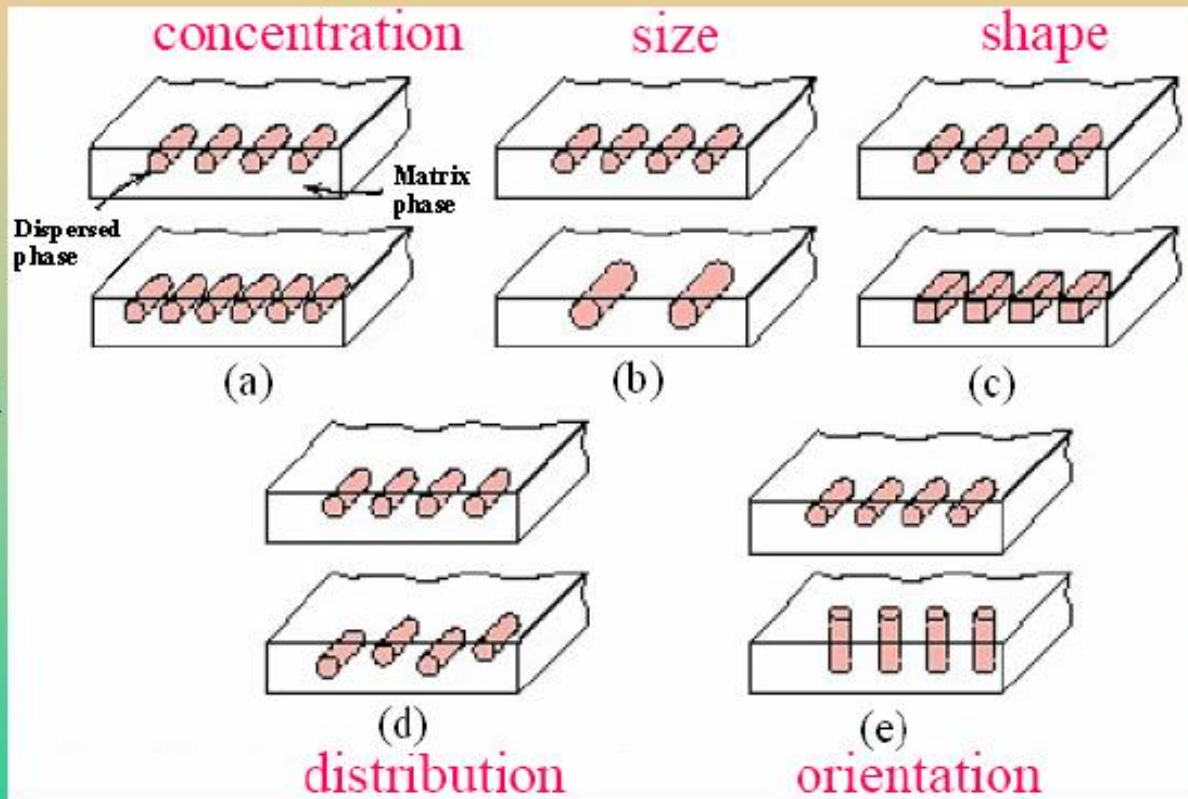
- **(Macro) composites:** bundles of fibers (scale \sim mm)
- **Micro-composite:** single fiber (or model) composite (scale \sim μm)
- **Nano-composite:** scale of reinforcement is \sim nm

Typically, **reinforcing materials** are **strong** with **low densities** while the **matrix** is usually a **ductile** or **tough** material.

Factors in Creating Composites

➤ Factors in creating composites:

- Matrix material
- Reinforcement material

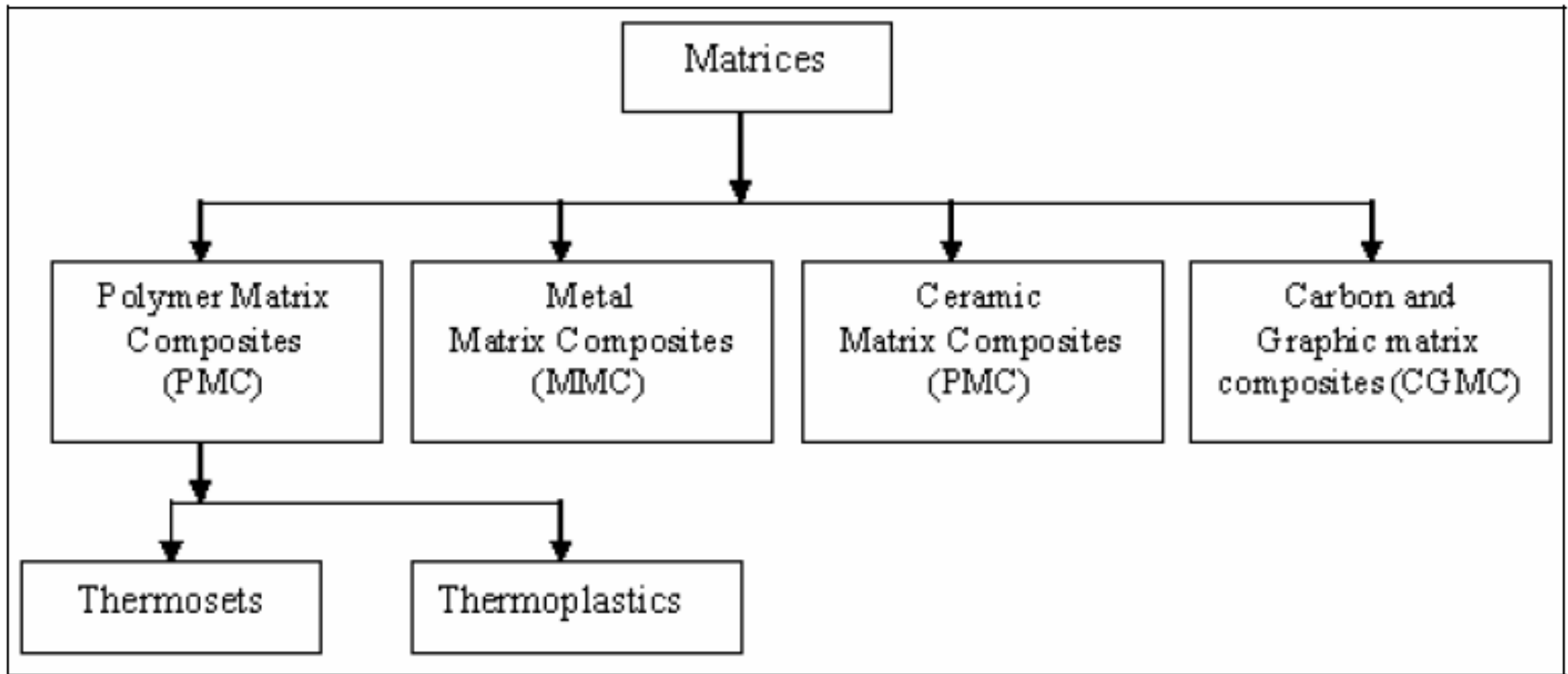


➤ → control
or design
properties

Properties of composite materials:

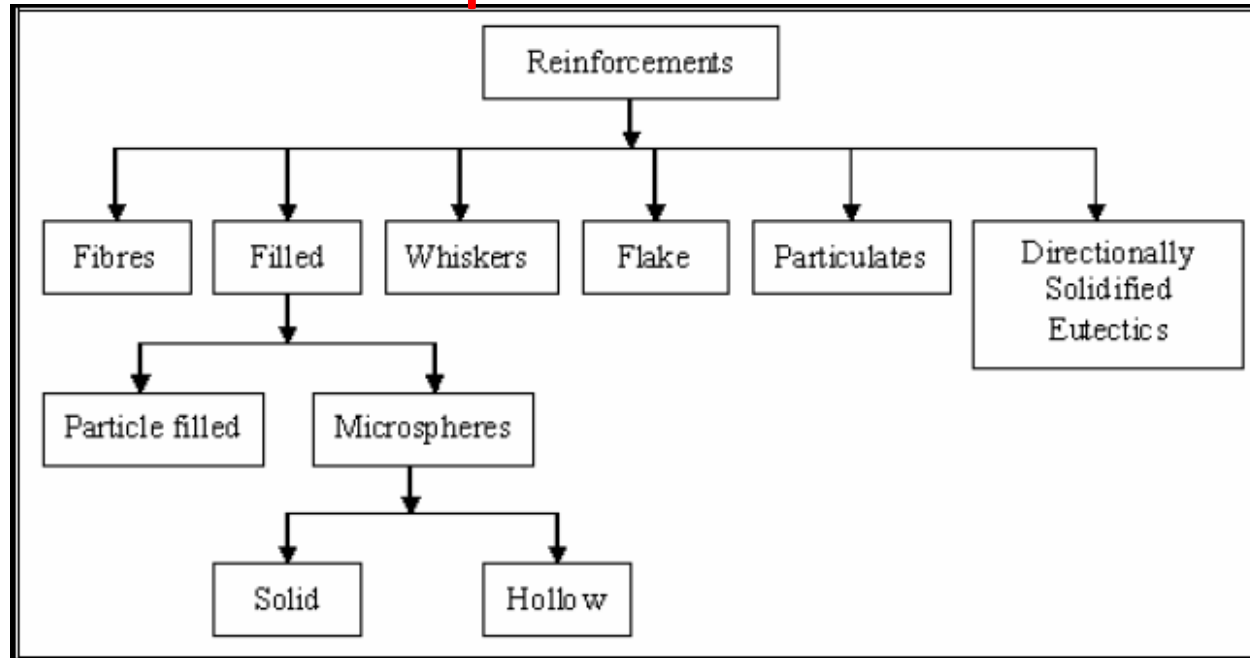
- High **strength** per unit weight
- High **flexibility**
- Easy to **fabricate**
- Good **chemical** and **heat resistance**
- Good **corrosion resistance**
- **Low maintenance**
- High **toughness** and retain toughness even at low temperature
- **Low thermal conductivity**

Classification of composites: based on matrix

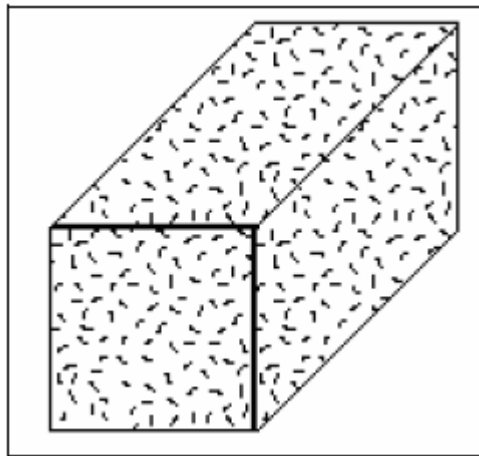


- The first level of classification is usually made with respect to the matrix constituent. The major composite classes include Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term organic matrix composite is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and carbon matrix composites commonly referred to as carbon-carbon composites.

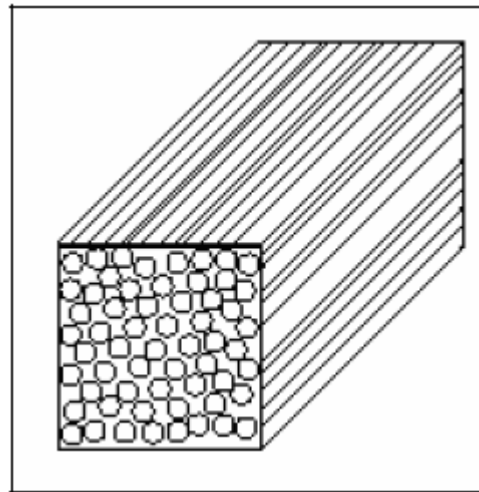
Classification of composites: based on reinforcements



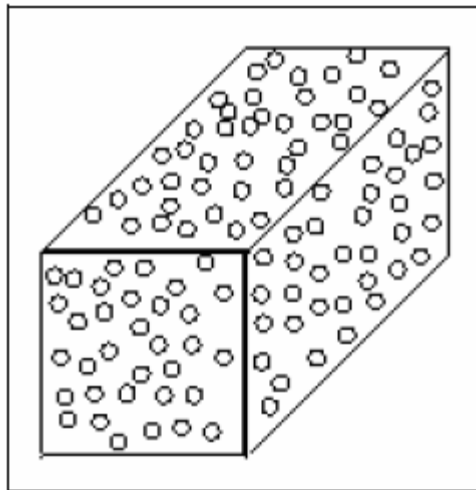
- The second level of classification refers to the reinforcement form - fibre **reinforced composites**, **laminar composites** and **particulate composites**. Fibre Reinforced composites (FRP) can be further divided into those containing discontinuous or continuous fibres.
- **Fibre Reinforced Composites** are composed of fibres embedded in matrix material. Such a composite is considered to be a discontinuous fibre or short fibre composite if its properties vary with fibre length. On the other hand, when the length of the fibre is such that any further increase in length does not further increase the elastic modulus of the composite, the composite is considered to be continuous fibre reinforced. Fibres are small in diameter and when pushed axially, they bend easily although they have very good tensile properties. These fibres must be supported to keep individual fibres from bending and buckling.
- **Laminar Composites** are composed of layers of materials held together by matrix. Sandwich structures fall under this category.
- **Particulate Composites** are composed of particles distributed or embedded in a matrix body. The particles may be flakes or in powder form. Concrete and wood particle boards are examples of this category.



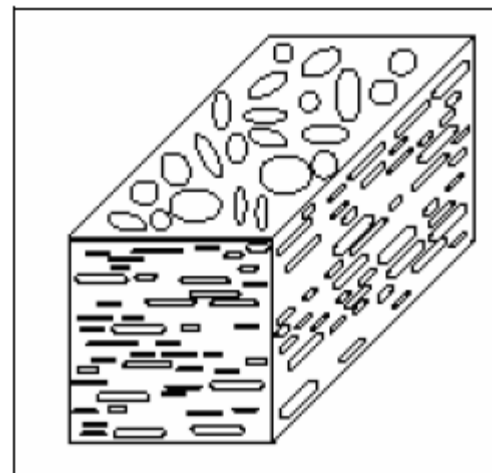
Short-fibre reinforced composites



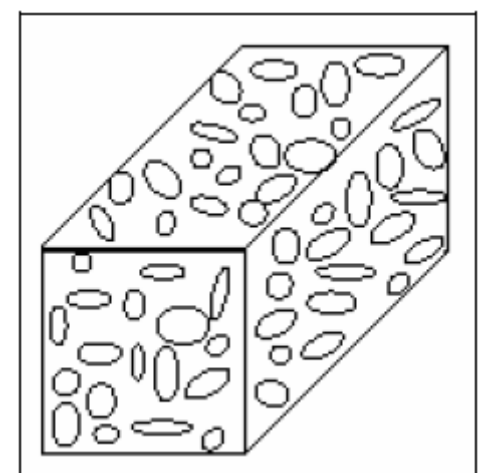
Long-fibre reinforced composites



Particulate Composites



Flake Composites



Filler Composites

Polymer matrix composites (PMCs)

- are present in almost all aspects of modern life - from gadget components to a vast selection of automotive accessories.
- Derived from its name, meaning many repeating units, polymers are often made up of branches of carbon and hydrogen chemically linked together to make a chain.
- Polymers that are often used as composites are either thermoplastic polymers, thermosetting polymers or elastomers. They are a source of a wide variety of low-priced, raw materials which offer many advantages like:
 - Low specific weight
 - High material stability against corrosion
 - Good electrical and thermal insulation
 - Ease of shaping and economic mass production
 - Attractive optical properties
- Yet, they suffer from some deficiencies as in strength and stiffness. To make up for those deficiencies, reinforcements are integrated into polymer materials to enhance their mechanical properties.

What is a polymer matrix composite?

- Polymer matrix composites are materials made up of fibres that are embedded in an organic polymer matrix.
- These fibres are introduced to enhance selected properties of the material.
- Polymer matrix composites are classified based on their level of strength and stiffness into two distinct types:
- **Reinforced plastics** - confers additional strength by adding embedded fibrous matter into plastics
 - **Advanced Composites** - consists of fibre and matrix combinations that facilitate strength and superior stiffness. They mostly contain high-performance continuous fibres such as high-stiffness glass (S-glass), graphite, [aramid](#), or other organic fibres

Properties of a PMC

The constituents of a PMC, which affect its overall properties, are:

- **Matrix** - This is the polymer, which is a continuous phase and is classified as the weak link in a PMC structure.
- **Reinforcement** - This is a discontinuous phase and is a principal load-bearing component. It can either be glass, quartz, basalt, or carbon fibre.
- **Interphase** - The interphase between the reinforcement and matrix phases where load transmission takes place.
- Aside from the types of matrix and reinforcement used, other factors affecting the properties of a PMC are the constituents' relative proportions, the reinforcement geometry and the nature of the interphase.
- The main advantages of polymer matrix composite materials are their strength and stiffness.

Other qualities that come with the reinforcement of polymers are as follows:

Improved processing	Density Control	Thermal Conductivity	Thermal Expansion Control
Flame retardancy	Cost reduction	Greater toughness	Impact resistance
Fatigue resistance	Fracture resistance	Abrasion resistance	Corrosion resistance
High specific strength to weight ratio	High specific stiffness to weight ratio	Improved fatigue strength	High creep resistance

Despite these many desirable qualities, polymer matrix composites are limited to service temperatures below 600° F (316° C), above which, polymers start to degrade [3].

What is a PMC used for?

PMCs are regarded due to their low cost and straightforward fabrication methods.

Automotive industry - Body panels, leaf springs, driveshaft, bumpers, doors, racing car bodies, and so on.

Aircraft and aerospace industry - Used in the construction of structural parts for military aircraft, space shuttles, and satellite systems. The main purposes of using PMCs are to reduce aircraft weight, which can improve its performance, and to reduce its costs.

Marine - Fibreglass boat bodies, as well as canoes and kayaks.

Sports goods - Used in performance footwear, sports equipment and other sporting goods because of their lightweight and high-strength properties.

Biomedical applications - Medical implants, orthopaedic devices, MRI scanners, X-ray tables, and prosthetics.

Electrical - Panels, housing, switchgear, insulators, and connectors. It also covers electronic devices like capacitors, Li-ion and flexible batteries and covers for digital portable equipment like headphones, etc.

Protective equipment - Since polymer matrix composites can withstand extreme hot or cold and other hazardous conditions, they are often made as raw materials for bulletproof vests and other armour.

Industrial - Chemical storage tanks, pressure vessels, pump housing, and valves. PMCs are also used in impellers, blades, blower and pump housings, and motor covers.

Structural - Polymer matrix composites are used to repair bridges and other construction materials and equipment like booms and cranes.

Examples of PMCs (polymer matrix composite)

- **FRP (Fibre reinforced plastic)**
 - GRP (glass reinforced plastic)
 - CRP (carbon reinforced plastic)

Characteristics of FRP depend on:

- Properties of **fiber**
- Properties of **matrix**
- **Contact area** between fiber material and the matrix material
- **Degree to which an applied load is transmitted** to the fibers by the matrix phase
- **Fiber length**: (for effective strength and stiffness, some critical fiber length is essential)
- Fiber **orientation** and **concentration**:
 - When fiber distribution is uniform, superior composite properties can be obtained

Polymers which are used as a continuous phase in PMCs

Types of Resins

- I. Thermoset Resin
 - a. Polyester
 - b. Vinyl Resin
 - c. Epoxy
 - d. Phenolic
 - e. Polyurethane
- II. Thermoplastic
 - a. Acetal
 - b. Acrylonitrile Butadiene Styrene (ABS)
 - c. Nylon
 - d. Polyethylene (PE)
 - e. Polypropylene (PP)

Fibres which are used as a reinforcement phase in PMCs

I. Natural Fibers:

- a. Cellulose
- b. Sisal

II. Man-Made Fibers:

- a. Aramid
- b. Boron
- c. Carbon/Graphite
- d. Glass
- e. Nylon
- f. Polyester
- g. Polyethylene
- h. Polypropylene

➤ **1. Glass Fiber Reinforcements**

- E-glass
- S-glass
- C-glass
- ECR-glass
- AR-glass

➤ **2. Aramid (Kevlar) Fiber Reinforcement:**

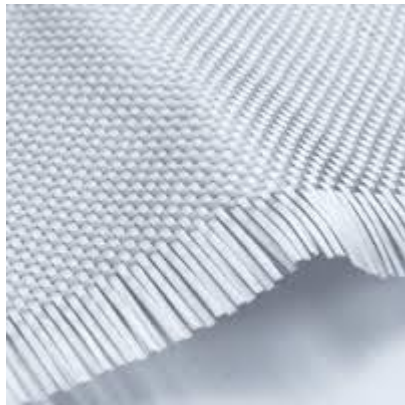
- Superior resistance to damage (energy absorber)
- Good in tension applications (cables, tendons)
- Moderate stiffness
- More Expensive Than Glass

➤ **3. Carbon Fiber Reinforcement:**

- Good modulus at high temperatures
- Excellent stiffness
- More expensive than glass
- Brittle
- Low electric insulating properties

Glass Reinforced Plastic (GRP):

- **Matrix:** polymer (e.g. epoxide, polyester, nylon etc.)
- **Reinforced phase:** glass fiber (polyhedral silica based structure)
- **Types** (based on composition of fiber): E-glass, R-glass, S-glass
- Freshly drawn fibers are **coated with matrix material** that protect the surface from damage and other undesirable interactions
- It also helps in promoting a **better bond between the fibers and matrix** materials.
- Have **high strength and high stiffness**
- **Inexpensive** and **easy to manufacture.**
- Glass fibers are **available in the form of** mats, tapes, cloth, continuous and chopped filaments, roving and yarn.
- **Applications:** automotive parts, marine bodies, storage tanks, plastic pipes, industrial flooring, high capacity storage tanks, roofing laminate, door and window canopies.



M2.2.2.7 Quartz and Silica Fibers

The glass-types typically contain about 50 to 78% silica. Silica glass is a purer glass fiber that can be made by treating fiberglass in an acid bath, which removes all impurities without affecting the silica. The final product contains 93 to 99% silica. Quartz is even more pure, and quartz fibers are made from natural quartz crystals that contain 99.9% silica, possessing nearly all the properties of pure solid quartz.

Ordinary fiberglass, high silica and quartz fibers share several characteristics and can be produced in a range of fiber diameters. Roving or yarns and other forms of fibers can be made from high silica as well as quartz. All matrix materials that accept fiberglass are amenable to high silica and quartz too.

They differ from glass in many factors, however, especially in heat-related properties.

Although quartz crystals are commonly available, pure crystals are hard to come by. On the other hand, high silica comes from the same material as glass fibers and is easily accessible. However, quartz makes up for its rarity with its capacity to withstand high temperatures, which silica is incapable of.

Barring this difference, silica and quartz are similar in other respects. They are highly elastic and can be stretched to 1 % of their length before break point. Both silica and quartz are not affected by acid attacks and are resistant to moisture

Owing to their thermal properties, silica and quartz are the natural choice as fibers in several applications. They have good insulating properties and do not melt at temperatures up to 1600°C. In addition, they have low thermal expansion coefficients which make them withstand high temperatures.



Carbon/graphite Fibers Reinforced Plastics (CRP):

- **Matrix:** polymer
- **Reinforced phase:** carbon/graphite fiber
- Carbon fibers produced by **carbonization** polyacrylonitrile, rayon and pitch.
- They have modulus in the range of 200 -900 GPa in the direction **parallel** to fibers (along the axis) and 15 GPa in **transverse** direction.
- Carbon fibers are **brittle**, strength depend on their **internal structures and distribution** in the matrix.
- **Low** or negative **coefficient of thermal expansion**.
- **High thermal and electrical conductivity.**
- If processing carried out at **high temperature, takes graphite** structure.
- **Applications:** sport equipment, motor cases, vessels, air craft components, civil engineering applications e.g bridges.

Preparation of Carbon fiber:

- New breed of **high strength** composite material.
- Contain 90 % carbon **obtained by the controlled pyrolysis** of appropriate fibers.
- Large variety of fibers called **precursors** used to produced carbon fibers of different morphologies and different characteristics.
- **Most prevalent precursors** are polyaacronitrile (PAN), cellulose (viscose, rayon, cotton), petroleum or coal tar pitch and certain phenolic fibers.
- **Manufacture:**
- by **controlled pyrolysis** of organic precursors in fibrous form.
- Basically it **removes O₂, N₂ and H₂** to form carbon fibers
- **Mechanical properties improved** by increasing crystallinity, orientation and decreasing defects

(i) Carbon fiber from PAN

- 1) **Oxidative stabilization:** PAN precursor is first stretched and simultaneously **oxidized at 200-300 °C**. This converts thermoplastic PAN to non-plastic, cyclic or ladder compound
- 2) **Carbonization:** carbonized at **1000 °C** without tension in inert atmosphere for few hours. **Noncarbon elements are removed** as volatiles
- 3) **Graphitization:** depending on the type of fiber required, fibers are treated at temperature between **1500 and 3000 °C** which improves the ordering and orientation of the crystallites in direction of the fiber axis.

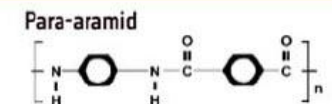


M2.2.2.6 Aramid Fibers : Kevlar

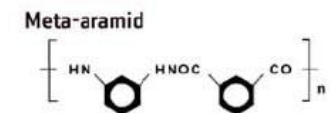
Aramid fibers are made from aromatic polyamides which are long polymeric chains and aromatic rings. They are structures in which six carbon atoms are bonded to each other and to combinations of hydrogen atoms. In aramid fibers, these rings occur and reoccur to form the fibers. They were initially used to reinforce automobile tires. Since then, they have also found other uses like bullet proof vests. As high strength applications, their use in power boats is not uncommon.

Aramid have high tensile strength, high modulus and low weight. Impact-resistant structures can be produced from aramid. The density of aramid fibers is less than that of glass and graphite fibers. They are fire resistant apart from being high-temperature resistant and also unaffected by organic solvents and fuels. But their resistance in acid and alkaline media is poor. They are supple and allow themselves to be woven into matrices by simple processes. Aramid fibers have a negative coefficient of thermal expansion in the fiber direction and the failure of aramid fibers is unique. When they fail, the fibers break into small fibrils, which are like fibers within the fibers. This unique failure mechanism is responsible for high strength.

poly para phenylene terephthalamide



poly(paraphenylene terephthalamide (aramid))



poly-(metaphenylene isophthalamide (MPIA))

Kevlar fiber

- Little creep only (thus resistant to impact and abrasion damage)
- Excellent temperature resistance (does not melt, decomposes at $\sim 500^{\circ}\text{C}$)
- Linear stress-strain curve until failure
- Low density : 1.44 (thus light weight)
- Negative CTE (thus thermally stable)
- Fiber diameter = 11.9 micron
- Fiber strength variability

Applications of kevlar:

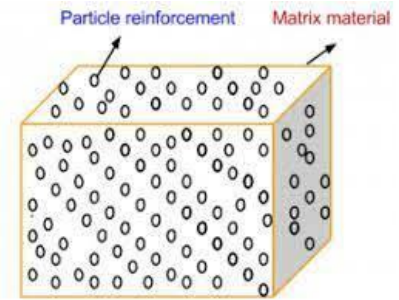
- Light weight boat hulls, aircraft fuselage, high performance race cars, **bullet proof vest** and puncture resistant tyres.

Demerits:

- **Fibre themselves absorb moisture**, so kevlar composites are **sensitive to the environment** than glass or graphite composites.
- Although tensile and modulus are high, compressive properties are relatively poor.

Applications of FRP:

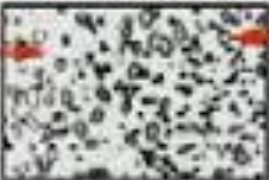

- Paper Industries
- Metals and mining and construction Industries
- Power station and chemical industry
- Oil and gas industry
- Air pollution
- Medical applications
- Satellites and launch vehicles
- Aircraft structures
- Marine applications
- Automobile Industry



Particle Reinforced Composites:

- **Particles used for reinforcing include:**
 - ceramics and glasses such as small mineral particles,
 - metal particles such as aluminum,
 - and amorphous materials, including polymers and carbon black.
- **Particles are used to increase the modulus of the matrix, to decrease the permeability of the matrix, or to decrease the ductility of the matrix.**
- **Particle reinforced composites support higher tensile, compressive and shear stresses**
- **Particles are also used to produce inexpensive composites.**
- **Examples:**
 - automobile tire which has carbon black particles in a matrix of elastomeric polymer.
 - spheroidized steel where cementite is transformed into a spherical shape which improves the machinability of the material.
 - concrete where the aggregates (sand and gravel) are the particles and cement is the matrix.

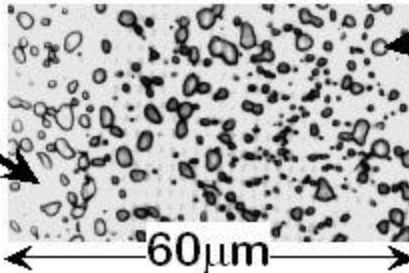
Particle Reinforced Composites

<u>Matrix:</u> Ferrite (α - iron) Ductile	Spheroidized Steel 	<u>Particle:</u> Fe_3C (cementite) Brittle
<u>Matrix:</u> Rubber (Compliant)		<u>Particle:</u> Carbon (Stiffer)
Automobile Tire		

Examples of particle reinforced composites

-Spheroidite steel

matrix:
ferrite (α)
(ductile)

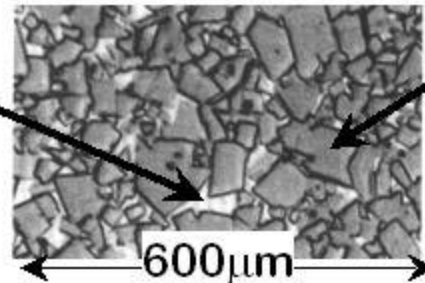


particles:
cementite
(Fe₃C)
(brittle)

Adapted from Fig. 10.10, *Callister 6e*.
(Fig. 10.10 is copyright United States Steel Corporation, 1971.)

-WC/Co cemented carbide

matrix:
cobalt
(ductile)
 V_m :
10-15vol%!

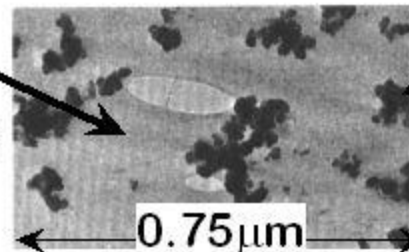


particles:
WC
(brittle, hard)

Adapted from Fig. 16.4, *Callister 6e*.
(Fig. 16.4 is courtesy Carboly Systems, Department, General Electric Company.)

-Automobile tires

matrix:
rubber
(compliant)



particles:
C
(stiffer)

Adapted from Fig. 16.5, *Callister 6e*.
(Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)



Metal matrix composites
(MMCs)

Particulate reinforced
MMCs

Short fibers or
whisker reinforced
MMCs

Continues fibers
reinforced MMCs

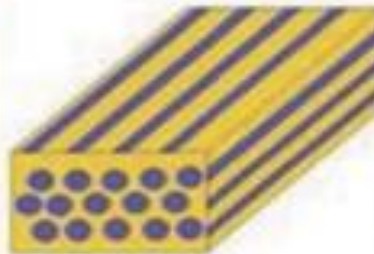
Continues sheet
reinforced MMCs



Particulates



Short fibers or whiskers



Continues fibers



Sheet laminates

Metal Matrix composites (MMCs)

- Metal matrix composites (MMCs) are a class of materials comprised of a metal fused with another substance. These two components appear in differing phases that are physically and chemically distinct.
- The base material is a metal matrix, while the other substance appears as fibres or particulates to work as reinforcing material.
- As with most metal matrix composites, the goal of manufacturing such a material is to enhance the existing properties of the metal matrix, by adding supplementary features that the reinforcement provides.

Properties of Metal Matrix Composites

High Strength

One of the most common features of metal matrix composite materials is increased strength and stiffness. Its high strength-to-weight ratio makes the material useful in a wide variety of applications.

This is evident when exposed to tension or compression, as most metal matrix composites have high mechanical strength.

High Heat Resistance

Some composites are built to have higher creep resistance than the pure metal counterparts. This reduces the risk of warping or deformation in the material, especially when exposed to welding or tensile stress with high temperature. Metal matrix composites work best in industries with a high risk of creep fatigue or sudden temperature changes.

In addition, these materials have a lower thermal expansion coefficient, which bodes well for applications that require material integrity in extremely high temperatures.

Other Unique Properties

Each composite has its own unique signature set of properties depending on the composition and orientation of the metal and reinforcing material. Some of these properties include the following:

- Fire resistance
- Inability to absorb moisture
- Radiation resistance
- Increased resistance to wear and tear

Examples of Metal Matrix Composites

Aluminium MMC

These composites make use of aluminium as the base metal matrix.

Examples include [SupremEX® 620XF T5 Precision Extrusion \(6061B\)](#), aluminium-graphite composite, and aluminium-beryllium composites such as [AlBeMet® AM162 HIP](#).

Magnesium MMC

Magnesium is another excellent matrix material for composites. Some products in this category include magnesium-silicon carbide (Mg-SiC), magnesium-aluminium oxide (Mg-Al₂O₃) and magnesium-titanium carbide (Mg-TiC).

Titanium MMC

[Pure titanium](#) is already a strong material in itself, but its composite form may enhance its superior strength.

Other MMCs

Other less common but highly useful matrix base materials used for composites include copper, cobalt, nickel, or a combination of metals. Meanwhile, some of the most common reinforcing materials used are carbon fibre, silicon carbide, alumina, and boron.

Applications of Metal Matrix Composites

Aerospace and Aircraft Industry

Metal matrix composites work well as components in transmission systems, gearboxes, engine parts and accessories, and other internal elements.

Sports

The superior strength-to-weight ratio of most metal matrix composites makes the material suitable for tennis rackets, bicycle frames, and other sports that involve speed and strength.

Automotive Applications

Car and motor racing make use of metal matrix composites for engine and vehicle body parts due to the lightweight nature of the material.

Composition:

- 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 fiber 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 fibre.
- To prevent this reaction, the carbon fibres are coated with nickel or titanium boride.

Applications of Aluminum MMCs:



Applications:

Metal matrix composite



A selection of ultra-hard and wear-resistant components manufactured from Fe/TiC MMCs under the trade name Ferro-Tic[®] from Pacific Sintered Metals (formerly Alloy Technology International, Inc.).

What are ceramic matrix composites (CMCs)?

- Ceramic matrix composites (CMC) are generally made from ceramic fibres or whiskers embedded in a ceramic matrix.
- These ceramics cover a varied range of inorganic materials that are usually non-metallic and commonly used at high temperatures.

CMC reinforcing materials

- **Reinforcing materials** used for ceramic matrix composites include carbon, alumina, silicon carbide and alumina-silica.
- The refractory fibre can be **in the form of whiskers, particles, long or short fibres, and nanofibres**. These fibres have a polycrystalline structure similar to that of conventional ceramics.
- Continuous or long fibres provide **better toughness** as they can support a load even after the ceramic matrix undergoes cracking, thus **slowing down the crack's propagation**.
- Short fibres and whiskers, on the other hand, give **improved resistance to crack growth**. This makes composites less sensitive to flaws, yet once a crack begins to propagate, failure could be disastrous.

Properties of ceramic matrix composites

- Conventional ceramics have limited thermal shock resistance and low fracture toughness. These drawbacks are addressed by the use of fibre-reinforcement in ceramic matrix composites.
- Common properties of ceramic matrix composites are:
 - High thermal shock and creep resistance
 - High temperature resistance
 - Excellent resistance to corrosion and wear
 - Inertness to aggressive chemicals
 - High tensile and compressive strength, thus no sudden failure as compared to conventional ceramics
 - Increased fracture toughness due to reinforcement
 - Lightweight due to reduced density
 - High strength retention at elevated temperatures

Applications of ceramic matrix composites

- **Heat exchangers and burner components**

- **Gas turbine components** – these include turbine blades, combustion chambers, stator vanes and turbine engines, where coated silicon carbide fibres are embedded in a ceramic matrix to impart temperature resistance, toughness, and low density.

- **Aerospace industry** – including body flaps, shrouds and space shuttle shielding, where coated ceramic tiles provide protection from extreme heat.

- **Engine exhaust systems** – including ceramic exhaust nozzles for commercial aircraft to increase component life and reduce weight and engine noise.

- **Hypersonic vehicles** – these utilise structural materials such as ultra-high-temperature ceramics, which make good candidates for high heat flux areas.

- **Nuclear power industry** – including internal reactor structures made from MAX phase composites that can withstand high temperatures and have high mechanical damage tolerance and good chemical compatibility with coolants such as sodium and molten lead.

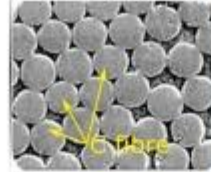
Ceramic Matrix composites (CMCs)

Silicon Carbide matrix composites

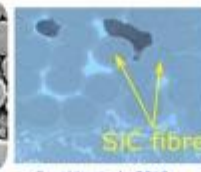
Key points

Used in high thermo-structural applications with long time exposures.

Reinforcements:



Heidenreich, 2015



Gavaldà et al., 2018

Applications:



Rocket nozzle
Di Carlo, 2015



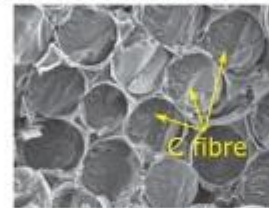
Aeroengine vane
Spriet, 2015

Carbon matrix composites

Key points

Used in frictional applications and short high temperature applications.

Reinforcements:



Hatta et al., 2015

Applications:



Break discs
Krenkel et Thiebault, 2015



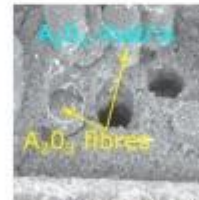
Ventilators gas
Hatta et al., 2015

Oxide matrix composites

Key points

Used in applications where superior thermal stability is needed.

Reinforcements:



Keller et al., 2015

Applications:



Mixer nozzle
Keller et al., 2015



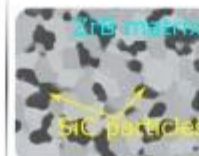
Acoustic nozzle
Keller et al., 2015

ZrB₂ or HfB₂ matrix composites

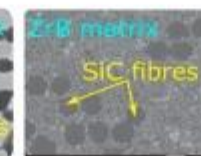
Key points

Used in applications where ultrahigh temperature is needed (>2000°C)

Reinforcements:



Kagawa et al., 2015

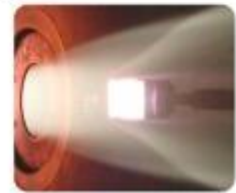


Kagawa et al., 2015

Applications:



Reentry nose
Johnson, 2015



Nozzle
Savino et al., 2015