

Module 6

CREEP

- When materials are placed under steady loads for longer periods of time, they undergo continuous deformation without any increase in load – creep
- Turbine rotors in steam turbines, high pressure pipe lines, beams etc.
- It is a time dependent part of strain resulting from stress applied continuously over longer period of time
- It is more active at higher temperatures
- For metals only for temperatures greater than about $0.4T_m$. For plastics and rubber – room temp:

- Stress, temp and time – factors causing creep
- Creep test and creep curve
- A creep curve shows the relationship b/w creep strain v/s time at a particular temp
- Test consists of subjecting a specimen to a constant load at const temperature .
Deformation or strain is measured and plotted as a function of elapsed time.

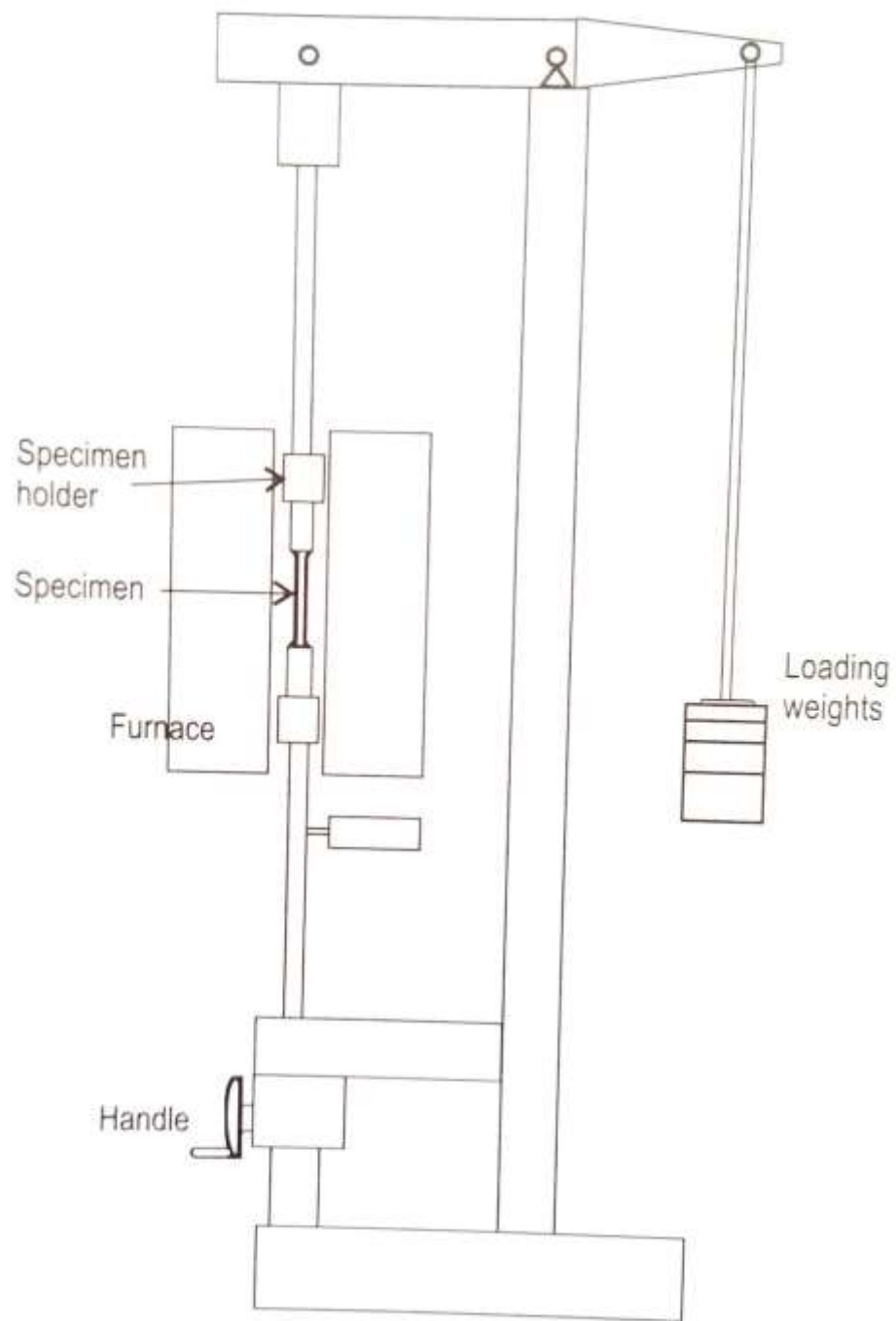


Figure 11.16 *Creep Test*

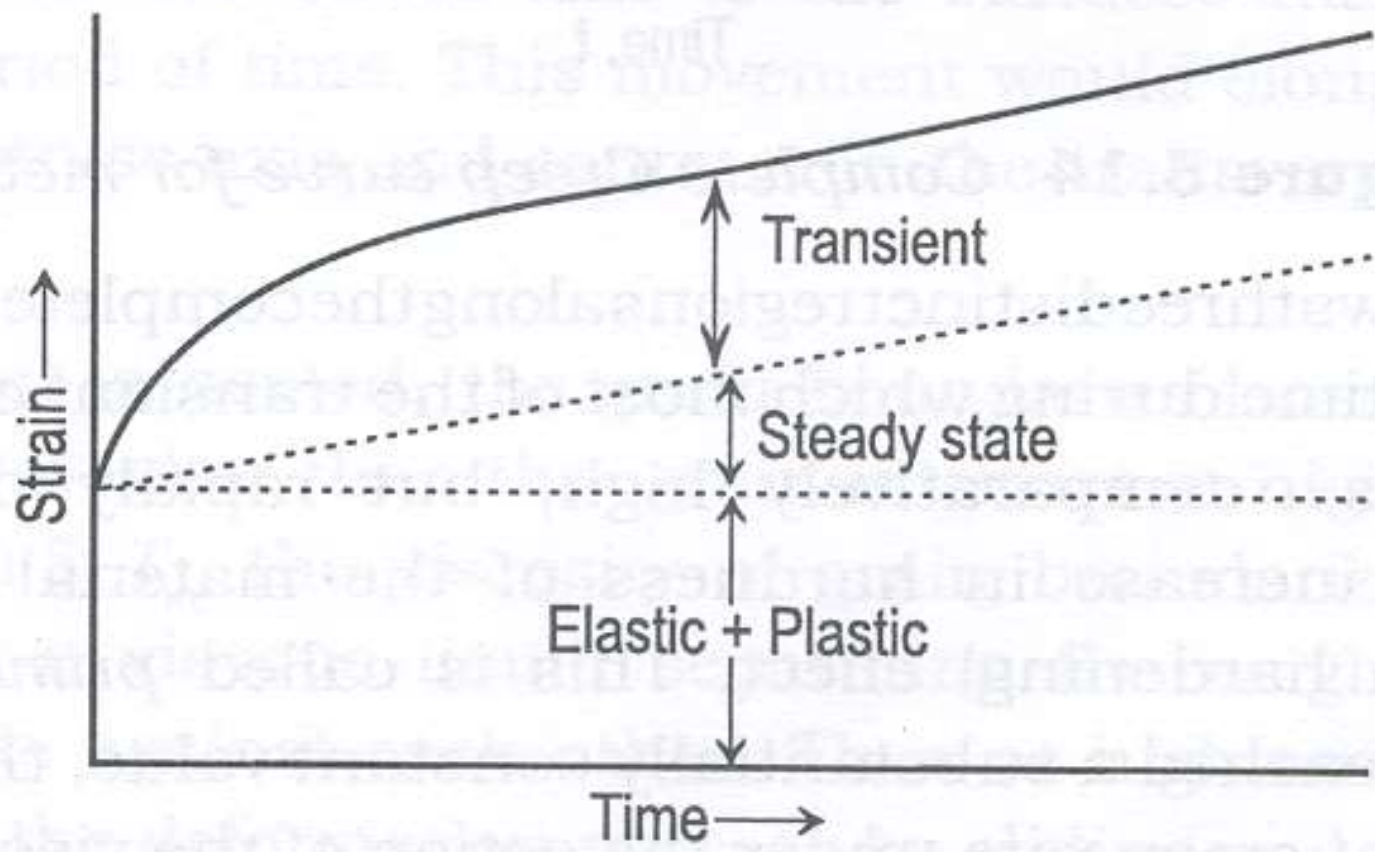


Figure 5.13 *Creep curve for metals*

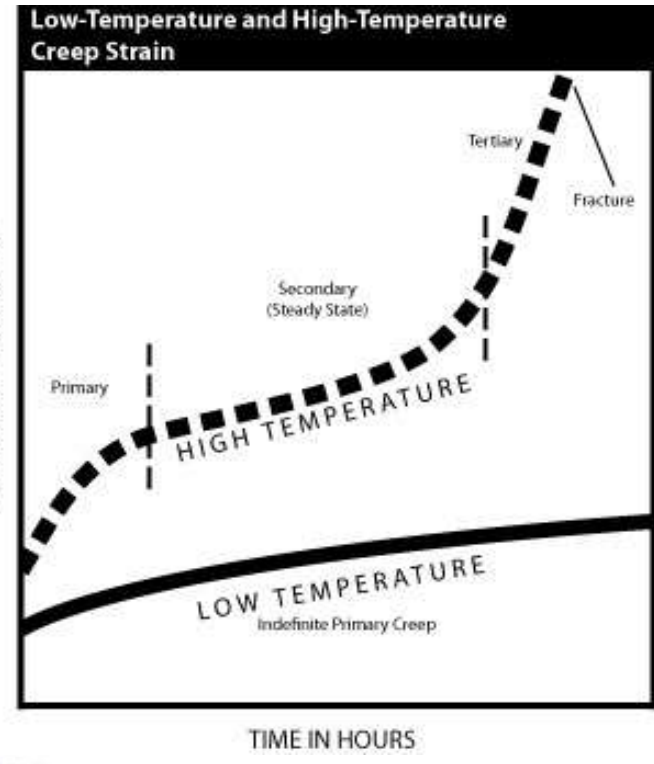
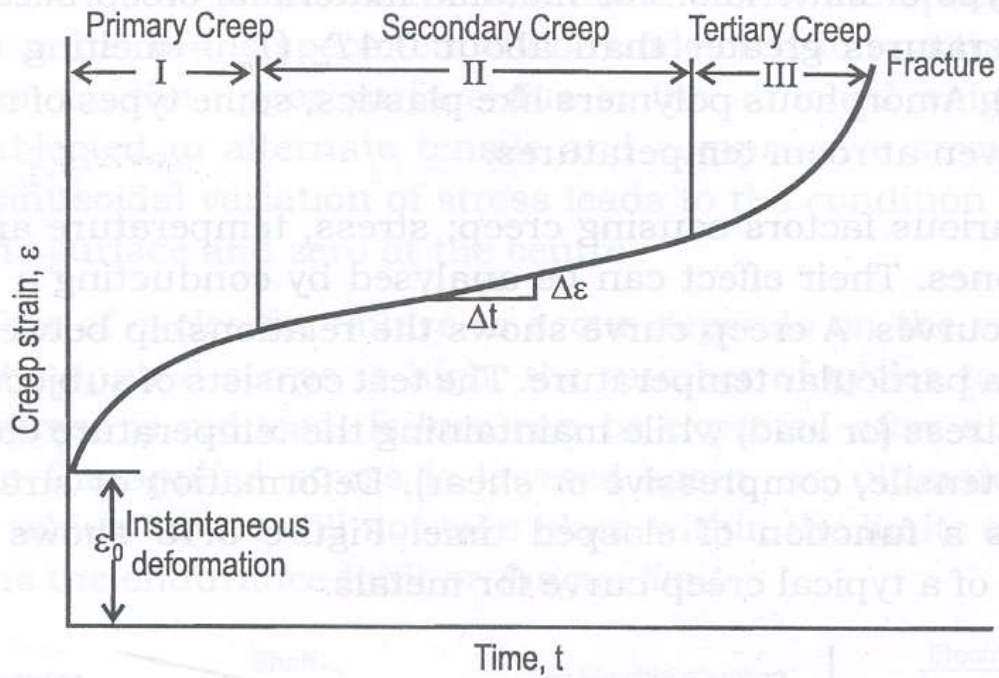
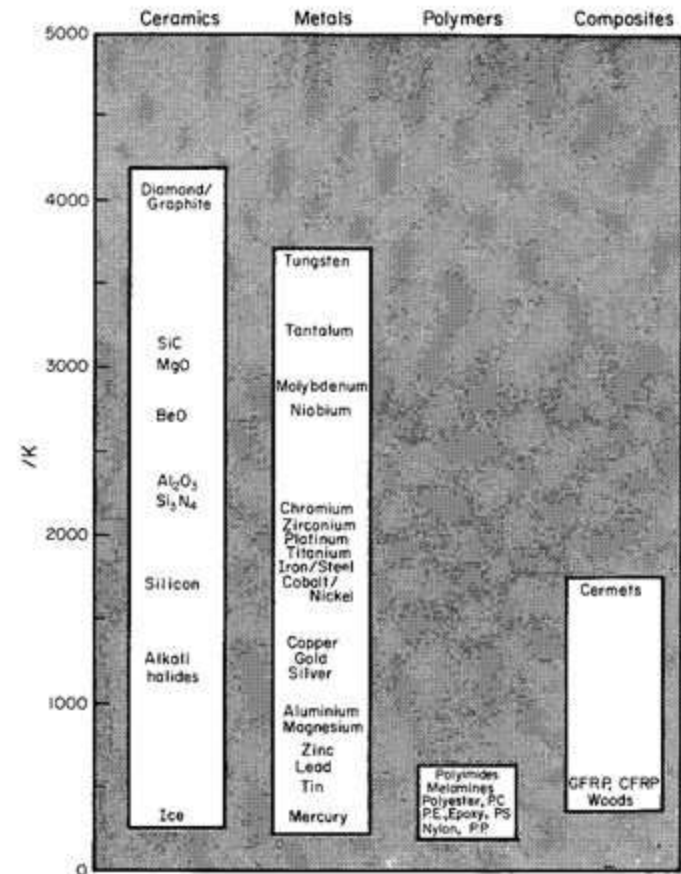
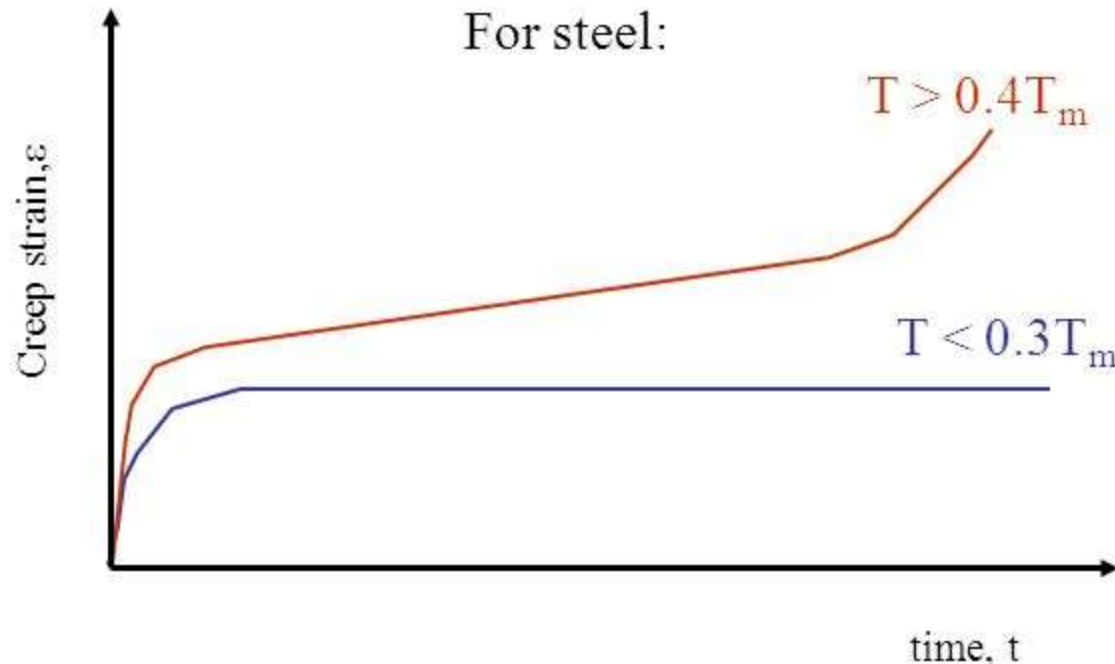


Figure 5.14 Complete Creep curve for metals

“High” Temperatures

- Metals: $T > 0.3-0.4 \cdot T_{\text{melt}}$
- Ceramics: $T > 0.4-0.5 \cdot T_{\text{melt}}$ (some $\sim 0.66 \cdot T_{\text{melt}}$)
- Amorphous polymers: $T > T_g$ (or $> 0.4 \cdot T_{\text{melt}}$)
- Crystalline polymers: $T > 0.4 \cdot T_{\text{melt}}$

For steel:



From: Ashby & Jones

In the initial stage, or primary creep, or transient creep, the strain rate is relatively high, but decreases with increasing time and strain due to a process analogous to work hardening at lower temperatures. For instance, the dislocation density increases and, in many materials, a dislocation subgrain structure is formed and the cell size decreases with strain.

The strain rate diminishes to a minimum and becomes near constant as the **secondary stage begins**. This is due to the balance between work hardening and annealing (thermal softening). The secondary stage, referred to as "steady-state creep", is the most understood. The microstructure is invariant during this stage, which means that recovery effects are concurrent with deformation. No material strength is lost during these first two stages of creep. The characterized "creep strain rate" typically refers to the constant rate in this secondary stage. Stress dependence of this rate depends on the creep mechanism.

In tertiary creep, the strain rate exponentially increases with stress because of necking phenomena or internal cracks or voids decreases the effective area of the specimen. Strength is quickly lost in this stage while the material's shape is permanently changed. The acceleration of creep deformation in the tertiary stage eventually leads to material fracture

Mechanism of creep

Several atomic processes are responsible for creep

- a) Dislocation cross slip
- b) Dislocation climb
- c) Diffusion of vacancies
- d) Grain boundary sliding

- At higher stresses dislocations move along slip planes and overcome barriers by thermal energy
- Edge dislocations piled up against an immobile dislocation can move to other parallel slip planes by climb
- Vacancies also move in due to applied stress from surfaces of the specimen transverse to stress axis to surfaces parallel to stress axis
- At high temperatures, grain boundaries lose their strength and become weaker than grain interiors
- Thus they facilitate deformation process by sliding and thus cause slip

Factors affecting creep

- Materials having high thermal stability and high T_m resist creep
- Coarse grained materials exhibit better creep resistance than fine grained ones. Also dendritic structures than eqi-axed ones
- Precipitation hardened and dispersion hardened alloys improve creep resistance
- Cold working or work hardening strengthens a metallic material
- Formation of substitutional solid solution improves creep resistance

Creep resistant materials

- Materials of high melting point like refractories, super alloys, ceramics etc
- Alloys with solute of lower diffusivity
- Coarse grained materials
- Directionally solidified alloys with columnar grains
- Single grained materials

Structural changes during creep

- Creep deformation rate is the result of changes in internal structure of the material, with creep strain and time
- Important structural changes are:
 - a. Deformation by slip
 - b. Sub-grain formation
 - c. Grain boundary sliding

a) Deformation by slip

- At high temperatures new slip systems become operative
- τ_{cr} on these new planes is much lower
- Hence dislocations continue their motion causing creep strain
- At low temp these slip systems wouldn't be operative

b) Sub-grain formation

- Due to creep lattice bending can take place which causes formation of excess dislocations of same sign
- At high temperatures dislocation climb occurs and they rearrange themselves in to a low angle boundary called sub boundaries
- Crystal regions separated by sub boundaries – sub grains – polygonisation or sub grain formation
- The sub grain boundaries serve as less effective barriers to moving dislocation

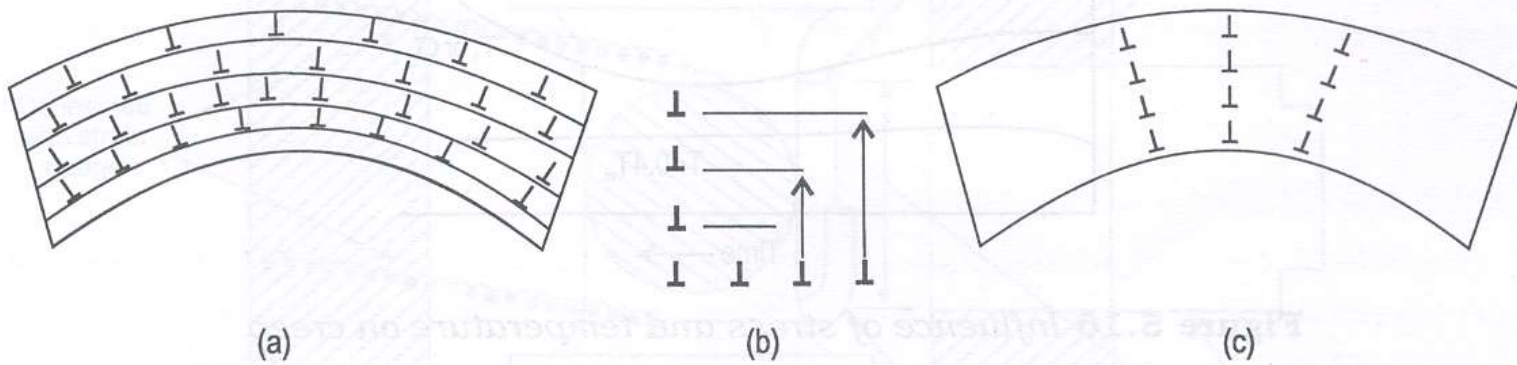
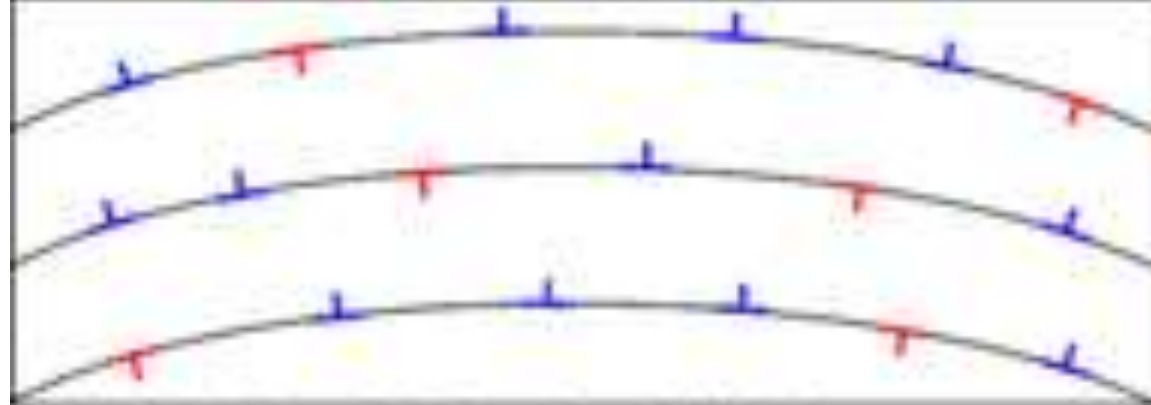
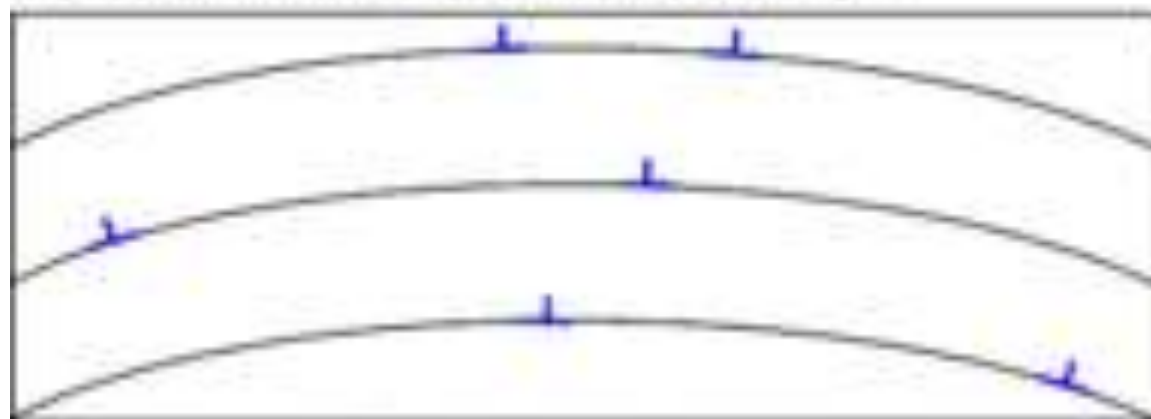


Figure 5.15 *Sub-grain formation*

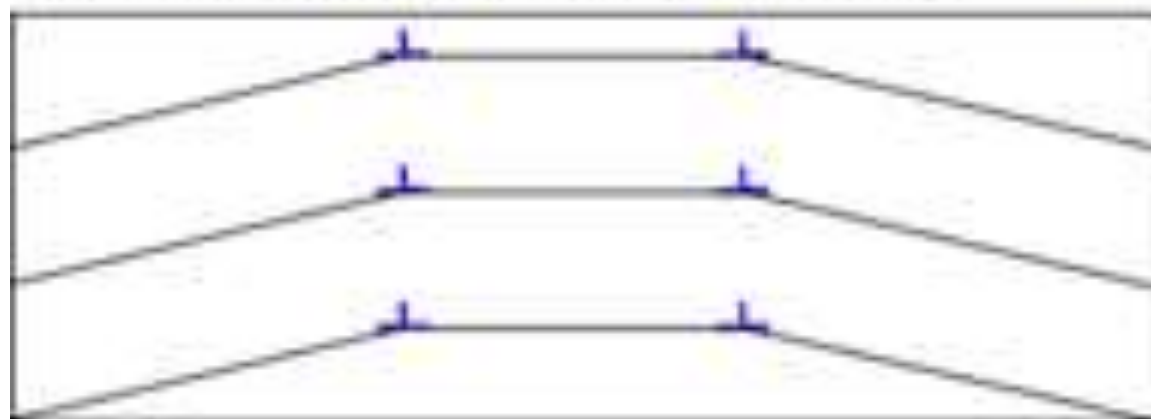
- (a) Excess dislocations in a bent crystal*
- (b) Dislocation climb*
- (c) Re-arrangement after polygonisation.*



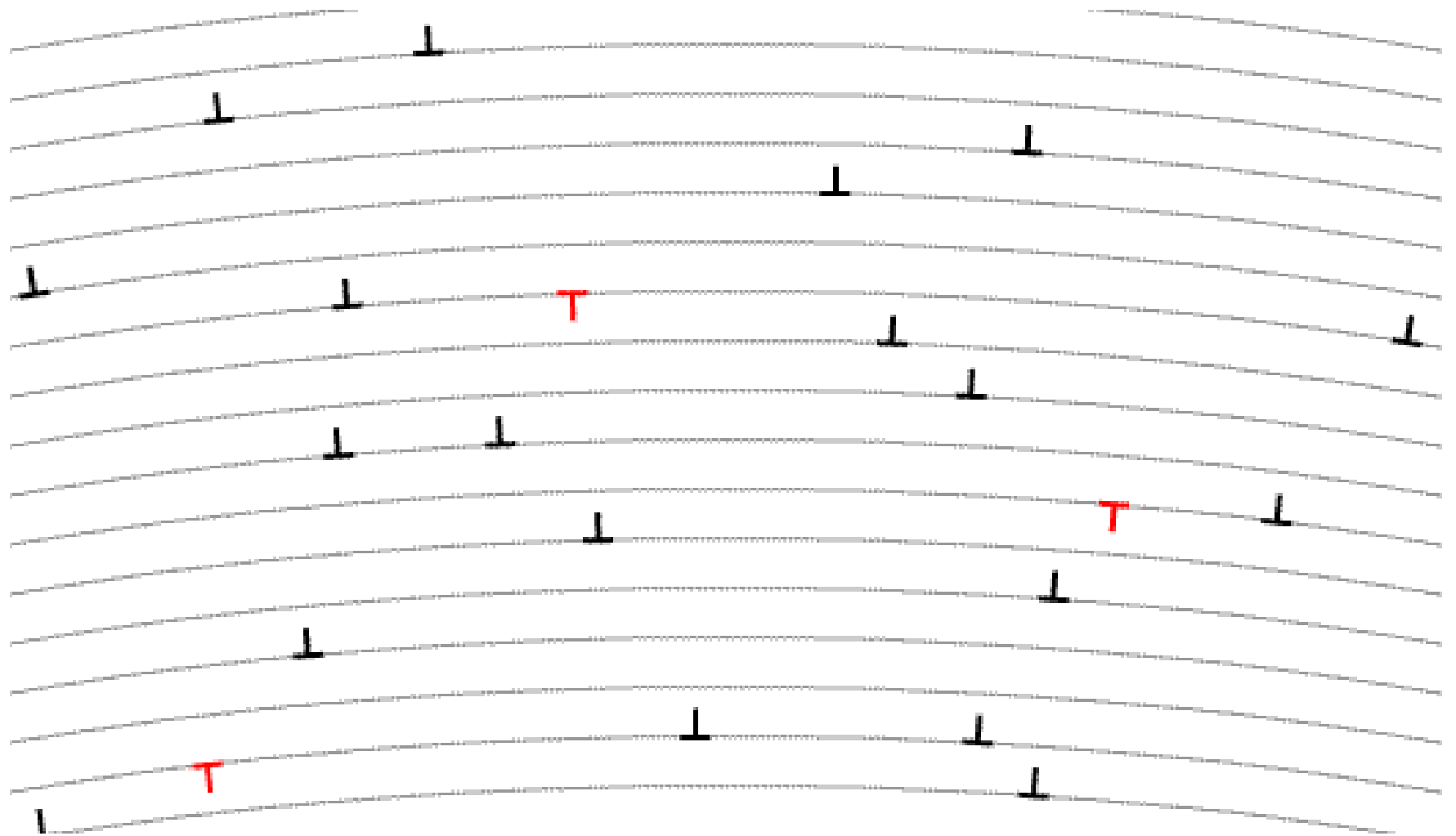
a) Bent lattice with dislocations of both sign



b) Annihilation of dislocations with opposite sign



c) Polygonization of the lattice



c) Grain boundary sliding

- When a poly crystalline material is heated, grain boundaries lose their strength and allow the adjacent grains to move relative to each other – grain boundary sliding
- This is a shear process promoted by increasing the temperature
- Due to sliding metals undergo a transition from transgranular fracture to intergranular fracture

Threshold for creep

- Temperature and level of applied stress influence the creep characteristics

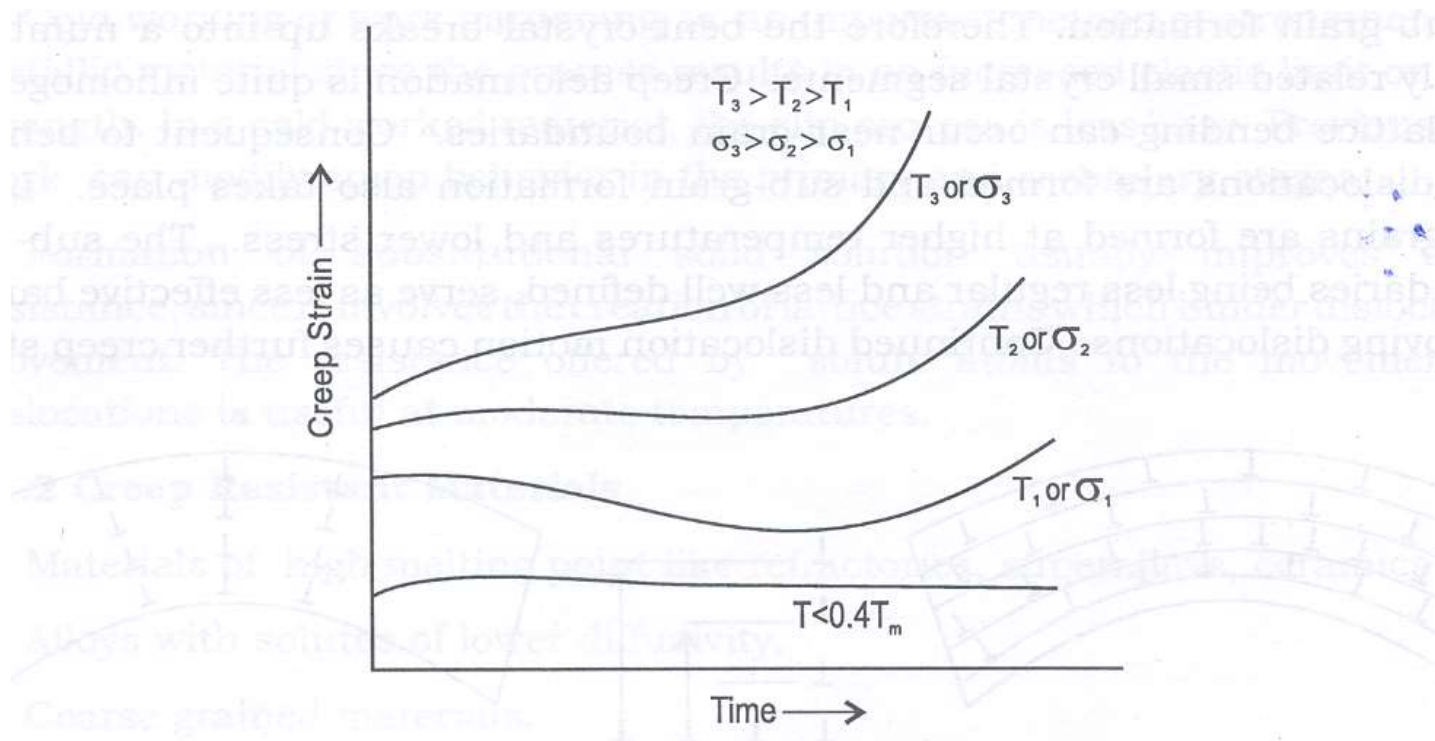


Figure 5.16 Influence of stress and temperature on creep

- Creep characteristics vary with material
- Higher the T_m of a metal better is its resistance to high temp creep
- The combination of stress level and temperature at which strain remains constant at the instantaneous deformation level – *threshold for creep*

Super plasticity

- Ability of some metals and alloys to deform as much as 2000 % at high temperatures and slow loading rates
- Conditions to achieve superplasticity:
 - very fine grain size(5-10 μm)
 - must be highly strain rate sensitive
 - high temp, ($>0.5T_m$)
 - low and controlled strain rate (0.01-0.001/s)

- Deformation mechanisms like grain boundary sliding, grain boundary diffusion are responsible for superplastic behaviour
- Applications:
- Metal forming processes (thermoforming, blow forming, vacuum forming etc) for production of large complex shaped products
- Disadvantage: low forming rate
- Compensated by elimination of subsequent operations

Composite Materials

- Is a physical mixture of two or more materials (or phases) that are chemically different and separated by a distinct interface.
- The materials are combined in such a way as to make the better use of their virtues, while minimizing to some extent their deficiencies.
- Thus by containing the advantages of different material classes, a composite achieves properties that could not be obtained from any of its constituents; at the same time it achieves properties superior to those of any of its constituents.

Need for development of composites

- **First:** due to advancement in technology there has been an increasing need for materials with unusual combination of properties.
- For aerospace applications we require materials which are light weight, strong, stiff, abrasion and impact resistant, not easily corroded and suitable for high temperature operations
- Such a combination of properties was impossible with the existing materials
- Strong materials like metals and ceramics are relatively dense and hence heavy and also increasing the strength results in a decrease in impact strength.

- Most of the metallic materials become soft and lose their strength at high temperatures
- So search for materials requiring a combination of conflicting properties resulted in the development of composite material
- Cermets (Cemented carbide – consists of extremely hard particles of refractory carbide ceramic (like WC, TiC) embedded in a metal matrix (such as Co, Ni etc.)), Fiberglass or Glass Fiber Reinforced polymers (GRP/GFRP), Carbon Fiber Reinforcement Polymers (CFRP) are examples
- **Second:** need for developing totally new materials with precise combination of properties needed for meeting the design requirements for specific tasks of the future.

What makes a composite

- Different material classes; **metals, ceramics and polymers** combined to produce the extraordinary materials
- The constituent phases must be **chemically dissimilar and separated by a distinct interface**
- Most of the composites are made up of continuous phase called **matrix** in which a stronger phase called **reinforcement** consisting of particles or fibres are embedded
- Properties of composites are a function of the properties of the constituent phases particularly the **geometrical and spacial characteristics of the dispersed phase**

- These characteristics refers to their:
 - concentration: volume fraction or the percentage of the dispersed phase
 - shape:
- particles: plate like, flake like, needle shaped, round(spherical) or polygon
- fiber: continuous or discontinuous
 - Size
- large (as in particle strengthened)
- small/fine (as in dispersion strengthened)
 - distribution: preferred distribution is uniform throughout the matrix, without direct contact with each other
 - orientation: aligned or random. Uniaxial, biaxial, tri or multiaxial

- Depending upon the nature, type and combination of the matrix and dispersed phases composite materials are classified into:

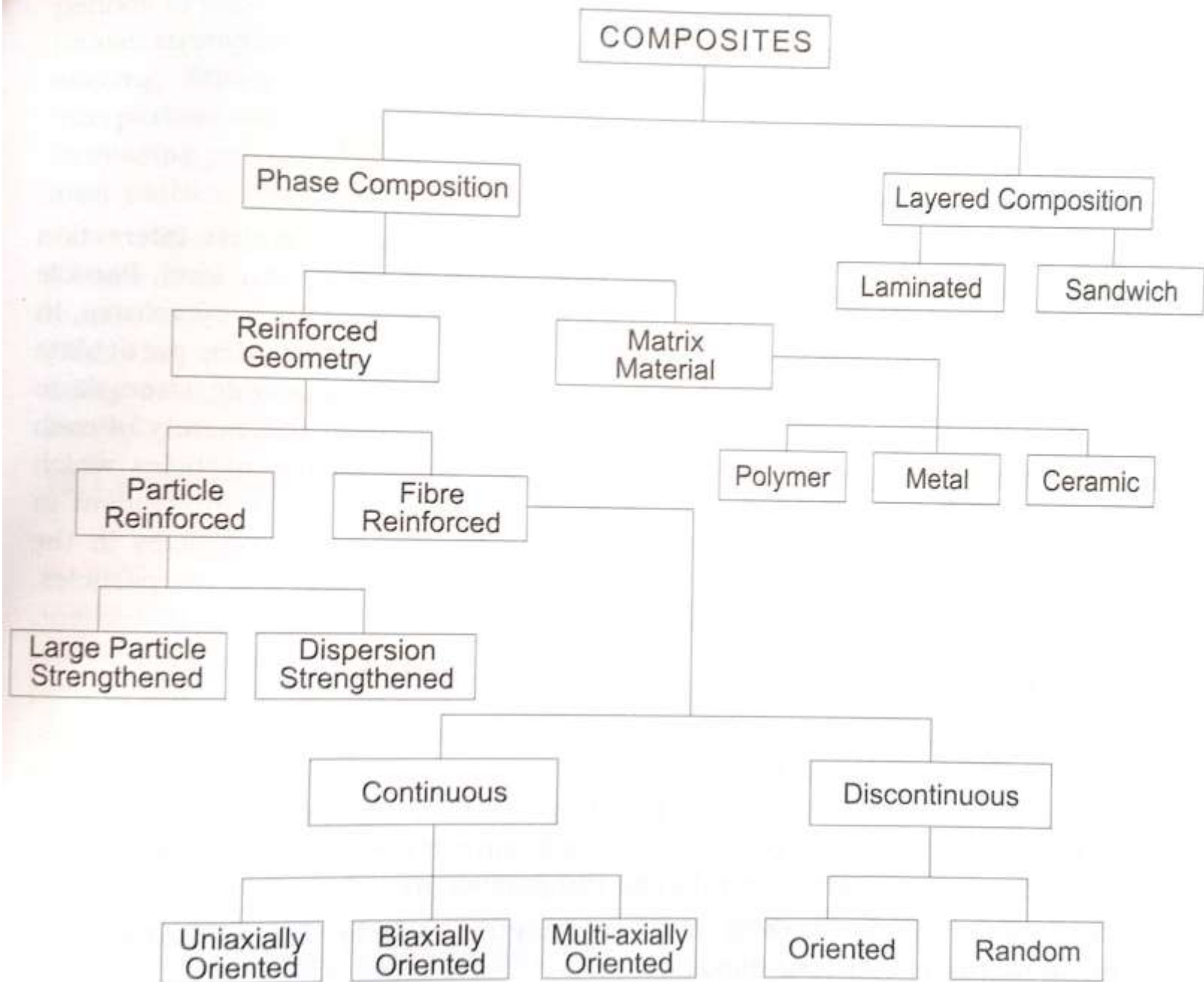


Figure 12.1 *Classification of Composites*

- **Role of constituent phases**

- Most composites have been developed to improve combinations of mechanical properties such as stiffness, toughness, strength and hardness at both ambient and high temperatures
- Some composites are designed and developed such that the applied load is borne by matrix, while in others the dispersed phase is to bear the major share of the load

Role of reinforcing phase

- In most of the composites the **load** on the material is mainly born by the **reinforcing phase**
- Reinforcing phase is usually of **low density, strong, stiff and thermally stable** in nature
- The reinforcing phase embedded in the matrix may be present in the form of either **particles or fibres**
- Accordingly composites are broadly classified as
 - A. Particle reinforced composites
 - Large particle reinforced composites
 - Dispersion strengthened composites
 - B. Fibre reinforced composites
 - Continuous fibre reinforced composites
 - Discontinuous fibre reinforced composites

Large particle reinforced composites

- The particle-matrix interaction is treated on a macroscopic level rather than atomic or molecular level
- Particle size is 1-50 μm
- Concentration usually ranges from 15-40% by volume
- In some special cases concentration and particle size may be even higher
- The particulate phase is **harder** and **stiffer** than the matrix
- The particles provide strength to the composite by **restraining the movement of the matrix** in the **vicinity of each particle**

- The matrix phase transfers the applied stress to the **particles** which **bear most of the applied load**
- The **degree of reinforcement or improvement in mechanical behaviour** depends on **the volume fraction of the particles** in the composite and the **strength of the bonding between the matrix and the particles**
- Mechanical properties are enhanced with increasing particulate content
- But there is an optimum volume fraction beyond which the effect is adverse because there will not be enough matrix phase to separate the particle from each other and also to cause effective bonding between matrix and the particles
- For **effective reinforcement** the particles should be **small** and **evenly distributed throughout the matrix**
- Particles may have different **geometrical shape, but preferably should be equiaxed**
- Eg.: Cermets- tungsten carbide or titanium carbide embedded in a metal matrix of cobalt or nickel
- Vulcanized rubber – carbon black in rubber
- Concrete – sand and gravel particulate in a slurry of cement matrix. Reinforced concrete is a multiphase composite

Dispersion strengthened composites

- In these **uniformly dispersed fine, hard and inert particles** of size **less than 0.1 μm** are used as reinforcement
- The volume fraction is between 5 – 15 %
- These particles are stronger than the pure metal matrix and can **be metallic, inter- metallic or non metallic.**
- Generally particles of **carbides, oxides and borides** are used as dispersoids
- Shapes of particles can be **round, disc or needle shaped**
- **Needle** shaped particles provide **maximum strength**

- **Dispersoids** strengthen the matrix **by impeding motion of dislocations** within the matrix and also due to the interaction between the dispersoids and the matrix
- This strengthening is **retained even at elevated temperatures** and that too for extended periods of time because the **dispersoids selected are unreactive with the matrix phase**, strengthening depends upon the size of the particles and the inter particle spacing
- **Strengthening is more effective with fine particles size and smaller interparticle spacing** (less than $0.1\ \mu\text{m}$), because of better pinning of dislocations
- Increasing particle size will result in lowering the number of particles and larger inter particle spacing which will lower the yield strength of the composite
- Eg: Sintered Aluminium Powder/Product in which fine Al_2O_3 particles are dispersed in pure aluminium matrix
- Thoria Dispersed Nickel in which fine particles of thoria are dispersed in nickel matrix
- Other examples are $\text{Cu-Al}_2\text{O}_3$, $\text{Cu-Zn-Al}_2\text{O}_3$, Cu-SiO_2 , and Cu-BeO

Fibre Reinforced Composites (FRC)

- A **polymer metal** or **ceramic** that has been drawn into a long thin filament is called a fibre (with length at least 100 times its diameter)
- An important characteristic of most materials is that a **small diameter fibre is much stronger than the bulk material or large diameter wires**
- In **bigger size wires** there is more probability for the presence of critical **surface flaws**, which can lead to fracture
- This is especially true in the case of wires and fibres of brittle materials

- As the **size** continuously **decreases strength** of fibre gradually **increases**
- This feature is used to the advantage in the fibre reinforced composites
- Also materials used for reinforcing fibres have high tensile strengths
- On the basis of diameter and character the filament materials are grouped into three types
 - **Whiskers**: very thin single crystals having extremely large length to diameter ratio. Very high strength
 - **Fibres**: Have very small diameters (5-10 μm) with moderately high strength
 - **Wires**: Relatively large diameters with minimum strength

- **Fibres** are **extensively** used as reinforcing phase in composites, while **whiskers and wires** are used for some **selected applications**
- Also the most important **composites** are those in which the **dispersed phase** is in the form of a **fibre**
- The **properties** of such composites are affected by the **kind, amount (volume fraction) and orientation of fibres**

- **Directional and non directional properties** in a given composite can be achieved using **oriented or random** distribution of fibres
- Since **fibres** are the principal **load bearing constituent**, in order to **maximise load** on to the fibres the **volume fraction** should be **maximized**
- Too large a value of volume of fraction is undesirable because it will lead to **poor coating of matrix on the fibre, poor bonding to the matrix and development of voids at the interface**
- Fibre reinforced composites are further sub classified, by fibre length, as continuous and discontinuous fibre composites

Influence of fibre length

- The **ability to transfer** the applied load from matrix to fibre depends on the **length of the fibre(l)**
- Some **critical length** is necessary for **effective strengthening and stiffening** of the composite material
- This **critical length** (l_c) is dependent on the **fibre diameter, its ultimate tensile strength and on the fibre matrix bond strength**
- For no. of fibre materials l_c is of the order of **1mm which is between 20 to 150 times fibre diameter**
- Fibres are classified as continuous when $l \gg l_c$ ($>15l_c$) and as short or as discontinuous when $l = l_c$ to $15 l_c$
- If the fibre length is **less than l_c** there is **no transfer of stress from matrix to fibre** and hence not effective as a reinforcement phase
- To have significant improvement in strength of the composite the fibres must be continuous

Influence of Fibre orientation and Concentration

- **The arrangement or orientation of the fibres relative to one another, the fibre concentration and distribution all have significant influence on strength and other properties of FRC.**
- Two extreme orientations are possible
 - (1) Arranged parallel to the longitudinal direction, called aligned or oriented
 - (2) Arranged in different directions called random
- **continuous fibres are generally aligned whereas discontinuous fibres are aligned, randomly oriented or partially aligned**

- Better overall properties are obtained when the distribution is uniform within the matrix
- When the **fibre orientation is aligned reinforcement efficiency is maximum in the direction parallel to the alignment and almost negligible in the transverse (perpendicular) direction**
- When fibres are **aligned randomly and uniformly distributed within a specific plane** the composites exhibit **isotropic properties in that plane with a reinforcement efficiency of about 40%**

- When the **fibres are randomly oriented and uniformly distributed in three dimensions** within the matrix the composite becomes **isotropic with a reinforcement efficiency of about 20%**

respectively.

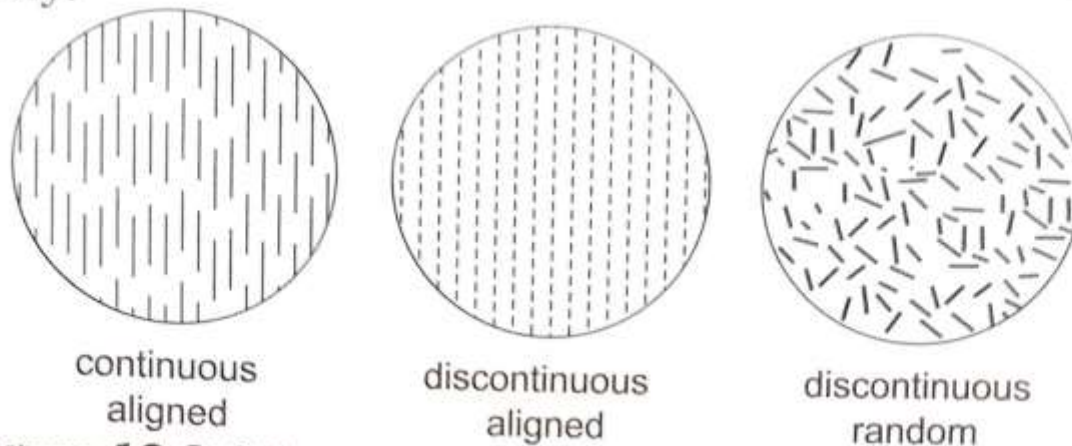


Figure 12.2 Schematic Representation of Fibre Orientation

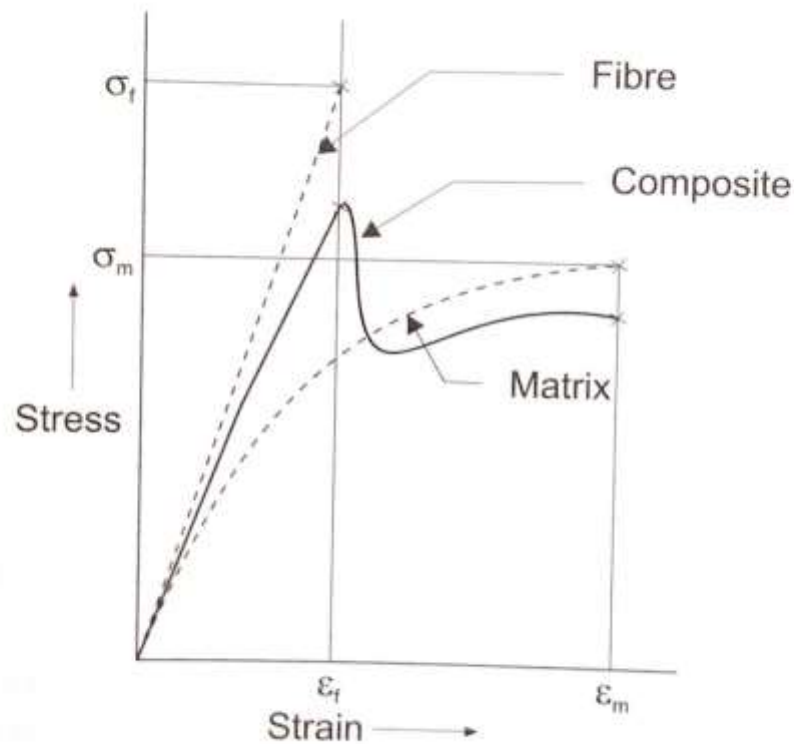


Figure 12.3 Schematic Stress- Strain curve for aligned fibre: Uniaxial loading

Fibre reinforcing materials

- In spite of their high strength **whiskers** are not utilized extensively as a reinforcement medium because they are **extremely expensive**
- Moreover it is **difficult or even impractical to incorporate whiskers into a matrix**
- Whiskers materials include graphite, silicon nitride, silicon carbide and aluminium oxide
- Fibres are extensively used as reinforcement phases where the **matrix phases are either polymers or ceramics**
- In a composite, the second phase in the **fibrous form is advantageous over the particle form**

- **Load transfer is more efficient with a fibrous phase** than with a particulate phase because the load transfer occurs through the interface between the matrix and the second phase
- For a **given volume fraction and same no. more interfacial area** is available with **fibrous** shape than the equiaxed particles.
- Some common fibre materials are **glass, carbon (graphite), silicon carbide, aluminium oxide, boron and polymer aramides(Kevlar)**
- **Fine wires** are used in special cases like radial reinforcement in automobile tyres, rocket castings and high pressure hoses. This materials include steel, molybdenum and tungsten

Role of Matrix Phase

- The primary function of the matrix phase in a composite is **to hold and bind the reinforcing phase in position** within it
- Any material that can fulfil this reinforcement may be used as a matrix material
- **Polymers and metals** are successful in this regard and are therefore widely used as matrices for majority of composites
- **Inorganic materials** such as **glasses and ceramics** are **not as successful** as polymers and metals
- The reasons are: they are **highly brittle, low tensile strength, and low strain to failure**

- However they are used in certain special cases because of their **high compressive strength, good strength at elevated temperatures and excellent resistance to oxidation**
- Other than holding the reinforcing phase the matrix has to perform many other functions
 - The **matrix binds and holds** the reinforcing phase in place
 - It acts as a **medium** through which the **external load is transmitted and distributed to the reinforcing phase**. In some cases the **matrix itself is the load bearing** constituent as in dispersion strengthened composites
 - Matrix **separates the fibres** from each other and keeps them separate entities. This prevents the propagation of the brittle cracks
 - Matrix protects the individual fibres from surface damage due to abrasion and oxidation

- Being ductile in nature the matrix improves **fracture toughness** of the composite
- Through the quality of its grip on the fibres(the interfacial bond strength) the matrix diminishes the **fibre pullout**. Also the ultimate strength of the composite depends on the magnitude of this bond strength
- In selected areas of application the matrix phase will be required to **withstand heat or cold, conduct or resist electricity, control chemical attack** etc.
- the usefulness of a material to act as a binding phase depends on a great extent on its ability to carry out some or all of the above mentioned functions. But there are often other considerations too

Polymer Matrix Composites (PMC)

- These composites are composed of a polymer resin (**a high molecular weight plastic**) in which are embedded the high strength, high stiffness fibres)
- PMCs have some advantages over metal or ceramic matrix composites because of their **low density, high specific strength, high specific stiffness, ease of fabrication, ability to be made into intricate shapes and low fabrication cost**

- In addition they also possess reasonably **good mechanical and electrical properties and good corrosion resistance**
- **Thermosetting plastics like epoxies and phenolics** which can withstand high temperatures are common polymer matrix materials with continuous fibres as the reinforcing phase
- Of these, **epoxies** have better mechanical and electrical properties but costlier

- **Phenolics**, though **cheaper** than epoxies can withstand **higher service temperatures**, but have relatively **lower mechanical properties**
- **Thermoplastics** are also used as matrix materials because they can be reworked, have low processing time, and at normal temperature they have an optimum combination of toughness, rigidity and creep resistance.
- **Glass, Graphite, carbon and aramid are the most common fibre materials** used with PMCs. To a lesser extent, other reinforcement materials like **boron silicon carbide, aluminium oxide** etc. are also used

Glass Fibre –Reinforced Polymer (GFRP) Composites

- Popularly known as **fibre glass**
- Contain **glass fibre** as **reinforcing phase** in a polymer matrix
- Glass fibre either **continuous** or **discontinuous** having a **diameter** between **3-20 μm** are provided from a type of glass known as **E-glass**
- **Glass fibres can easily be drawn into high strength fibres** and when embedded in a plastic matrix, produces a composite having very **high specific strength**.
- Glass reinforced plastic composites may be fabricated economically using a wide variety of composite manufacturing techniques

- GFRPs are **chemically inert** to a wide variety of corrosive environments
- In spite of having very **high strength**, they are **not very stiff and rigid**, hence **not suitable for structural applications in aerospace industry**
- Service temperature is also limited to about **2000° C**
- Still applications of fibre glass are many fold: **Automotive and marine bodies, storage containers, industrial floorings, plastic pipes etc.**

Carbon Fibre- Reinforced Polymer (CFRP) Composites

- **Carbon is a high performance fibre material** that is the most commonly used reinforcement in advanced polymer matrix composites
- The reasons are: of all the reinforcing fibre materials carbon fibres have the **highest specific strength and specific modulus, they retain their higher strength even at elevated temperatures**
- At **room temperatures** carbon fibres are **not affected by moisture** or a wide variety of **solvents and acids**
- Relatively **inexpensive manufacturing process**

- Carbon fibre diameter ranges between **4-10 μm**
- Fibres are generally coated with a **protective epoxy to improve bonding with the matrix phase**
- CFRP applications include: **aerospace structural components, filament wound rocket motor cases, sports and recreational equipment's, pressure vessels etc.**

Aramid Fibre Reinforced Polymer composites

- Aramids chemically known as **polyamide** (**paraphenylene terephthalamide**) fibres are **high strength, high modulus materials with strength to weight ratios even superior to metals**
- There are no. of aramid materials with different mechanical properties, the most common are having the trade names **Kevlar** and **Nomex**
- These materials are known for their **toughness, impact resistance and resistance to creep and fatigue failure**

- The fibres are **resistant to combustion** and **stable between the temperature range -200 to +200°C** retaining their high mechanical properties
- Chemically they are **attacked by strong acids** but relatively **inert to other solvents**
- Applications: **bullet proof vests and armor, sporting goods, tyres, ropes, missile cases, pressure vessels, automotive brake and clutch linings and gaskets**

Polymer Matrix Composites with other reinforcements

- **Boron fibre** reinforced composites are used in **military aircraft components, helicopter rotor blades, sporting goods etc.**
- **Silicon carbide and aluminium oxide fibres** are utilized in **military armor, rocket nose cones, circuit boards, tennis rackets etc.**

Metal Matrix Composites (MMC)

- Metal matrix composites are **not as popular** as polymer composites
- This is mainly because of the **high density of metals**
- However metals not only offer **greater strength and stiffness**, but also can **withstand much higher temperatures** than polymer matrices
- In practise metal matrices are used for those applications where **polymer matrices are unable to meet the service and engineering requirements**
- Moreover MMCs are capable of developing **better characteristics than their base metals**

- Hence reinforcing metal matrices are observed to have **improved specific strength, specific stiffness, abrasion resistance, creep resistance, thermal conductivity and dimensional stability**
- Some of the advantages of MMCs over PMCs are their **higher operating temperatures, non flammability and greater resistance to degradation by organic fluids**
- **MMCs** are much more **expensive** than **PMCs**
- Hence their use is somewhat restricted

- The most commonly used **metal matrices** are **aluminium, magnesium, titanium and their alloys**
- The other metal matrices which are used for special purpose include **super alloys, copper, nickel and silver**
- The reinforcement may be in the form of **particulates both continuous and discontinuous fibres and whiskers** in selected applications
- The concentration range is between **10-60%** by volume

- The suitable reinforcement for **low melting point metals** like **Al and Mg** can be **metals, ceramics or intermetallics**
- For **high melting point metals** like **super alloys and refractory metals**, high melting point fibres such as **oxides and intermetallics** can be used
- **Continuous fibre** materials include **carbon, silicon carbide, boron, aluminium oxide and the refractory metals**
- **Discontinuous reinforcement** consists primary of **silicon carbide and aluminium oxide**
- **MMCs with Al, Mg, and Ti** matrices are used in **automobile and aerospace applications**
- **MMCs with super alloys** as matrices are used for higher temperature applications like, **gas turbine blades** because of their high temperature creep and rupture properties, together with high temperature oxidation resistance and impact resistance
- **Copper and Silver based MMCs** are used for **electrical contacts** and such other applications

Ceramic Matrix Composites(CMC)

- Ceramic materials have **high melting points** and **good resistance to oxidation and deterioration at elevated temperature**
- But they are **brittle with very low tensile strength, impact resistance and thermal shock resistance**
- The primary objective for developing CMCs was to **enhance the toughness while retaining the high temperature properties**
- The fracture toughness of ceramic materials have been improved significantly by embedding particles, fibers or whiskers of another suitable material

- The improvements in the fracture properties result from the interaction between the advancing cracks and the dispersed phase particles
- **Crack initiation** normally occurs with the **matrix phase** while the **crack propagation** is **impeded or hindered** by the **embedded second phase particles**
- Eg.: small particles of partially stabilized Zirconia are dispersed within the matrix material Al_2O_3
- Whiskers of SiC or Si_3N_4 are also used as second phase materials

- CMCs are used for components in **automobile** and **aircraft gas turbine engines**, as **cutting tool inserts for machining hard metal alloys**

Carbon carbon composites

- **Carbon carbon composites** are developed by reinforcing the carbon matrix with carbon fibres
- **High elastic strength** and **elastic modulus** are achieved in these composites which are **retained even at high temperatures** of the order of 2000°C
- Carbon – carbon composites are used in **rocket motors**, as **frictional material in aircrafts** and in **high performance automobiles**

Hybrid Composites

- These are obtained by using **two or more different kinds of fibres in a single matrix**
- Hybrids have a **better combination of properties** than the composites containing only a single type of fibre
- A variety of fibre combinations are used but in most common applications **carbon and glass fibres** are incorporated into a polymer matrix
- Principal applications of hybrid composites are for **structural components of light weight land, water and air transport vehicles, sporting goods and light weight orthopaedic components**

Applications of composites

Aircraft and Aerospace applications

- A wide range of load bearing and non load bearing components are made using composites like light weight, high strength glass fibre, carbon fibre and Kevlar fibre polymer composites
- Parts like windows, ceiling panels, overhead storage bins, consoles, landing gear doors etc. of aerospace vehicles
- For structural components like body, wings, rudder, helicopter rotor blades and propellers requiring better strength; MMCs of Al, Mg, or Ti are used
- Compressors and fan blades are made of MMCs with Al or super alloys as matrices and Borosilicon or refractory metal fibres
- For elevated temperature applications like rocket motors and gas engine components, carbon-carbon composites are used

Automotive applications

- Light weight, low cost polymer matrix composites are used for body components
- For engine block, piston, piston rods, connecting rods, push rods, chases, motor cycle frame etc, Al-SiC composites are used
- MMC composites are used for transmission shafts
- For brake and clutch lining, gaskets, epoxy/polyester matrix-aramid fibre composites are used
- Rubber-carbon or epoxy-aramid composites are used for manufacture of tyres

Marine Applications

- Applications include surface vessels, offshore structures and underwater applications
- A vast range of components are made of GRP
- Some examples are hull, body parts, ladder, walkways, storage tanks, piping, flooring etc

Sporting Industry

- High strength coupled with rigidity and light weight of many composite materials make them ideal for many sports goods
- Items like tennis rackets, hockey sticks, cricket bats, golf clubs, vaulting poles, skiing poles, archery equipment, surf boards, canoes, and skate boards are some examples of composite sporting goods
- PMCs of different matrix-fibre combinations are generally used for these applications

Biomaterials

- Carbon fibre reinforced plastics and carbon components are in use for prosthetic applications like orthopedic fixation plates, femoral stems, hip replacements, jaw remodeling etc.
- Certain ceramic composites are used in dental applications

Other Engineering and Industrial Applications

- Injection moulded reinforced thermoplastics and polyester composites are extensively used for many consumer items of domestic use
- Kitchen equipment, electrical equipment, television and computer casings, furniture, helmets and such other gadgets are some examples
- Storage and pressure vessels, pipings, valves, centrifuges etc employed in chemical engineering industries also are made of suitable composite materials like GRP or CRP
- Electrical industry makes use of Cu/Ag matrix composites as electric contact materials
- Printed circuit boards, casings for electrical equipments, high strength insulators are also made of suitable composite materials
- GRP and CRP composites are rapidly replacing wood in civil engineering application
- Glass reinforced cement (GRC) products are gradually replacing ordinary structural cement based composites

INTERMETALLICS

- Intermetallic or intermetallic compound or intermetallic phase is a solid phase containing two or more metallic elements, with optionally one or more non metallic elements
- There is a stronger atomic bonding than in a solid solution
- Intermetallic compounds are a special type of substitutional solid solution with higher amount of solute atoms
- Solid solutions have the solute atoms and solvent atoms distributed within the lattice type of the solvent material
- Intermetallics have ordered arrangement of the different atom types
- In the intermetallics atomic bonding is metallic covalent while in solid solution alloys atomic bonding is metallic only

- The following conditions are to be satisfied for the formation of an intermetallic compound
- a) it has to be formed by at least two different elements (preferably metals, but there are exceptions)
- b) it must have a different crystal structure from the one observed in the pure components
- c) The component elements should be having opposite electrochemical nature

- An intermetallic compound is a chemical compound just like H_2O or CH_4 or any other compound
- It exists with its own features and characteristics, different from its constituents
- Water is nothing like hydrogen or oxygen
- Generally intermetallic compounds are formed when one metal (eg.: Mg) having chemical properties which are strongly metallic and the other metal (eg.: Sb, Sn, Bi) having chemical properties which are only weakly metallic
- Eg.: Mg_2Sn , Mg_2Pb , Mg_3Sb_2 , Fe_3C , Zr_3Al , Al_6Mn , Ti_3Al and Mg_3Bi_2
- Have higher melting point than either of the parent metal
- They are always very hard and brittle

- There are certain intermetallic compounds having fixed composition
- These are called stoichiometric intermetallic compounds
- Iron carbide is an example which imparts strength to steel
- In a phase diagram a stoichiometric intermetallic compound will exist as an essentially straight vertical line (It could be at one of the edges of the diagram)
- On the other hand, non stoichiometric intermetallic compounds have a range of compositions and are also called intermediate solid solutions
- In Cu-Al alloy system the intermediate solid solution CuAl_2 act as a strengthening agent in this alloy system

- Intermetallics like Ti_3Al and Ni_3Al can exist as stand alone materials having high strength and usable ductility at high temperatures
- The intermetallic compound platinum silicide is used in microelectronics and Nb_3Sn is useful as a superconductor
- Titanium aluminides, TiAl and Ti_3Al are considered for a variety of applications including gas turbine engines
- The intermetallic compound families include the borides, carbides, hydrides, nitrides, silicides, and aluminides, of the transition metal elements of Group V and VI in the periodic table combined with semimetallic elements of small diameter
- More than 1000 possible compounds fit this definition with approximately 200 of them having melting points above 1500°C
- There can be solid solutions where one constituent is an intermetallic compound and the other constituent is an element and there could be a eutectic point between them

MARAGING STEEL

- Maraging steels are carbon free iron nickel alloys with additions of cobalt, molybdenum, titanium and aluminium,
- The term maraging (age hardening) is derived from the strengthening mechanism which is transforming the alloy to martensite with subsequent age hardening
- Air cooling the alloy to room temperature from 820°C creates a soft iron nickel martensite which contains molybdenum and cobalt in super saturated solid solution
- The martensite transformation occurs without quenching
- Tempering at 480 to 500°C results in strong hardening due to precipitation of a number of intermetallic phases including nickel-molybdenum, iron-molybdenum, and iron-nickel varieties
- Freedom from decarburization, minimal distortion during aging, good formability, machinability, and weldability, and a low coefficient of thermal expansion are certain other features of maraging steels
- With yield strength between 1400 and 2400MPa maraging steels belong to the category of ultra high strength materials
- The high strength is associated with excellent toughness, resistance to crack propagation and weldability
- Applications: rocket motor casings, light aircraft landing gear, power shafts, low temperature tooling etc.

SUPERALLOYS

- Are high performance alloys which exhibit high strength and creep resistance at elevated temperatures
- Commonly classified into 3 main categories: nickel-based, cobalt-based and iron-based
- The superalloys develop high temperature strength and creep resistance through the mechanisms of solid solution strengthening, precipitation hardening and dispersion hardening
- Other important properties of these are fatigue life, phase stability, oxidation and corrosion resistance

- Typical applications are in the aerospace and industrial gas turbine blades, for hot sections of aircraft engines and bimetallic engine valves for use in diesel and automotive applications
- Hastelloy, nichrome, kanthol, udimet and inconel are nickel based superalloys which possess excellent thermal shock resistance and high electrical resistivity
- Cobalt based superalloys contain chromium, nickel, molybdenum and tungsten as alloying elements
- Stellite, haynes and vitallium are typical alloys of this category
- Incolony is an example of iron nickel based super alloy which typically contain 46% Ni and 21% Fe in addition to chromium is used in heat exchangers
- Stainless steel containing Al, Si, and higher amounts of Cr and Ni also qualify as superalloys

NUCLEAR MATERIALS

- When a large fissile atomic nucleus such as uranium-235 or plutonium-239 absorbs a neutron, it may undergo nuclear fission
- The heavy nucleus splits into two or more lighter nuclei, releasing kinetic energy, gamma radiation and free neutrons collectively known as fission products
- A portion of these neutrons may later be absorbed by other fissile atoms and trigger further fission events, which release more neutrons and so on
- The reaction can be controlled with the help of neutron moderators which reduce the velocity of fast neutrons
- Increasing or decreasing the rate of fission has a corresponding effect on the energy output of a nuclear reactor

- In a nuclear reactor the primary group of materials include fuel, moderator and coolant
- The secondary group includes structural and shielding materials
- Reactors are extremely sensitive to the materials used in their construction
- The structural materials need to show a superior mechanical and chemical behaviour to guarantee the safe operation of the reactor during its whole lifetime

Nuclear fuels

- Is a material that can be consumed to derive nuclear energy by analogy to chemical fuel that is burned for energy
- Are the most dense sources of energy available
- Most nuclear fuels contain heavy fissile elements that can be made to undergo a nuclear fission chain reaction in a nuclear reactor
- The fuel is normally used in the form of rods, plates or wires which are clad or coated with a suitable material

Moderator Materials

- Ideal moderator material should have a negligible neutron capture cross section and a high neutron scattering cross section
- In a reactor it is convenient if the moderator can also serve as coolant
- 3 popular moderator materials are : graphite, ordinary water and heavy water
- Graphite is easy to fabricate and presents no contaminant problems
- Light water is the cheapest moderator material
- Heavy water is expensive, its use as a moderator will result in a more compact reactor

Structural Materials

- The structural materials of concern in a nuclear reactor are those materials used:
 - To construct the reactor itself
 - To clad the fuel in order to contain the fission products
 - To form conduits for the coolant
 - To add strength and rigidity to control rods and other moving parts
- The cladding material for the fuel elements must be resistant to abrasion, resist corrosion, be resistant to radiation damage and bond well to uranium
- Al, Stainless steel, Zirconium and zirconium alloys like zircalloy are being used as cladding materials

- The engineering materials utilized for the structural applications are concrete, steel both carbon and stainless, which are widely used in large amounts with much smaller quantities of nickel alloys, titanium, zirconium, hafnium, polymer and glass
- Concrete is used extensively for building foundations and also as a biological shielding in a number of operating areas
- Concrete offers the most cost effective way of achieving this
- Carbon steels are used extensively for structural steel work, cranes, lifting beams, drive shafts, reinforcing bars, bolts etc.
- Austenitic stainless steels are used extensively as the main material of construction for the process vessels and piping
- The advantages of austenitic stainless steels are their inherently high resistance to corrosion in oxidising media such as nitric acid
- Nickel alloys are generally used in situations involving high temperatures
- Inconel alloy is suitable for this purpose
- Other uses for nickel alloys have been found in nuclear plants which treat the large amounts of solvent arising from the solvent extraction process
- Ceramic materials are necessary for several critical applications in fusion power reactors or as alternative for metallic materials
- The leading candidate ceramic material for this is SiC because of its low induced radioactivity, capability of withstanding high temperatures and abundant availability

SMART MATERIALS

- Smart or intelligent materials have one or more properties that can be significantly changed in a controlled fashion by external stimuli such as stress, temperature, moisture, pH, electric or magnetic fields
- Refers to a class that is highly responsive and have inherent capability to sense and react according to changes in the environment
- A smart material should consist of a sensor (that detects an input signal) and an actuator (that performs a responsive and adaptive function)

- In simple words “smart material responds to a stimulus with one predictable action”
- Normal materials have limited responses while smart materials have appropriate responses but response is the same every time
- Examples are photo chromatic glass that darkens in bright light; low melting point wax in a fire sprinkler which blocks the nozzle until it gets hot; embedded optical fibres whose broken ends reflect light back

Advantages

- No moving parts
- High reliability
- Low power requirements
- Provide new capabilities that are presently not possible

Applications

- Active control inceptors using smart material motion control
- Removing toxic pollutants from water
- Advanced liquid crystal displays
- Artificial muscles
- Embedded sensors

Types of smart materials

Piezoelectric materials

- Materials which produce a voltage when stress is applied
- Since this effect also applies in the reverse manner a voltage across the sample will produce stress within the sample
- Suitably designed structures made from these materials can therefore be made to bend, expand or contract when a voltage is applied
- These can operate as both actuators and sensors
- In actuator mode elongation takes place when an electric field is applied
- In sensor mode a voltage is produced when a mechanical strain is applied
- Some applications are in ink jet printers, medical diagnostics, high frequency stereo-speakers, computer keyboards and microphones

Shape memory alloys

- Shape memory alloys and shape memory polymers are materials in which large deformation can be induced and recovered through temperature changes or stress changes
- The large deformation results due to martensitic phase change
- A shape memory alloy is an alloy that remembers its original, cold forged shape: returning the predeformed shape by heating
- Currently SMAs are mainly applied in medical sciences, electrical, aerospace and mechanical engineering
- This material is a lightweight, solid state alternative to conventional actuators such as hydraulic, pneumatic, and motor based systems

Magnetostrictive materials

- exhibit change in shape under the influence of magnetic field and also exhibit change in their magnetization under the influence of mechanical stress
- These materials expand and contract with the application of magnetic fields
- Some of the applications are in high power sonar transducers, motors and hydraulic actuators

Magnetic Shape memory alloys

- Or ferromagnetic shape memory alloys are ferromagnetic materials exhibiting large changes in shape and size in response to a significant change in the magnetic field

BIOMATERIALS

- Are used to make devices to replace a part or a function of the human body in safe, reliably, economically and physiologically acceptable manner.
- A biomaterial is essentially a material that is used and adapted for a medical application.
- Biomaterials are used for heart valve, for hip implants, in dental applications, surgery and drug delivery.
- A biomaterial is any material, natural or manmade that comprises whole or part of a living structure or biomedical device which performs, augments or replaces a natural function
- A biomaterial used for implant should possess some important properties for long term usage in the human body without rejection

Problem Area	Examples
Replacement of diseased or damaged part	Artificial hip joint, kidney dialysis machine
Assist in healing	Sutures, bone plates, screws
Improve function	Cardiac pacemaker, intraocular lens
Correct functional abnormality	Cardiac pacemaker
Correct cosmetic problem	Augmentation mammoplasty
Aid to diagnosis	Probes and catheters
Aid to treatment	Catheters, drains

Uses of Biomaterials

Organ	Examples
Heart	Cardiac pacemaker, artificial heart valve, total artificial heart, blood vessels
Lung	Oxygenator machine
Eye	Contact lens, intraocular lens
Ear	Cochlear implant
Bone	Bone plate, intramedullary rod
Kidney	Catheters, stent, Kidney dialysis machine
Bladder	Catheter and stent

Biomaterials in Organs

The most common classes of materials used as biomedical materials are polymers, metals, ceramics and composites

Polymeric Biomaterials

- They are used as implants or part of implant systems
- The polymeric systems include acrylics, polyamides, polyesters, polyethylene, polysiloxanes, polyurethane and a no. of reprocessed biological materials
- Applications include artificial heart, kidney, liver, pancreas, bladder, bone cement, catheters, contact lenses, cornea, and eye lens replacements, external and internal ear repairs, heart valves, cardiac assist devices, implantable pumps, joint replacements, pacemaker, encapsulations, soft tissue replacement, artificial blood vessel, artificial skin and suture.

Metallic Biomaterials

- Metals are used as biomaterial due to their excellent electrical and thermal conductivity and mechanical properties
- Some metallic parts are used as passive substitutes for hard tissue replacement such as
 - Total hip
 - Knee joints
 - Bone plates and screws
 - Spinal fixation devices
 - Dental implants
 - Vascular stents
 - Catheter guide wires

- The first metal alloy developed specifically for use as biomaterial is the vanadium steel which was used to manufacture bone fracture plates and screws
- The biocompatibility of the metallic implant is of considerable concern because these implants can corrode in prolonged usage
- The consequences of the corrosion are the disintegration of the implant material and the harmful effect of corrosion products on the surrounding tissues and organs

Stainless steel

- SS of different types are used successfully as biomaterials
- Type 302 SS is stronger and more resistant to corrosion than the vanadium steel
- Type 316 SS contains a small percentage of molybdenum to improve the corrosion resistance in chloride solution
- Type 316L SS carbon content is reduced from 0.08 to a maximum amount of 0.03 % for better corrosion resistance to chloride solution
- The inclusion of molybdenum enhances resistance to pitting corrosion in salt water
- 316L SS may corrode in the body under certain circumstances in highly stressed and oxygen depleted region, such as the contacts under the screws of the bone fracture plate
- These SS are suitable for use only in temporary implant devices such as fracture plates, screws and hip nails

CoCr Alloys

- Two types of cobalt chromium alloys popularly used as biomaterials are:
- CoCrMo alloy (Cr(27-30%), Mo(5-7%), Ni(2.5%)) has been used for many decades in dentistry and in making artificial joints
- CoNiCrMo alloy (Cr(19-21%), Ni (33-37%), and Mo (9-11%)) has been used for making the stems of prostheses for heavily loaded joints, such as knee and hip

- ASTM lists four types of CoCr alloys for surgical implant applications
 - CoCrMo alloy (Cr(29-30%), Mo(5-7%), Ni(2.5%))
 - CoCrWNi alloy (Cr(19-21%), W(14-16%), Ni(9-11%))
 - CoNiCrMo alloy (Ni(33-37%), Cr(19-21%), Mo(9-11%))
 - CoNiCrMoWFe alloy (Ni(15-25%), Cr(18-22%), Mo(3-4%), W(3-4%), Fe(4-6%))
- The two basic elements of CoCr alloys form a solid solution of upto 65%Co
- The Mo is added to produce finer grains which results in higher strength after casting
- The Cr enhances corrosion resistance as well as solid solution strengthening of the alloy
- The CoNiCrMo alloy contains approximately 35% Co and Ni each
- The alloy is highly corrosion resistant under stress

Titanium and its Alloys

- They are getting attention in both medical and dental fields because
 - Excellent biocompatibility
 - Light weight
 - Excellent balance of mechanical properties
 - Excellent corrosion resistance
- They are commonly used for implant devices replacing failed hard tissue like artificial hip joints, artificial knee joint, bone plate, dental implants, dental products, such as crowns, bridges and dentures
- The titanium alloy Ti6Al4V is widely used to manufacture implants
- The main alloying elements of this alloy are Aluminium(5.5-6.6%) and vanadium (3.5-4.5%)
- The addition of alloying elements to titanium enables it to have a wide range of properties
 - Al tends to stabilize the alpha phase; it increases the transformation temperature from alpha to beta phase
 - Vanadium stabilises the beta phase by lowering the temperature of transformation from alpha to beta

Ceramic Biomaterials

- The most important properties for a biomaterial like, non toxic, non carcinogenic, non allergic, non inflammatory, biocompatible and biofunctional for its lifetime in the host are all satisfied by certain ceramic materials
- Ceramics such as alumina, zirconia, silicone nitrides, and carbons are inert bioceramics
- Certain glass ceramics are semi-inert(bioreactive) and calcium phosphates and calcium aluminates are resorbable ceramics

Composite Biomaterials

- Composites contain two or more distinct materials
- In biomaterials it is important that each constituent of the composite be biocompatible
- The interface between constituents should not be degraded by the biological environment
- Some applications of composites in biomaterial applications are: dental filling composites, reinforced methyl methacrylate bone cement and ultra high molecular weight polyethylene and orthopedic implants with porous surfaces

- The dental composite resins consists of a polymer matrix and stiff inorganic inclusions
- The inorganic inclusions confer a relatively high stiffness and high wear resistance on the material
- Available dental composite resins use quartz, barium, glass and colloidal silica as fillers.
- Rubber used in catheters, rubber gloves, etc. is usually reinforced with very fine particles of silica to make the rubber stronger and tougher

CERAMICS

- Ceramic was originated from the greek word kermikos **meaning burnt stuff**
- The ceramic materials achieve their properties through a **high temperature processing** called **firing**
- Traditional ceramic materials like bricks, tiles, porcelain and glasses were developed from clay as raw material
- A ceramic is a compound formed by the combination of **metallic** and **nonmetallic elements**
- All metal oxides, carbides, nitrides, and silicates are considered as ceramics
- Refractories, glasses, abrasives, clays, enamels, cement etc are some examples for ceramic materials

- These materials possess **high hardness, brittleness, high melting point and chemical inertness**
- The ceramics also are **good electrical insulators**
- Most of these properties are due to the presence of **strong ionic and covalent bonds**
- The **crystal structures** of these materials are influenced by **electrical charges and relative sizes of the component ions**

- The **metallic ions** or **cations** are **positively** charged while the **nonmetallic ions** or **anions** are **negatively** charged
- The ratio r_c/r_a is known as **radius ratio** where r_c is the radius of cation and r_a is that of anion
- Each cation likes to have as many nearest anion neighbours as possible
- The anions also prefer to have maximum no. of cations as nearest neighbours
- At the same time the anions around a cation need to be in contact with the cation so that a **stable crystal structure is obtained**

- For a specific coordination no there is a critical radius ratio for which the cation-anion contact is established
- The size of an ion or ionic size depends on the coordination no, the charge of the ion and several other factors
- The ionic radius increases as the coordination no increases

Crystal Structures of Ceramic Materials

AX type crystal structure

- Ceramic materials having equal no. of cations and anions are referred to as AX compounds where A represents cation and X represents anion
- Most popular AX crystal structure is that of NaCl
- Coordination number for both anion and cation is 6 and the radius ratio is between 0.414 and 0.732nm
- Some of the ceramic materials having this type of crystal structure are MgO, MnS, LiF, FeO
- In Cesium Chloride crystal structure the coordination no. is 8
- In some other ceramic materials like ZnS, ZnTe, and SiC coordination no is 4
- AX type of compounds results when the anions and cations have the same magnitude of charges

A_mX_p type crystal structure

- In certain compounds the anions and cations may not qualify for the AX type structure
- Here compound may be formed with the formula A_mX_p where m is not equal to p
- Common example is CaF_2 in which a radius ratio of 0.8 and coordination no of 8
- Some other compounds of this structure are ZrO_2 , PuO_2 and ThO_2

$A_m B_n X_p$ type crystal structure

- Category of ceramic compound having more than one type of cations
- Chemical formula is $A_m B_n X_p$
- Examples are $BaTiO_3$, $SrZnO_3$, $MgAl_2O_4$ and $FeAl_2O_4$
- Barium titanate follows FCC crystal structure with coordination no 12 for Ba^{2+} , 6 for Ti^{4+} , and 6 for O^{2-}

Applications of Ceramic Materials

- Glasses
 - Glasses
 - Glass Ceramics
- Clay Products
 - Structural clay products
 - Whiteware
- Refractories
 - Fireclay
 - Silica
 - Basic refractories
 - Special refractories
- Abrasives
- Cements
- Advanced ceramics

Glass

- Glass is used to describe a **particular state of matter known as glassy state** which is obtained when **liquid cools without crystallisation**
- So glass can be called a **supercooled** liquid
- It can be considered as a very viscous liquid when it is solidified
- It has apparent physical properties of a solid like **brittleness, hardness, transparency and chemical inertness**

- The basic **ingredient** for the glasses is **silica sand**
- Other components like **CaCO₃ (Limestone)**, **Na₂CO₃ (soda ash)**, **CaO**, **Na₂O** etc are also added to make different types of glasses
- Different combinations of silica and these oxides lead to specific characteristics and hence applications
- **Two prime properties** of this group of materials are the **optical transparency** and the **ease of fabrication** (in comparison with other ceramic materials)

- Glasses are popularly used in construction and engineering applications
- **Glass fibres** are used for **insulation purposes** and as **reinforcing materials** along with plastics
- **Safety glasses** used in **automobiles** are laminated one which is a sandwich of a tough plastic material between two sheets of glass

Glass-Ceramics

- The **non crystalline glass** can be subjected to high temperature treatment to convert it into a **crystalline material**
- The fine grained polycrystalline material obtained is called **glass ceramic**
- The transformation is similar to the phase transformation process in metallic alloys
- The glass ceramic are found when the cooling rate is more than the critical cooling rate for glass
- The glass ceramics have a number of characteristics that make them suitable for specific applications

- Some of these are:
 - Relatively high mechanical strength
 - Low coefficient of thermal expansion
 - High temperature resistance
 - Good dielectric properties
 - Good biocompatibility
 - Ease of fabrication
- Most common applications are **table ware, oven ware, oven windows, electrical insulators, heat exchangers and for architectural cladding**

Clay Ceramics

- One of the most widely used ceramic raw material is clay
- Clay is used to make structural clay products like bricks, tiles and pipes
- The other category of ceramics become white after the high temperature firing and hence called whiteware
- Porcelain, pottery, tableware, and sanitary ware come under this category

Refractory Ceramics

- These materials can withstand high temperature without decomposing or melting and provide thermal insulation even in severe environments
- Typical applications include furnace linings for glass manufacturing, metal refining, and heat treatments
- Based on the composition the refractory ceramics can again be classified into fireclay, silica, basic and special refractories

- High purity fireclay, alumina and silica are the ingredients of **fireclay refractories**
- Thermal insulation of structural members in furnaces is the principal application of bricks made of fireclay refractory ceramics
- Silica is the principal ingredient in **silica refractories** and are used for high temperature load bearing applications
- Typical applications is for arched roofs of steel and glass making furnaces
- The refractories that are rich in magnesia (MgO) are called **basic refractories**

- These may also contain Ca, Al, and Fe compounds
- Major application of **basic refractories** is in steel making open hearth furnaces where alkaline (basic) slags are involved
- Refractory materials like alumina, silica, magnesia, beryllia, zirconia and carbide compounds can be specially processed with high purity to make them suitable for special applications
- Some of these special applications are electrical heating elements, crucible material, internal furnace components etc
- The processing under high purity makes the **special refractories** highly expensive also

Abrasives

- Abrasive ceramics are used to **grind or cut** away some other soft material
- Abrasives possess **high hardness and wear resistance** along with **higher toughness**
- Silicon carbide, tungsten carbide, aluminium oxide and silica sand are some commonly used abrasive materials
- These are used in different forms as bonded to grinding wheels as coated on paper or cloth and as loose grains depending on the applications

Cements

- The cements when mixed with water forms a paste which subsequently sets and hardens at room temperature
- **Portland cement, plaster of paris and lime** are in this group of ceramics
- Among these portland cement is the widely used one
- Its properties like setting time and final strength depend on the composition of its ingredients (clay, lime, gypsum etc)

Advanced Ceramics

- Properties like electrical, magnetic, optical and their combinations unique for ceramic materials are made use of by the advanced ceramic materials
- Some areas of application of these materials are in optical fibre communication systems, micromechanical systems and piezoelectric devices
- Lead zirconate titanate (PZT) is a ceramic material that shows a good **piezoelectric** effect
- PZT based compounds are composed of the chemical elements lead and zirconium and the chemical compound titanate which are combined under extremely high temperatures
- These compounds are used in the manufacturing of ultrasound transducers, in the manufacturing of ceramic capacitors for sensors and actuators
- PZT is the most common piezoelectric ceramic in use today

- Being piezoelectric it develops a voltage across two of its faces when compressed (useful for sensor applications) or physically changes shape when an external electric field is applied (useful for actuator applications)
- Being **pyroelectric** this material develops a voltage difference across two of its faces when it experiences a temperature change
- As a result it can be used as a sensor for detecting heat
- It is also **ferroelectric** which means it has a spontaneous electric polarization (electric dipole) which can be reversed in the presence of an electric field
- When PZT is modified by doping it with lanthanum the resulting material is called lanthanum-doped lead zirconate titanate which is also called lead lanthanum zirconate titanate (PLZT)

