Module 6

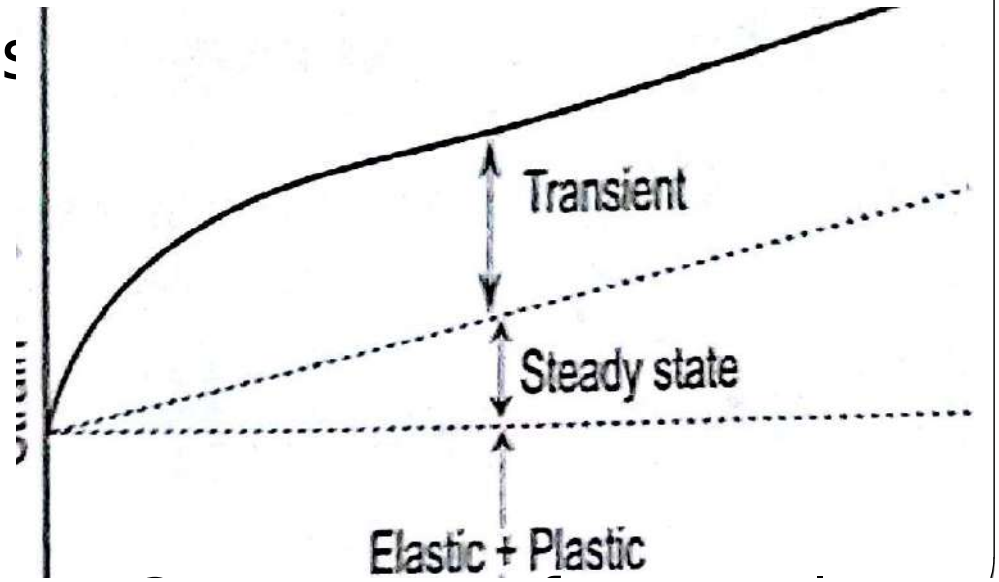
Creep: - Creep curves – creep tests - Structural change:- deformation by slip, sub-grain formation, grain boundary sliding, Mechanism of creep deformation - threshold for creep, prevention against creep - Super plasticity: need and applications. Composites:- Need of development of composites - geometrical and spatial Characteristics of particles –classification - fiber phase: - characteristics, classifications - matrix phase:- functions – only need and characteristics of PMC, MMC, and CMC – applications of composites: aircraft applications, aerospace equipment and instrument structure, industrial applications of composites, marine applications, composites in the sporting goods industry, composite biomaterials. Modern engineering materials: - only fundamentals, need, properties and applications of, intermetallics, maraging steel, super alloys, Titanium – introduction to nuclear materials, smart materials and bio materials. Ceramics:-coordination number and radius ratios- AX, AmXp, AmBmXp type structures – applications.

Creep

- In many applications, materials are often placed under steady loads for longer periods of time (eg. turbine rotors in steam turbines, jet engines, high pressure pipe lines, beams in the roof of buildings etc).
- Under such conditions, material undergoes continuous deformation without any increase in load, until its usefulness is seriously affected.
- Deformation under such conditions is termed as "Creep".
- Creep is defined as the time dependent part of the strain resulting from stress applied continuously over long period of time.
- Such time dependent deformation, over the life time of a structure, can grow larger and even result in final fracture without any increase in load.
- Creep is more predominant at higher temperature and hence it is usually thought of as an elevated temperature effect.
- “When subjected to a constant load for longer periods, creep is a phenomenon that occurs in all type of materials.
- For metallic materials, creep becomes important only for temperatures greater than about 0.4Tm (T = melting temperature in absolute units).
- Amorphous polymers like plastics, rubber, lead etc. exhibit creep at room temperature.

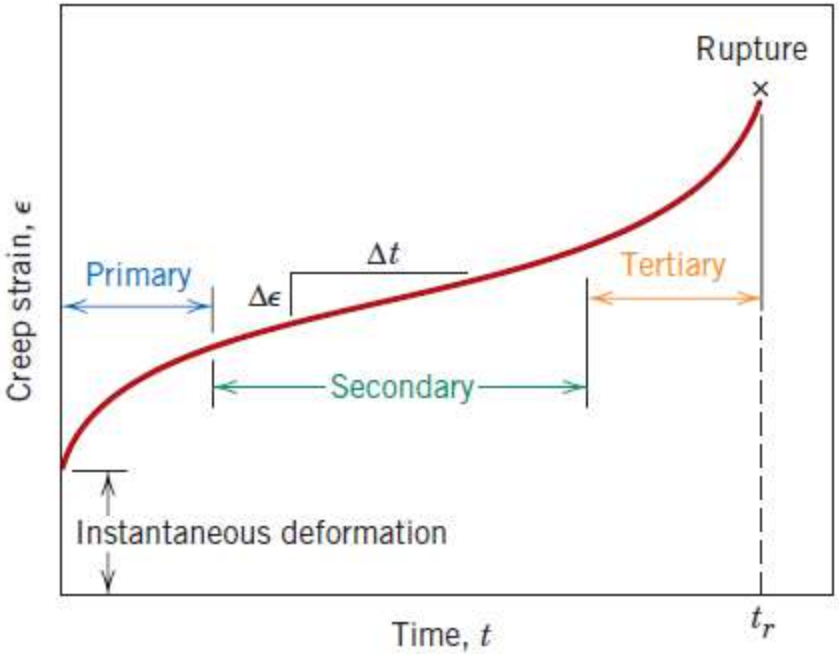
Creep

- Of the various factors causing creep; stress, temperature and time are the predominant ones.
- Their effect can be analyzed by conducting a creep test and plotting creep curves.
- The test consists of subjecting a specimen to a constant stress, while maintaining temperature constant.
- Deformation or strain is elapsed time.



Creep curve

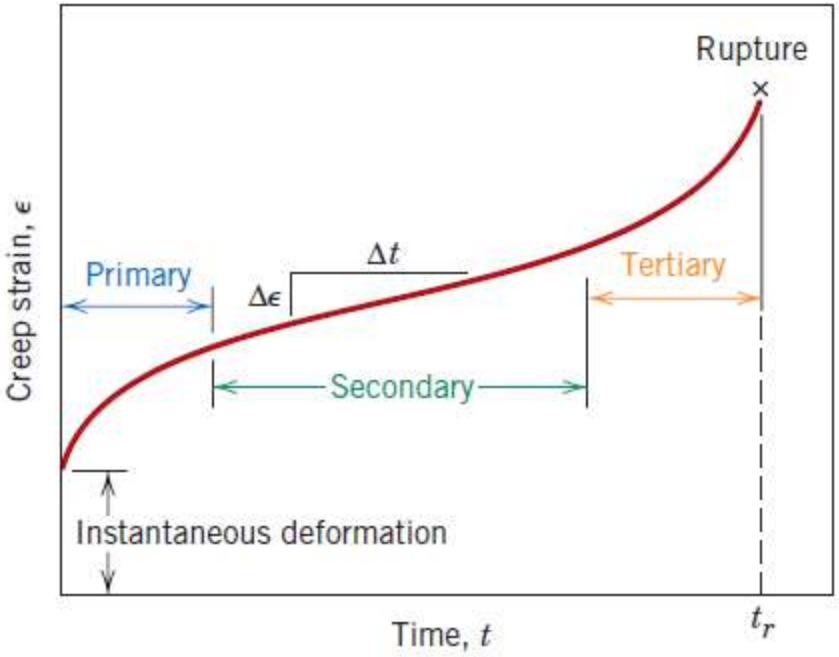
Schematic of a typical constant load creep behavior of metals.



- Upon application of the load there is an instantaneous deformation, which is mostly elastic.
- The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.
- **Primary or transient creep** occurs first, characterized by a continuously decreasing creep rate; that is, the slope of the curve diminishes with time.
- This suggests that the material is experiencing an increase in creep resistance or strain hardening and deformation

Creep curve

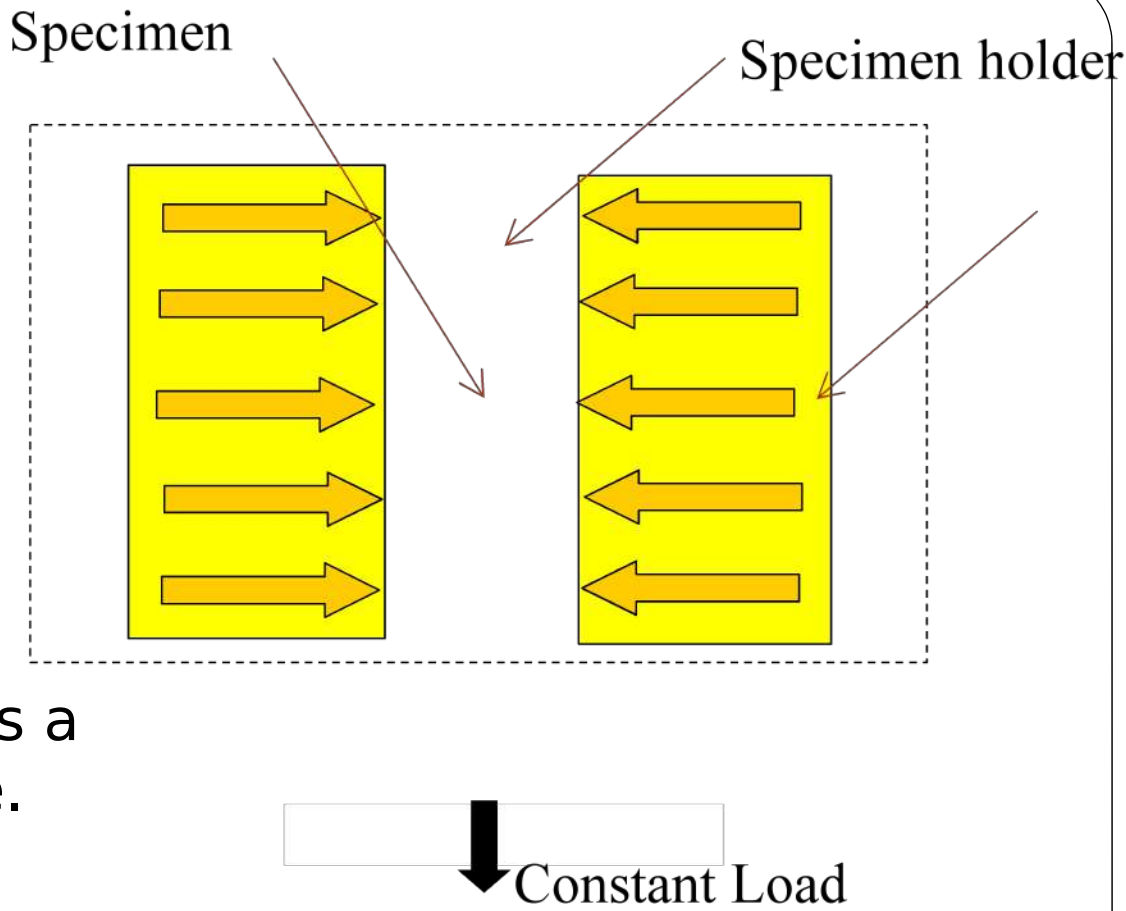
- **For secondary creep**, sometimes termed steady-state creep, the rate is constant; that is, the plot be-comes linear. This is often the stage of creep that is of the longest duration.
- The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery, (recovery being the process whereby a material becomes softer and retains its ability to experience deformation).



- Finally, for **tertiary creep**, there is an acceleration of the rate and ultimate failure. This failure is frequently termed rupture and results from microstructural and/or metallurgical changes;
- For example, grain boundary separation, and the formation of internal cracks, cavities, and voids. Also, for tensile loads, a neck may form at some point within the deformation region. These all lead to a decrease in the effective cross-sectional

Creep Test

- A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant;
- Deformation or strain is measured and plotted as a function of elapsed time.



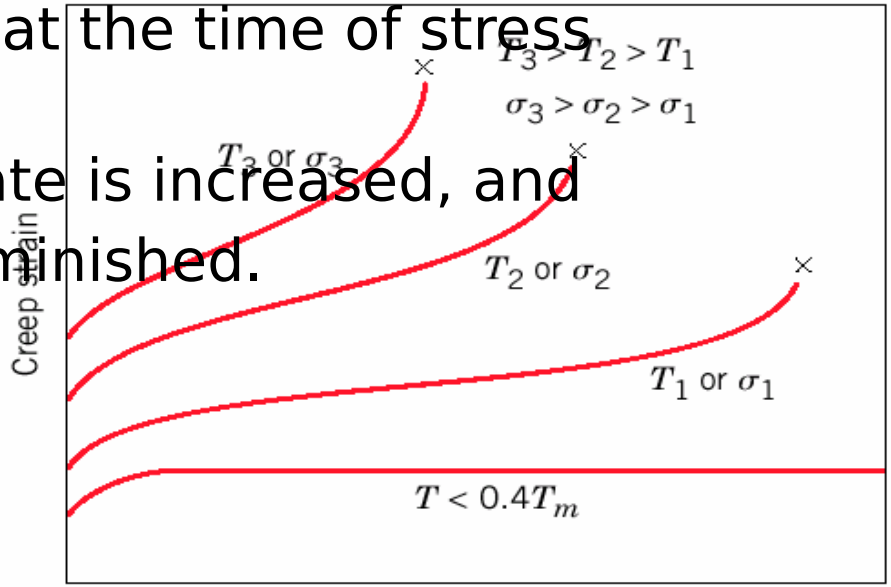
- For metallic materials most creep tests are conducted in uniaxial tension using a specimen having the same geometry as for tensile tests.
- Uniaxial compression tests are used for brittle materials; these provide a better measure of the intrinsic creep properties inasmuch as there is no stress amplification and crack

Creep test

- Possibly the most important parameter from a creep test is the slope of the secondary portion of the creep curve ($\Delta\varepsilon/\Delta t$); this is often called the minimum or *steady-state creep rate* ε_s.
- It is the engineering design parameter that is considered for long-life applications, such as a nuclear power plant component that is scheduled to operate for several decades, and when failure or too much strain are not options.
- On the other hand, for many relatively short-life creep situations (e.g., turbine blades in military aircraft and rocket motor nozzles), *time to rupture, or the rupture lifetime* t_r, is the dominant design consideration;
- For these determinations, creep tests must be conducted to the point of failure; these are termed creep rupture tests.

Threshold for Creep
(stress and temperature effects on creep)

- Both temperature and the level of the applied stress influence the creep characteristics.
- At a temperature substantially below 0.4Tm, and after the initial deformation, the strain is virtually independent of time.
- With either increasing stress or temperature, the following will be noted:
  - (1) the instantaneous strain at the time of stress application increases,
  - (2) the steady-state creep rate is increased, and
  - (3) the rupture lifetime is diminished.

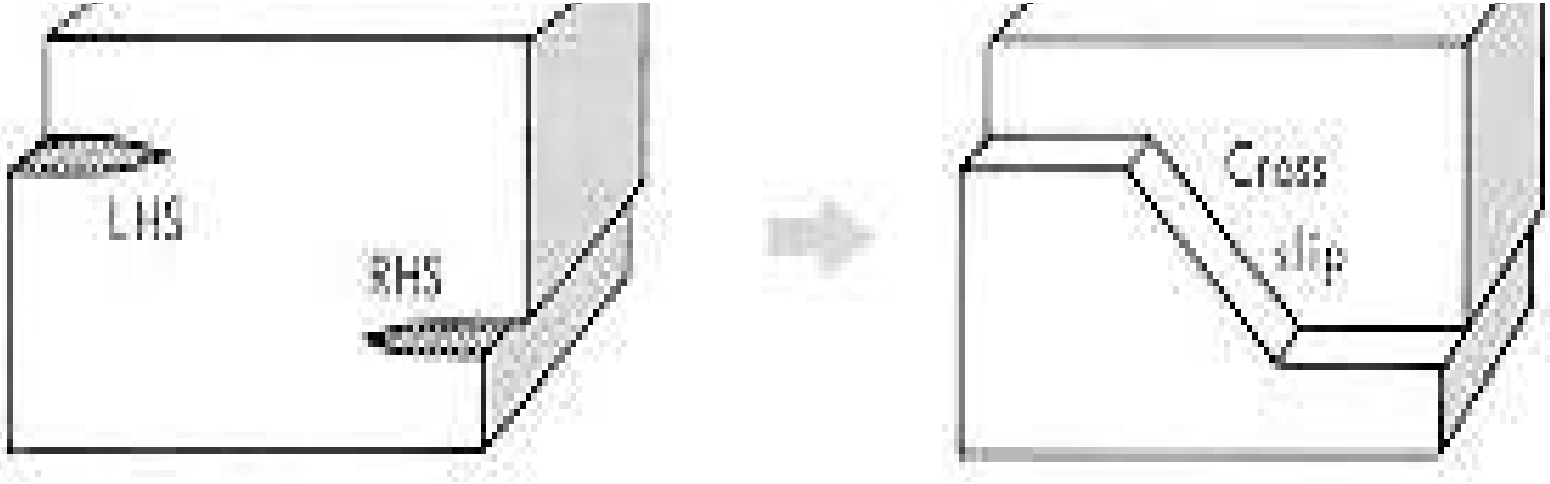


Mechanism of creep

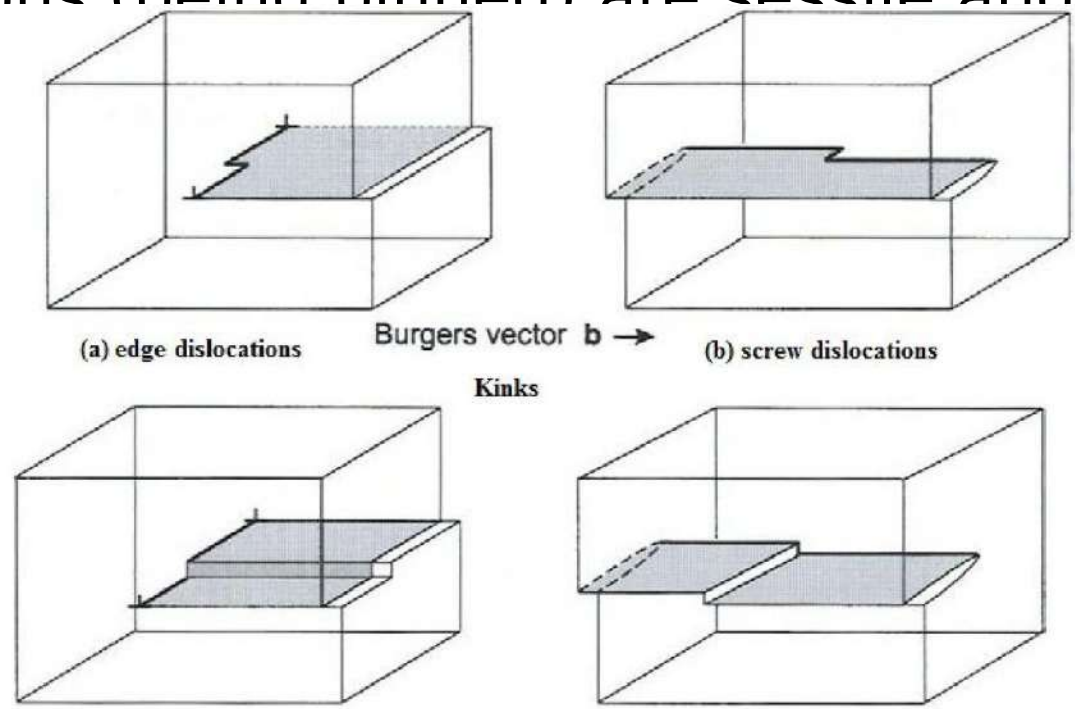
- Several theoretical mechanisms have been proposed to explain the creep behavior for various materials; these mechanisms involve
  - Stress-induced vacancy diffusion
  - Grain boundary diffusion
  - Dislocation motion
  - Grain boundary sliding.
- At high temperatures the grain boundary becomes weaker than the grain interior and two grains can slide past one another due to shear stress.
- At temperature above $0.5T_m$, the viscosity of the grain boundaries is low enough for them to behave like a liquid separating the neighboring grains and slide past each other.

Mechanism of creep Dislocation related mechanisms

- Cross-slip
- This kind of creep is observed at relatively low temperatures. Herein screw dislocations cross-slip by thermal activation and give rise to plastic strain as a function of time.(Cross slip is the process by which a screw dislocation can r

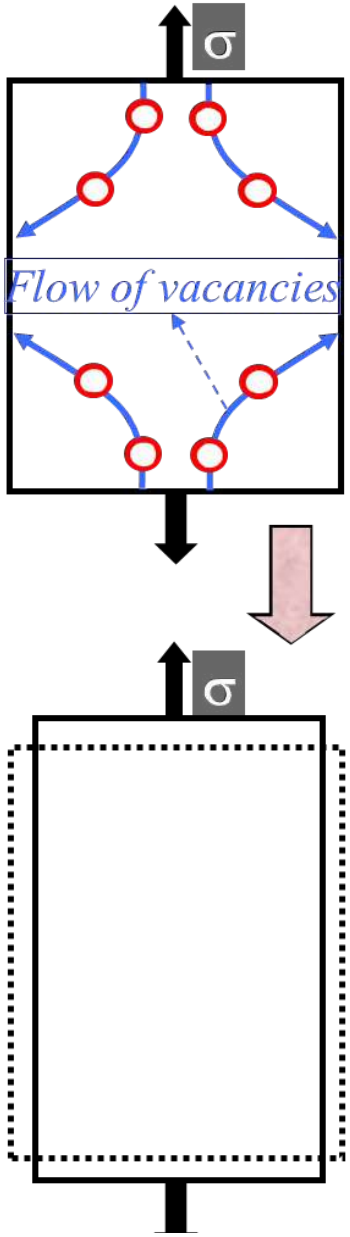


- Dislocation climb
  - Edge dislocations piled up against an obstacle can climb to another slip plane and cause plastic deformation.
  - In response to stress this gives rise to strain as a function of time.
  - It is to be noted that at low temperatures these dislocations (being pinned) are sessile and become
  - Rate con ancies.



Mechanism of creep Diffusion mechanisms

- In response to the applied stress, vacancies preferentially move from surfaces/interfaces of specimen transverse to the stress axis to surfaces/interfaces parallel to the stress axis→ thus causing elongation.
- Diffusion of vacancies in one direction can be thought of as flow of matter in the opposite direction.
- This process like dislocation creep (involving climb) is controlled by the diffusion of vacancies (but diffusional creep does not require dislocations to operate).
- The diffusion could occur predominantly via the lattice (at high temperatures) or via grain boundaries (at low temperatures). The former is known as Nabarro-Herring creep, while the later is known as Coble creep.



Factors affecting creep

Heat Treatment and melting point

- Materials with high thermal stability and higher melting point resist creep.
- An annealed material has higher thermal stability than a quenched material and therefore its creep resistance.

Grain size and shape

- The major factor in creep is grain size.
- Fine grained material exhibit better mechanical properties at low temperature.
- Fine grained materials are prone to grain boundary sliding at high temperature, due to large number of grain boundaries.
- Therefore, large grained materials exhibit better creep resistance than fine grained one based on the temperature.
- Dendritic structures show better creep resistance than equi-axed grains.

Precipitation hardening

- Precipitation hardening improves creep resistance.
- The insoluble precipitates can prevent the dislocation movement

Dispersion hardening

- Improves creep resistance
- Hard insoluble particles of second phase are uniformly distributed in a finely divided form in the metal matrix.
- These particles does not allow the grain boundaries to move and hence reduce creep deformation.

Strain Hardening/cold working/work hardening

- Strain hardening of steel increases its creep resistance, due to the increased elastic limit or yield strength.
- In a cold worked material, the slip process is less easy.
- Previous cold work can modify creep behavior in primary and secondary stages.

Alloying additions-substitutional solid solutions

- Formation of substitutional solid solution usually improves creep resistance, since it involves the creation of lattice strains which hinder dislocation movement.

Superplasticity

- The phenomenon of extensive plastic deformation without necking is termed as structural superplasticity. Superplastic deformation in tension can be >300% (up to even 2000% at elevated temperatures at low loading rates).
- Typically superplastic deformation occurs when:
  1) high loading temperature, greater than 50% of the melting temperature of the metal (T > 0.5Tm)
  2) Fine grain size, typically < 10 μm, grains are equiaxed (which usually remain so after deformation)
  3) Low and controlled strain rate (0,01-0.001 s^{-1})
  4) grain boundaries are glissile (with a large fraction of high angle grain boundaries).
- Presence of a second phase (of similar strength to the matrix-reduces cavitation during deformation), which can inhibit grain growth at elevated temperatures helps (e.g. Al-33% Cu, Zn-22%)).

Applications of superplasticity

- The superplasticity has been widely used for metal forming operations, like thermoforming, blow forming, vacuum forming, deep drawing etc.
- Deep and complex shapes can be made as one piece, in single step pressing rather than conventional pressing or multi-piece assemblies.
- Even though, the forming rate in superplastic materials are low, this rate is compensated by reducing the number of assembly operations, for instance, reducing fastening of holes.
- *Reduction in fatigue, cracks, tooling cost, weight of the product, etc.*
- Superplastic forming is used for the fabrication of aerofoils in gas turbines from super alloys.

Composite

- *A composite, in the present context, is a multiphase material that is artificially made, in which constituent phases are chemically dissimilar and separated by a distinct interface.*
- In designing composite materials, scientists and engineers have creatively combined various metals, ceramics, and polymers to produce a new generation of extraordinary materials.
- Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.
- Many composite materials are composed of just two phases; one is termed the ***matrix***, which is continuous and surrounds the other phase, often called the ***dispersed phase***.
- The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase.
- “Dispersed phase geometry” means the shape of the particles and the particle size, distribution, and orientation.

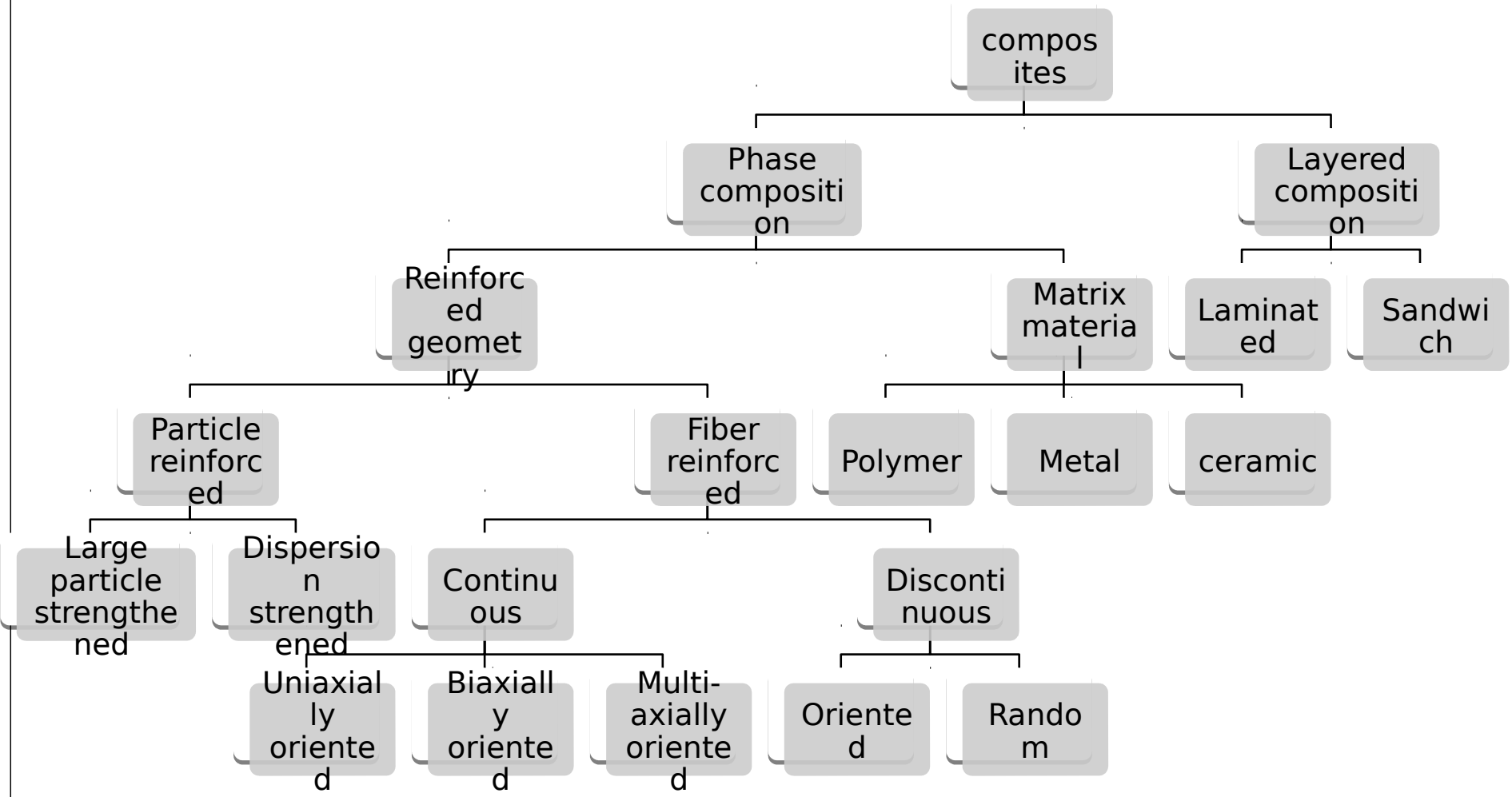
Composites

- Many of our modern technologies require materials with unusual combinations of properties that cannot be met by the conventional metal alloys, ceramics, and polymeric materials.
- Frequently, strong materials are relatively dense; also, increasing the strength or stiffness generally results in a decrease in impact strength.
- **Generally speaking, a composite is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized.**
- According to this principle of combined action, better property combinations are obtained by the appropriate combination of two or more distinct materials.
- Property trade-offs are also made for many composites.

Need for developing composites

- With the advancement of technology, especially in the field of aerospace engineering, there is increasing need of lightweight materials with unusual combination of properties of high strength, high elastic modulus and at the same time suitability at high temperature operation.
- Many of our modern technologies require materials with unusual combinations of properties that cannot be met by the conventional metal alloys, ceramics, and polymeric materials.
- This is especially true for materials that are needed for aerospace, underwater, and transportation applications.
- For example, aircraft engineers are increasingly searching for structural materials that have low densities, are strong, stiff, and abrasion and impact resistant, and are not easily corroded.
- Frequently, strong materials are relatively dense; also, increasing the strength or stiffness generally results in a decrease in impact strength.

Classification



Classification

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- “Dispersed phase geometry” in this context means the shape of the particles and the particle size, distribution, and orientation.
- Based on this, the composites are broadly classified as;

A. Particle reinforced composites
   i. Large particle reinforced composites
   ii. Dispersion strengthened composite
B. Fiber reinforced composite
   i. Continuous fiber reinforced composites

Large particle reinforced composites

- In large particle composites, the particle-matrix interaction is treated on a macroscopic level rather than atomic or molecular level.
- The particle size is 1-50 μm and concentration ranges from 15-40% by volume.
- The particle phase is stiffer and harder than matrix.
- The particles give strength to the matrix by restraining the movement of the matrix in the vicinity of the particles.
- The matrix transfers the applied stress to the particles, which bear most of the applied loads.
- The degree of reinforcement or improvement in mechanical behavior depends on the volume fraction of the particles in the composite and the strength of the bonding between the matrix and the particles.

Large particle reinforced composites

- Mechanical properties are enhanced with increasing particulate content, up to a certain critical fraction.
- There is an optimum volume fraction above which the properties degrade, since the available matrix phase will not be enough to separate the particle as well as to cause the effective bonding between the matrix and the filler.
- For effective reinforcement, the particles should be small and evenly distributed through out the matrix.
- Common large particle composites are:
  - Cermets: Tungsten carbide (WC) or titanium carbide (TiC) embedded in a metal matrix of cobalt or nickel.
  - Vulcanized rubber: Carbon black in rubber
  - Concrete: Sand, gravel particulate in a slurry of cement matrix. Reinforced composite is a multiphase material.

Composites

- Metals and metal alloys may be strengthened and hardened by the uniform dispersion of several volume percent of fine particles (<0.1 μm) of a very hard and inert material.
- The dispersed phase (5-15%) may be metallic or nonmetallic; oxide materials are often used and are stronger than the matrix materials.
- The strengthening mechanism involves interactions between the particles and dislocations within the matrix, as with precipitation hardening; the matrix is the load bearing phase.
- The dispersion strengthening effect is not as pronounced as with precipitation hardening; but more effective for fine particles and smaller inter particle spacing.
- The strengthening is retained at elevated temperatures and for extended time periods because the dispersed particles are chosen to be unreactive with the matrix phase.
- For precipitation-hardened alloys, the increase in strength may disappear upon heat treatment as a consequence of precipitate growth or dissolution of the precipitate phase.
- The high-temperature strength of nickel alloys may be enhanced significantly by the addition of about 2 vol% of thoria (ThO_2) as

Fiber-Reinforced Composites

- Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber.
- Design goals of **fiber-reinforced composites** is their high strength and/or stiffness on a weight basis.
- These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity.
- Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low-density fiber and matrix materials.

The Fiber Phase

- An important characteristic of most materials, especially brittle ones, is that a small-diameter fiber is much stronger than the bulk material.
- The probability of the presence of a critical surface flaw that can lead to fracture diminishes with decreasing specimen volume, and this feature is used to advantage in the fiber-reinforced composites.
- On the basis of diameter and character, fibers are grouped into three different classifications: **whiskers, fibers, and wires.**
- ***Whiskers*** are very thin single crystals that have extremely large length-to-diameter ratios and exceptionally high strengths; they are among the strongest known materials.
  - Whisker materials include graphite, silicon carbide, silicon nitride, and aluminum oxide
- Materials that are classified as ***fibers*** are either polycrystalline or amorphous and have small diameters; fibrous materials are generally either polymers or ceramics

Influence of fiber length

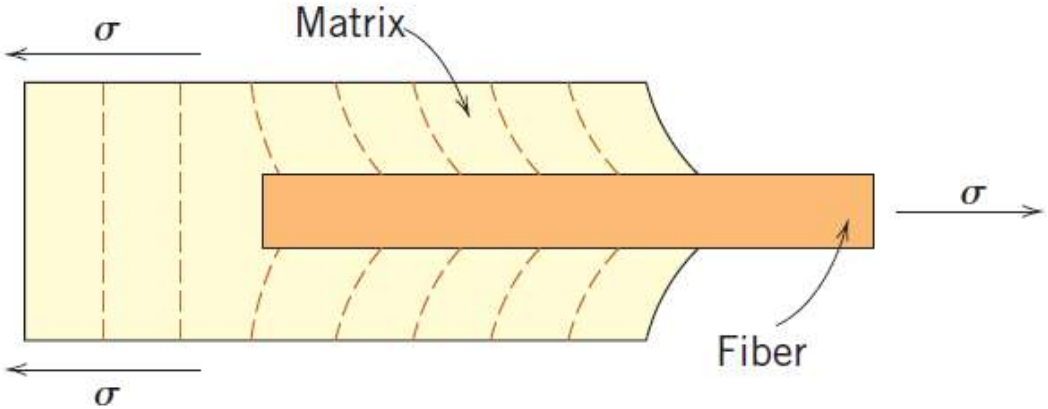
- The mechanical characteristics of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase.
- Important to the extent of this load transmittance is the magnitude of the interfacial bond between the fiber and matrix phases.
- Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length, l_c is dependent on the fiber diameter d and its ultimate (or tensile) strength σ_f^* and on the fiber–matrix bond strength τ_c; as follows;

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

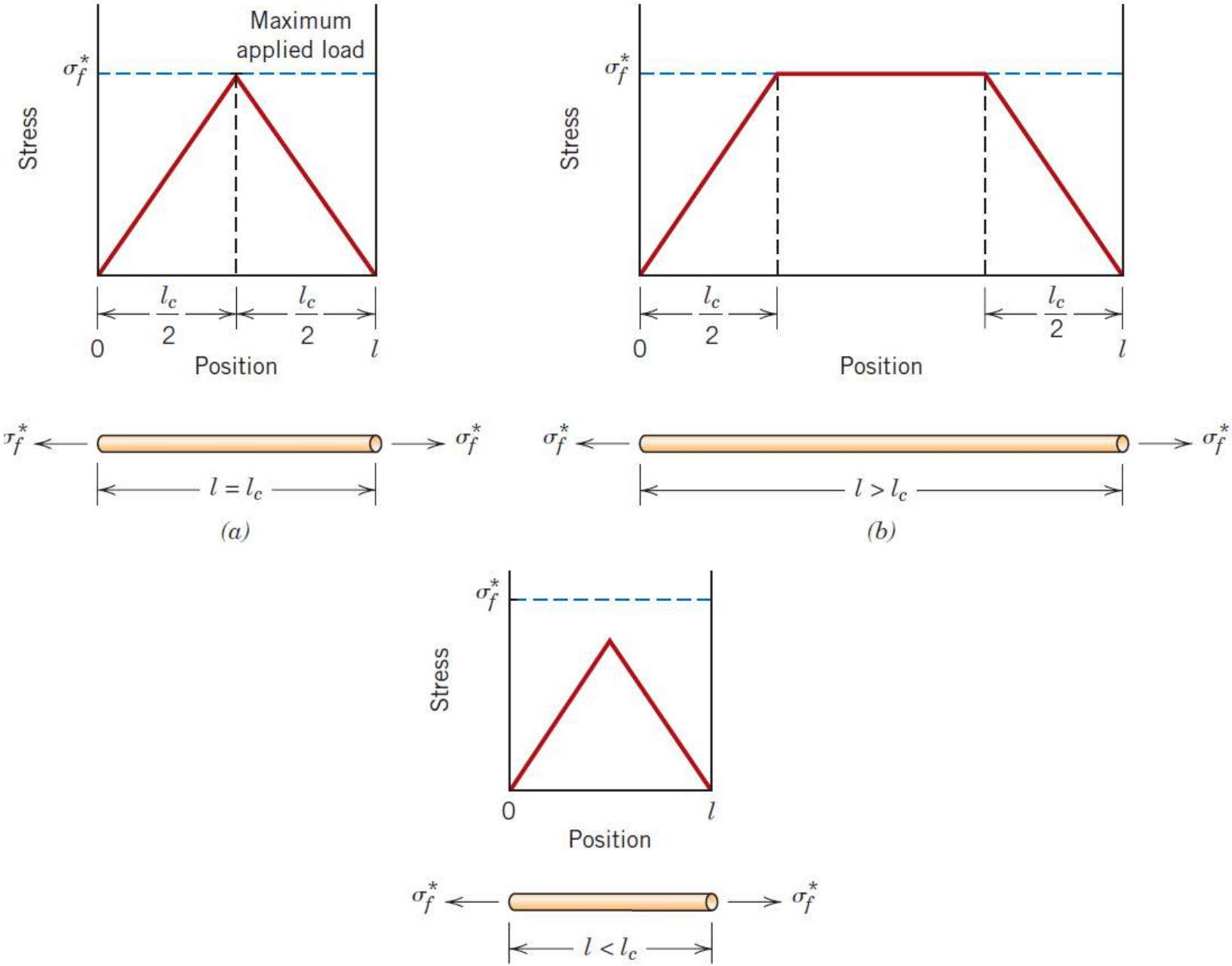
- For a number of glass and carbon fiber–matrix combinations, this critical length is on the order of 1 mm, which ranges between 20 and 150 times the fiber diameter.

Influence of fiber length

- As fiber length l increases, the fiber reinforcement becomes more effective;
- Fibers for which $l >> l_c$, normally $l > 15.l_c$ are termed as continuous fibers



The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load

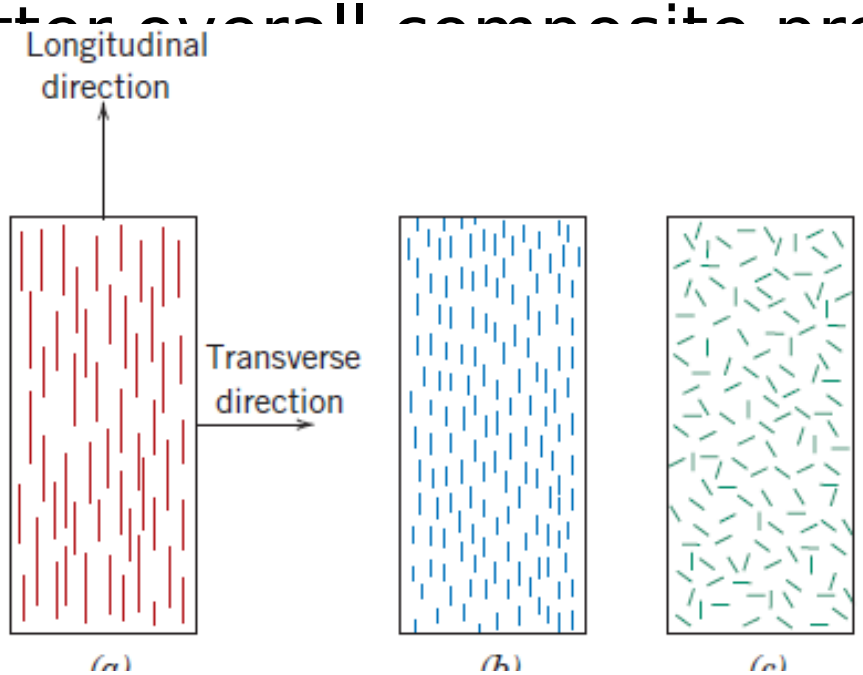

Maximum applied load
σ_f^*
Stress
$\frac{l_c}{2}$
$\frac{l_c}{2}$
0
l
Position
σ_f^*
σ_f^*
$l = l_c$
(a)
σ_f^*
Stress
$\frac{l_c}{2}$
$\frac{l_c}{2}$
0
l
Position
σ_f^*
σ_f^*
$l > l_c$
(b)
σ_f^*
Stress
0
l
Position
σ_f^*
σ_f^*
$l < l_c$

Influence of fiber orientation and concentration

Continuous and Aligned Fiber Composites

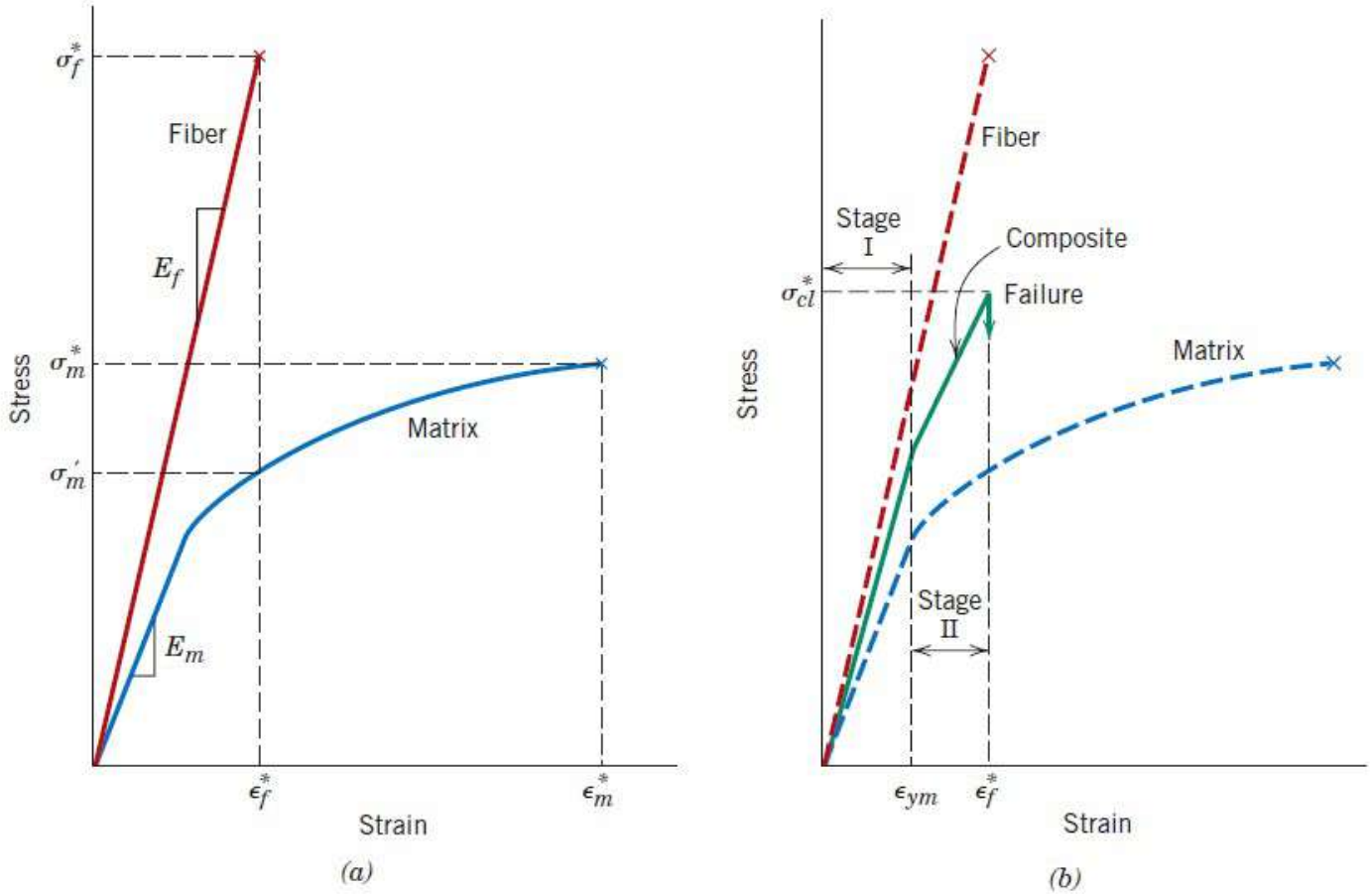
Tensile Stress–Strain Behavior—Longitudinal Loading

- Continuous fibers are normally aligned, whereas discontinuous fibers may be aligned, randomly oriented, or partially oriented.
- Better overall composite properties are realized when [illegible] is uniform.



Schematic representations of
(a) continuous and aligned,
(b) discontinuous and aligned, and

Influence of fiber orientation and concentration



(a) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (b) Schematic stress–strain curve for an aligned fiber-reinforced composite that is

Influence of fiber orientation and concentration

- In the initial Stage I region, both fibers and matrix deform elastically; this portion of the curve is linear.
- Typically, for a composite of this type, the matrix yields and deforms plastically while the fibers continue to stretch elastically, inasmuch as the tensile strength of the fibers is significantly higher than the yield strength of the matrix.
- This process constitutes Stage II as noted in the figure; this stage is ordinarily very nearly linear, but of diminished slope relative to Stage I.
- While passing from Stage I to Stage II, the proportion of the applied load that is carried by the fibers increases.

Influence of fiber orientation and concentration

- When the fiber orientation is aligned, reinforcement efficiency is maximum in the direction parallel to the alignment and almost negligible in the transverse direction.
- When the fibers are distributed uniformly and randomly oriented, in three dimension within the matrix, the composite become isotropic with a reinforcement efficiency about 20%.

The matrix phase

- The matrix phase of fibrous composites may be a metal, polymer, or ceramic. In general, metals and polymers are used as matrix materials because some ductility is desirable;
- For ceramic-matrix composites, the reinforcing component is added to improve fracture toughness.
- For fiber-reinforced composites, the matrix phase serves several functions.
  1. Matrix bind and holds the reinforcing phase in place
  2. It binds the fibers together and acts as the medium by which an externally applied stress is transmitted and distributed to the fibers; only a very small proportion of an applied load is sustained by the matrix phase.
  3. The matrix material is ductile and thus improves the fracture toughness in composites.
  4. The second function of the matrix is to protect the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels.
  5. The matrix separates the fibers and, by virtue of its relative softness and plasticity, prevents the propagation of brittle cracks from fiber to

Polymer-matrix composites

- Polymer-matrix composites (PMCs) consist of a polymer resin as the matrix, with fibers as the reinforcement medium.
- Generally thermosetting plastics like epoxies and phenolics are the matrix materials.
- Epoxies have better mechanical properties than phenolics but phenolics are cheaper than epoxies.
- Thermoplastics are also used as matrix, since they can be reworked, low processing time and at normal temperatures they have an optimum combination of toughness, rigidity and creep resistance.
- PMCs have advantages over metal and ceramic matrix composites because of their low density, high specific strength and high specific stiffness.
- These materials are used in the greatest diversity of composite applications, as well as in the largest quantities, in light of their room-temperature properties, ease of fabrication, and cost.
- In this section the various classifications of PMCs are discussed according to reinforcement type (i.e., glass, carbon, and aramid), along with their applications and the various polymer resins that are employed.

Glass Fiber-Reinforced Polymer (GFRP) Composites

- Fiberglass is simply a composite consisting of glass fibers, either continuous or dis-continuous, contained within a polymer matrix; this type of composite is produced in the largest quantities.
- The composition of the glass that is most commonly drawn into fibers (sometimes referred to as E-glass) is 55% SiO_2, 16% CaO, 15% Al_2O_3, 10% B_2O_3 and 4% MgO 13.1; fiber diameters normally range between 3 and 20 mm.
- Glass is popular as a fiber rein-forcement material for several reasons:
  - It is easily drawn into high-strength fibers from the molten state.
  - It is readily available and may be fabricated into a glass-reinforced plastic economically using a wide variety of

(GFRP) Composites

- The surface characteristics of glass fibers are extremely important because even minute surface flaws can deleteriously affect the tensile properties.
- Surface flaws are easily introduced by rubbing or abrading the surface with another hard material. Also, glass surfaces that have been exposed to the normal atmosphere for even short time periods generally have a weakened surface layer that interferes with bonding to the matrix.
- Newly drawn fibers are normally coated during drawing with a "*size*," a thin layer of a substance that protects the fiber surface from damage and undesirable environmental inter-actions.
- This size is ordinarily removed prior to composite fabrication and replaced with a "coupling agent" or finish that produces a chemical bond between the fiber and matrix.
- In spite of having high strengths, they are not very stiff and do not display the rigidity that is necessary for some applications (e.g., as structural members for airplanes and bridges).
- Most fiberglass materials are limited to service temperatures

Carbon Fiber Reinforced Polymer (CFRP) Composites

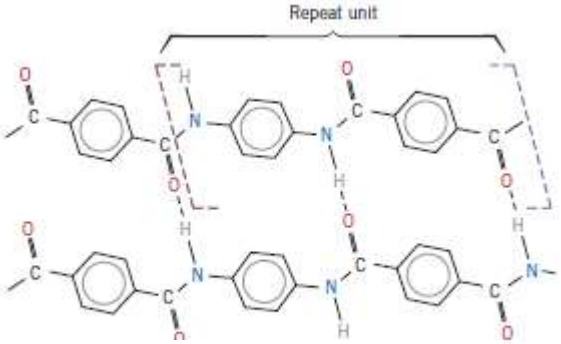
- Carbon is a high-performance fiber material that is the most commonly used reinforcement in advanced (i.e., nonfiberglass) polymer-matrix composites.
- The reasons for this are as follows:
  - Carbon fibers have the highest specific modulus and specific strength of all reinforcing fiber materials.
  - They retain their high tensile modulus and high strength at elevated temperatures; high-temperature oxidation can be a problem.
  - At room temperature, carbon fibers are not affected by moisture or a wide variety of solvents, acids, and bases.
  - These fibers exhibit a diversity of physical and mechanical characteristics, allowing composites

Carbon Fiber Reinforced Polymer (CFRP) Composites

- Carbon fibers are not totally crystalline, but are composed of both graphitic and noncrystalline regions; these areas of noncrystallinity are lacking of the three-dimensional ordered arrangement of hexagonal carbon networks that is characteristic of graphite .
- Organic precursor like: rayon, polyacrylonitrile (PAN), and pitch are used for the fabrication of carbon fibers.
- Carbon fiber diameters normally range between 4 and 10 mm; both continuous and chopped forms are available.
- In addition, carbon fibers are normally coated with a protective epoxy size that also improves adhesion with the polymer matrix.

Aramid Fiber-Reinforced Polymer Composites

- Aramid fibers are high-strength, high-modulus materials that were introduced in the early 1970s.
- They are especially desirable for their outstanding strength-to-weight ratios, which are superior to metals.
- Chemically, this group of materials is known as poly(paraphenylene terephthalamide). There are a number of aramid materials; trade names for two of the most common are Kevlar™ and Nomex™.
- During synthesis, the rigid aromatic molecules are aligned in the direction of the fiber axis; and these fibers have longitudinal tensile strengths and tensile moduli that are higher than other polymeric fiber materials; however, they are relatively weak in compression.
- These materials are known for its toughness, impact resistance, and resistance to creep and fatigue failure.
- Aramids are thermoplastics, they are, nevertheless, resistant to combustion and stable to relatively high temperatures
- Chemically, they are susceptible to degradation by strong acids and bases, but they are relatively inert in other solvents and chemicals.
- The aramid fibers are most often used in composites having polymer matrices; common matrix materials are the epoxies and polyesters. Since the fibers are relatively flexible and somewhat ductile, they may be processed by most common textile operatio



- Typical applications of these aramid composites are in ballistic products (bullet-proof vests and armor), sporting goods, tires, ropes, missile cases, pressure vessels, and as a replacement for asbestos in automotive brake and clutch linings, and gaskets.

Other Fiber Reinforcement Materials

- Glass, carbon, and the aramids are the most common fiber reinforcements incorporated in polymer matrices.
- Other fiber materials that are used to much lesser degrees are boron, silicon carbide, and aluminum oxide;
- Boron fiber-reinforced polymer composites have been used in military aircraft components, helicopter rotor blades, and some sporting goods.
- Silicon carbide and aluminum oxide fibers are utilized in tennis rackets, circuit boards, military armor, and rocket nose cones.

Metal-matrix Composites

- In metal-matrix composites (MMCs), the matrix is a ductile metal.
- These materials can be utilized at higher service temperatures than their base metal counterparts; furthermore, the reinforcement may improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity, and dimensional stability.
- Some of the advantages of these materials over the polymer-matrix composites include higher operating temperatures, non-flammability, and greater resistance to degradation by organic fluids.
- Metal-matrix composites are much more expensive than PMCs, and, therefore, MMC's use is somewhat restricted.
- The superalloys, as well as alloys of aluminum, magnesium, titanium, and copper, are employed as matrix materials.
- The reinforcement may be in the form of particulates, both continuous and discontinuous fibers, and whiskers;

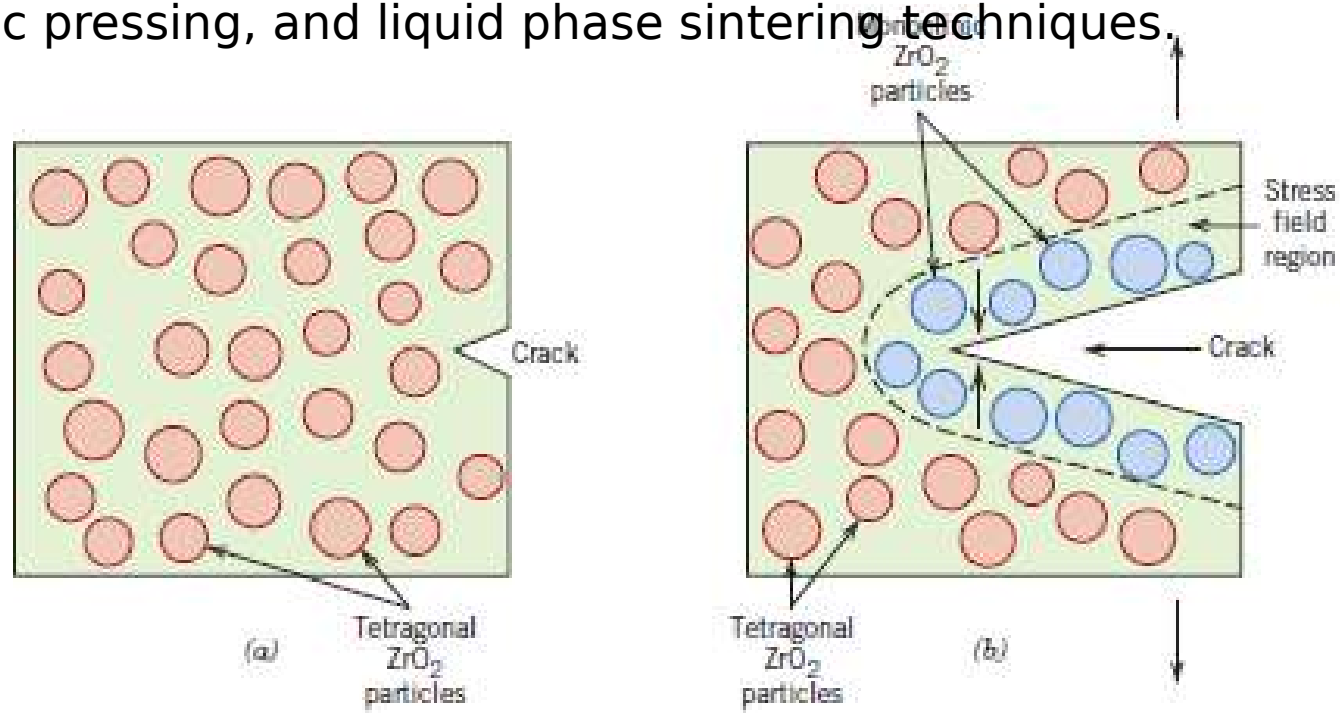
Metal-matrix Composites

- Normally the processing of MMCs involves at least two steps: consolidation or synthesis (i.e., introduction of reinforcement into the matrix), followed by a shaping operation.
- MMCs are shaped by standard metal-forming operations (e.g., forging, extrusion, rolling).
- Automobile manufacturers have recently begun to use MMCs in their products.
  - Some engine components have been introduced consisting of an aluminum-alloy matrix that is reinforced with aluminum oxide and carbon fibers; this MMC is light in weight and resists wear and thermal distortion.
  - Metal-matrix composites are also employed in drive shafts (that have higher rotational speeds and reduced vibrational noise levels), extruded stabilizer bars, and forged suspension and transmission components.
- The aerospace industry also uses MMCs. Structural applications include advanced aluminum alloy metal-matrix composites; boron fibers are used as the reinforcement for the Space Shuttle Orbiter, and continuous graphite fibers for the Hubble Telescope.

Ceramic-matrix Composites

- Ceramic materials are inherently resistant to oxidation and deterioration at elevated temperatures; some of the ceramic materials are ideal candidates for use in high-temperature and severe-stress applications, specifically for components in automobile and aircraft gas turbine engines.
- The fracture toughness of ceramics can be improved significantly by the development of ceramic-matrix composites (CMCs)—particulates, fibers, or whiskers of one ceramic material that have been embedded into a matrix of another ceramic.
- The improvement in the fracture properties results from interactions between advancing cracks and dispersed phase particles.
- Crack initiation normally occurs with the matrix phase, whereas crack propagation is obstructed or hindered by the particles, fibers, or whiskers.
- Small particles of partially stabilized zirconia are dispersed within the matrix material, in Al_2O_3 or ZrO_2 matrices. Typically, CaO, MgO, Y_2O_3, and CeO are used as stabilizers.
- Whiskers of SiC or Si_3N_4 are also used as second phase particles.

- Other recently developed toughening techniques involve the utilization of ceramic whiskers, often SiC or Si3N4.
- These whiskers may inhibit crack propagation by
  (1) deflecting crack tips,
  (2) forming bridges across crack faces,
  (3) absorbing energy during pull-out as the whiskers debond from the matrix,
  (4) causing a redistribution of stresses in regions adjacent to the crack tips.
- Ceramic-matrix composites may be fabricated using hot pressing, hot isostatic pressing, and liquid phase sintering techniques.



Schematic demonstration of transformation toughening. (a) A crack prior

Hybrid Composites

- Hybrid composite is obtained by using two or more different kinds of fibers in a single matrix;
- Hybrids have a better all-around combination of properties than composites containing only a single fiber type.
- A variety of fiber combinations and matrix materials are used, but in the most common system, both carbon and glass fibers are incorporated into a polymeric resin.
- The carbon fibers are strong and relatively stiff and provide a low-density reinforcement; but, they are expensive.
- Glass fibers are inexpensive and lack the stiffness of carbon fibers.
- The glass–carbon hybrid is stronger and tougher, has a higher impact resistance, and may be produced at a lower cost than either of the comparable all-carbon or all-glass reinforced plastics.
- When hybrid composites are stressed in tension, failure is usually noncatastrophic (i.e., does not occur suddenly).
- The carbon fibers are the first to fail, at which time the load is transferred to the glass fibers. Upon failure of the glass fibers

Applications of composites

- **Aircraft and aerospace application**
  - Load bearing and non-load bearing components are made using composites like light weight, high strength glass fiber, carbon fiber and Kevlar fiber composites.
  - Windows, ceiling panels, storage bins, landing gear doors, etc.
  - Structural composites like body, wings, helicopter rotor blades and propellers requiring better strength made of MMCs of Al, Mg or Ti are used.
- **Automotive application**
  - Low cost polymer matrix composites are used for body components.
  - For engine block, piston, piston rods, connecting rods, push rods, chases, motor cycle frames etc. Al-SiC composites are used.
  - MMC composites are used for transmission shafts.
  - For brake and clutch lining, gaskets, epoxy polyester matrix-aramid fiber composites are used.
  - Rubber carbon composites are used in tyres.

Applications of composites

- **Marine application**
  - Marine application include surface vessels, offshore structures and under water 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 making them ideal for many sports goods.
  - Tennis rackets, hockey sticks, cricket bats, golf clubs, vaulting poles, skiing poles, archery equipment, surf boards,canoes and skate boards.
  - PMC composites are generally used for these applications.

Application of composites

- **Biomaterials**
  - Carbon fiber reinforced plastics and carbon components are in use for prosthetics 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 molded reinforced thermoplastics and polyester composites are extensively used for many consumer items of domestic use.
  - Kitchen equipment, electrical equipment, television and computer casing, furniture, helmets, etc.
  - Storage and pressure vessels, piping, valves centrifuges in chemical industries are made with GRP and CRP.
  - Cu/Ag composites are used in electrical industries as contact materials.
  - Printed circuit boards, casting for electrical equipments, high strength insulators are made using composite materials.
  - GRP and CRP composites are replacing wood in many civil engineering applications and structural cement based components.

Intermetallic Compounds

- An intermetallic compound contains two or more metallic elements, producing a new phase with its own composition, crystal structure, and properties.
- Intermetallic compounds are almost always very hard and brittle.
- Intermetallics or intermetallic compounds are similar to ceramic materials in terms of their mechanical properties.
- Intermetallic: solid phases containing two or more metallic elements, with optionally one or more non-metallic element. stronger bonding than solid.
- The best distinction between an intermetallic and a simple substitutional solid solution is to require the following conditions to be satisfied by the candidate compound:
  1. It has to be formed by at least two different elements (preferably metals, but there are exceptions)
  2. It must have a different crystal structure from the one observed in the pure components.
  3. The component element should have opposite electrochemical nature.
- Intermetallic compounds are special type of substitutional solid solution with higher amount solute element.

Intermetallic Compounds

- An intermetallic compound is a chemical compound just like H_2O or CH_4 or any other compound. It exists as its own thing, different from its constituents. Water is nothing like hydrogen or oxygen.
- Solid solutions have the solute atoms and matrix atoms distributed randomly. The lattice type is that of the matrix material.
- Intermetallics have ordered arrangements of the different atom types. The lattice type is different from that of the matrix material(s) - a bigger unit cell with more atoms per lattice point.
- Intermetallic compounds are generally formed when one metal (for example magnesium) has chemical properties which are strongly metallic and the other metal (for example antimony, tin or bismuth) has chemical properties which are only weakly metallic.
- Examples of intermetallic compounds are Mg_2Sn, Mg_2Pb, Mg_3Sb_2 and Mg_3Bi_2 . These intermetallic compounds have higher melting point than either of the parent metal.
- This higher melting point indicates the high strength of the chemical bond in intermetallic compounds.

Intermetallic Compounds

- **Stoichiometric intermetallic compounds** have a fixed composition.
- Steels are often strengthened by a stoichiometric compound, iron carbide (Fe_3C), which has a fixed ratio of three iron atoms to one carbon atom.
- **Nonstoichiometric intermetallic compounds** have a range of compositions and are sometimes called **intermediate solid solutions**.
- Precipitation of the nonstoichiometric intermetallic copper aluminide $CuAl_2$ causes strengthening in a number of important

Intermetallic Compounds-Applications

- Intermetallics such as Ti_3Al and Ni_3Al maintain their strength and even develop usable ductility at elevated temperatures.
- Ordered compounds of NiAl and Ni_3Al are also candidates for supersonic aircraft, jet engines, and high-speed commercial aircraft.
- platinum silicide play a useful role in microelectronics and intermetallics such as Nb_3Sn are useful as superconductors.
- **The intermetallic compound families include the borides,** hydrides, nitrides, silicides, and aluminides of the transition metal elements of Groups 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.

Maraging steels

- Maraging steels are carbon free iron-nickel alloys with additions of cobalt, molybdenum, titanium and aluminium.
- The term maraging 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 supersaturated solid solution.
- Tempering at 480 to 500°C results in strong hardening due to the precipitation of a number of intermetallic phases, including, nickel-molybdenum, iron-molybdenum and iron-nickel varieties.
- With yield strength between 1400 and 2400 MPa maraging steels belong to the category of ultra-high-strength materials. The high strength is combined with excellent toughness properties and weldability.
- Typical applications areas include:
  - aerospace, e.g. undercarriage parts and wing fittings,
  - tooling & machinery , e.g. extrusion press rams and mandrels in tube production, gears
  - Ordnance components and fasteners.
- Freedom from decarburization, minimal distortion during aging, good formability, machinability, weldability and low coefficient of thermal

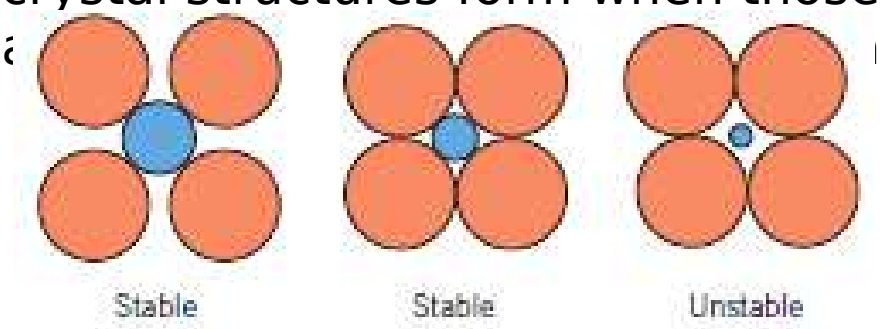
Super alloys

- Superalloys, or high performance alloys, are alloys that exhibit excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance.
- They typically have an austenitic face-centered cubic crystal structure with a base alloying element of nickel, cobalt, or nickel-iron. The development of superalloys has primarily been driven by the aerospace and power industries.
- The high strength and creep resistance, the alloying elements must produce a strong, stable microstructure at high temperatures. Solid-solution strengthening, dispersion strengthening, and precipitation hardening are generally employed.
- Typical applications include vanes and blades for turbine and jet engines, heat exchangers, chemical reaction vessel components, and heat-treating equipment.
- Hastellloy, nichrome, kanthol, udimet and inconel are nickel based super alloys which possess excellent thermal shock resistance and high electrical resistivity.
- Stellite, hayness, and vitallium are the super alloys of cobalt containing chromium, nickel, molybdenum and tungsten as alloying elements.
- Incoloy is an iron-nickel super alloy contain 46 % Ni and 21% Fe and rest is chromium, used in heat exchangers.

Ceramic Structures

- For those ceramic materials for which the atomic bonding is predominantly ionic, the crystal structures may be thought of as being composed of electrically charged ions instead of atoms.
- The metallic ions, or cations, are positively charged, because they have given up their valence electrons to the nonmetallic ions, or anions, which are negatively charged.
- Two characteristics of the component ions in crystalline ceramic materials influence the crystal structure: **the magnitude of the electrical charge** on each of the component ions, and **the relative sizes of the cations and anions**.
- With regard to the first characteristic, the crystal must be electrically neutral; that is, *all the cation positive charges must be balanced by an equal number of anion negative charges.*
- The chemical formula of a compound indicates the ratio of cations to anions, or the composition that achieves this charge balance.

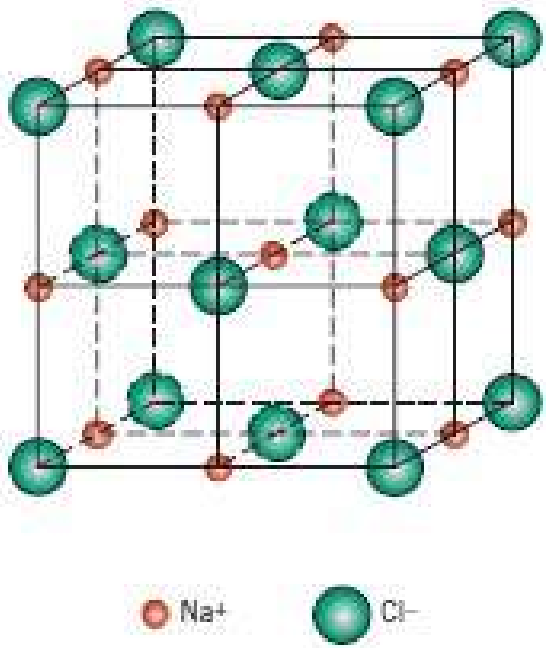
- The second criterion involves the sizes or ionic radii of the cations and anions,
- r_C and r_A respectively.
- The metallic elements give up electrons when ionized, cations are ordinarily smaller than anions, and, consequently, the ratio is less than unity.
- Each cation prefers to have as many nearest-neighbor anions as possible. The anions also desire a maximum number of cation nearest neighbors.
- Stable ceramic crystal structures form when those anions surrounding a ca tion.



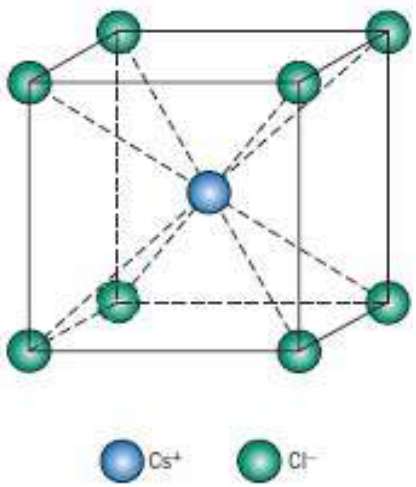
- The coordination number (i.e., number of anion nearest neighbors for a cation) is related to the cation–anion radius ratio.
- For a specific coordination number, there is a critical or minimum ratio for which this cation–anion contact is established.

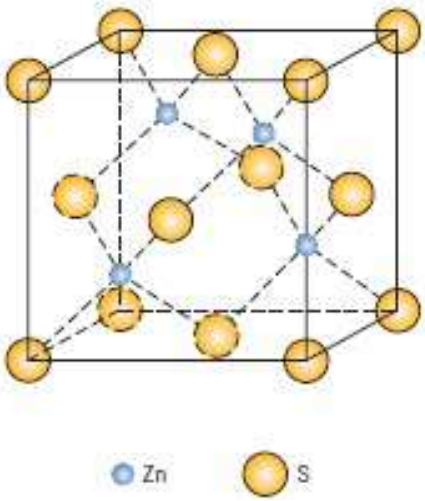
AX-Type Crystal Structures

- Some of the common ceramic materials are those in which there are equal numbers of cations and anions.
- These are often referred to as AX compounds, where A denotes the cation and X the anion.
- There are several different crystal structures for AX compounds; each is normally named after a common material that assumes the particular structure.
- ***Rock Salt Structure***
- The most common AX crystal structure is the sodium chloride (NaCl), or rock salt, type.
- The coordination number for both cations and anions is 6, and therefore the cation–anion radius ratio is between approximately 0.414 and 0.732.
- A unit cell for this crystal structure is generated from an FCC arrangement of anions with one cation situated at the cube center and one at the center of each of the 12 cube edges.
- An equivalent crystal structure results from a face-centered arrangement of cations



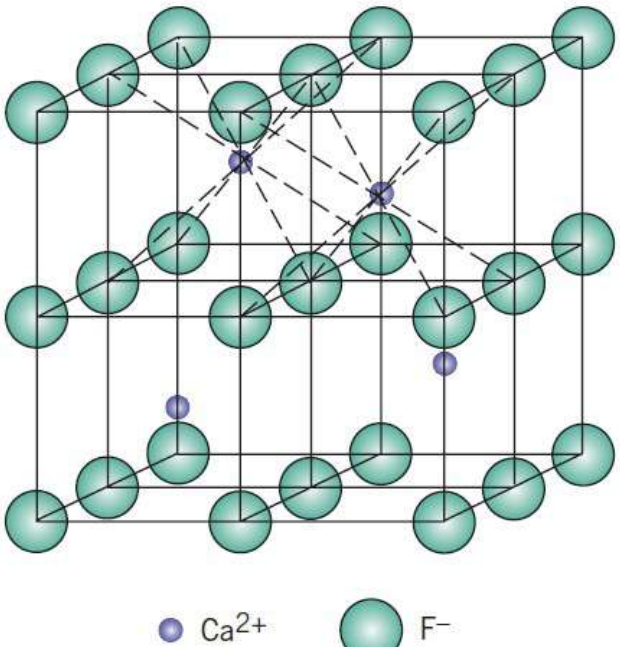
- ***Cesium Chloride Structure***
- For a unit cell for the cesium chloride (CsCl) crystal structure; the coordination number is 8 for both ion types.
- The anions are located at each of the corners of a cube, whereas the cube center is a single cation.
- Interchange of anions with cations, and vice versa, produces the same crystal structure.
- This is not a BCC crystal structure because ions of two different kinds are involved.
- ***Zinc Blende Structure***
- A third AX structure is one in which the coordination number is 4; that is, all ions are tetrahedrally coordinated.
- This is called the zinc blende, or sphalerite, struc-ture, after the mineralogical term for zinc sulfide (ZnS).
- all corner and face positions of the cubic





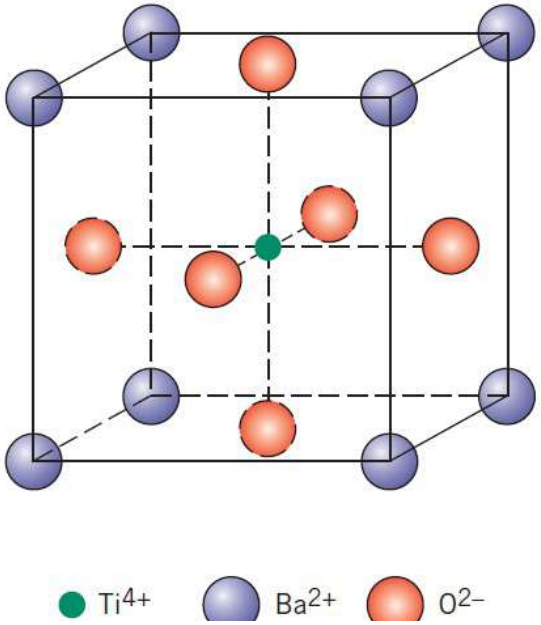
A_mX_p-Type Crystal Structures

- If the charges on the cations and anions are not the same, a compound can exist with the chemical formula A_xM_p where *m* and *p* are not equal.
- An example would be for which a common crystal structure is found in *fluorite* *(CaF_2)*
- The ionic radii ratio for is about 0.8 which, gives a coordination number of 8.
- Calcium ions are positioned at the center fluorine ions at the corners.
- The chemical formula shows that there a Ca^{2+} ions as F^- ions, and therefore the cry similar to CsCl, except that only half the are occupied by ions.
- Other compounds that have this crystal s include ZrO_2 (cubic), UO_2, PuO_2, ThO_2.

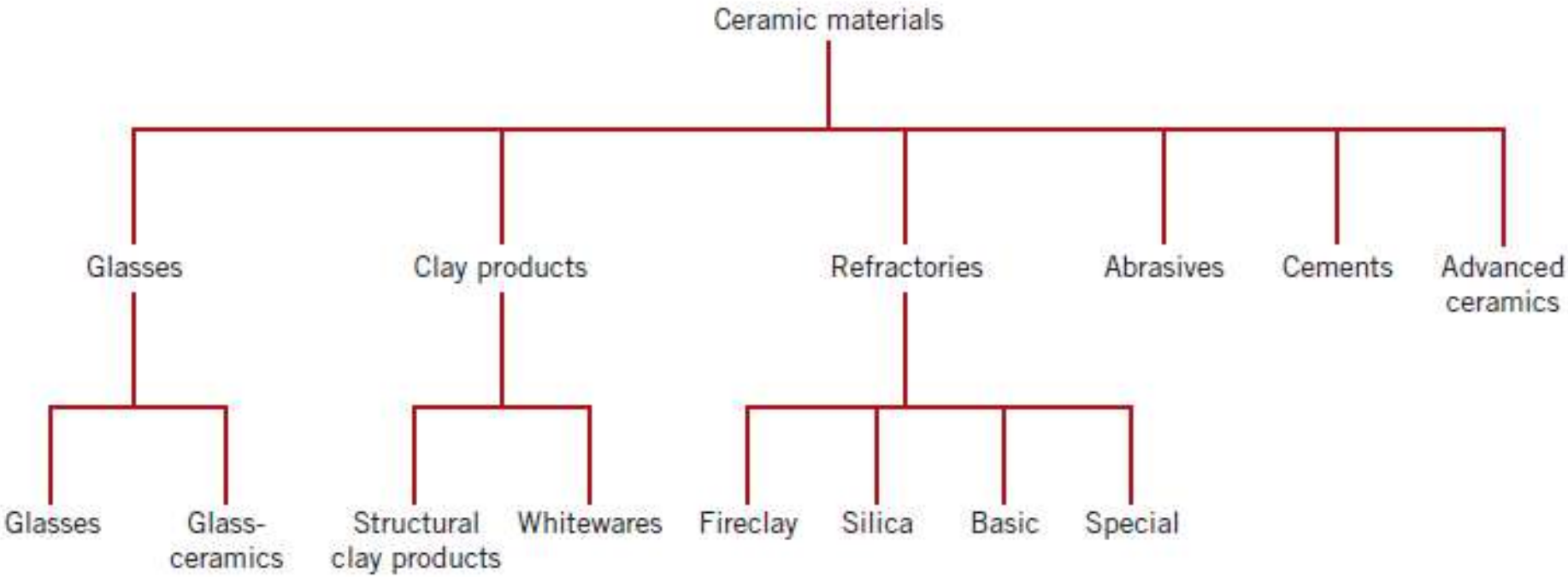


$A_mB_nX_p$-Type Crystal Structures

- It is also possible for ceramic compounds to have more than one type of cation; for two types of cations (represented by A and B).
- Their chemical formula can be designated as $A_mB_nX_p$.
- This material has a ***perovskite crystal structure*** and interesting electromechanical properties
- Barium titanate ($BaTiO_3$), having both Ba^{2+} and Ti^{4+} cations falls into this classification.
- At temperatures above 120 °C the crystal structure is cubic. ***as shown in Figure***
- Ba^{2+} ions are situated at all eight corners of the cube and a single



Applications of ceramic materials

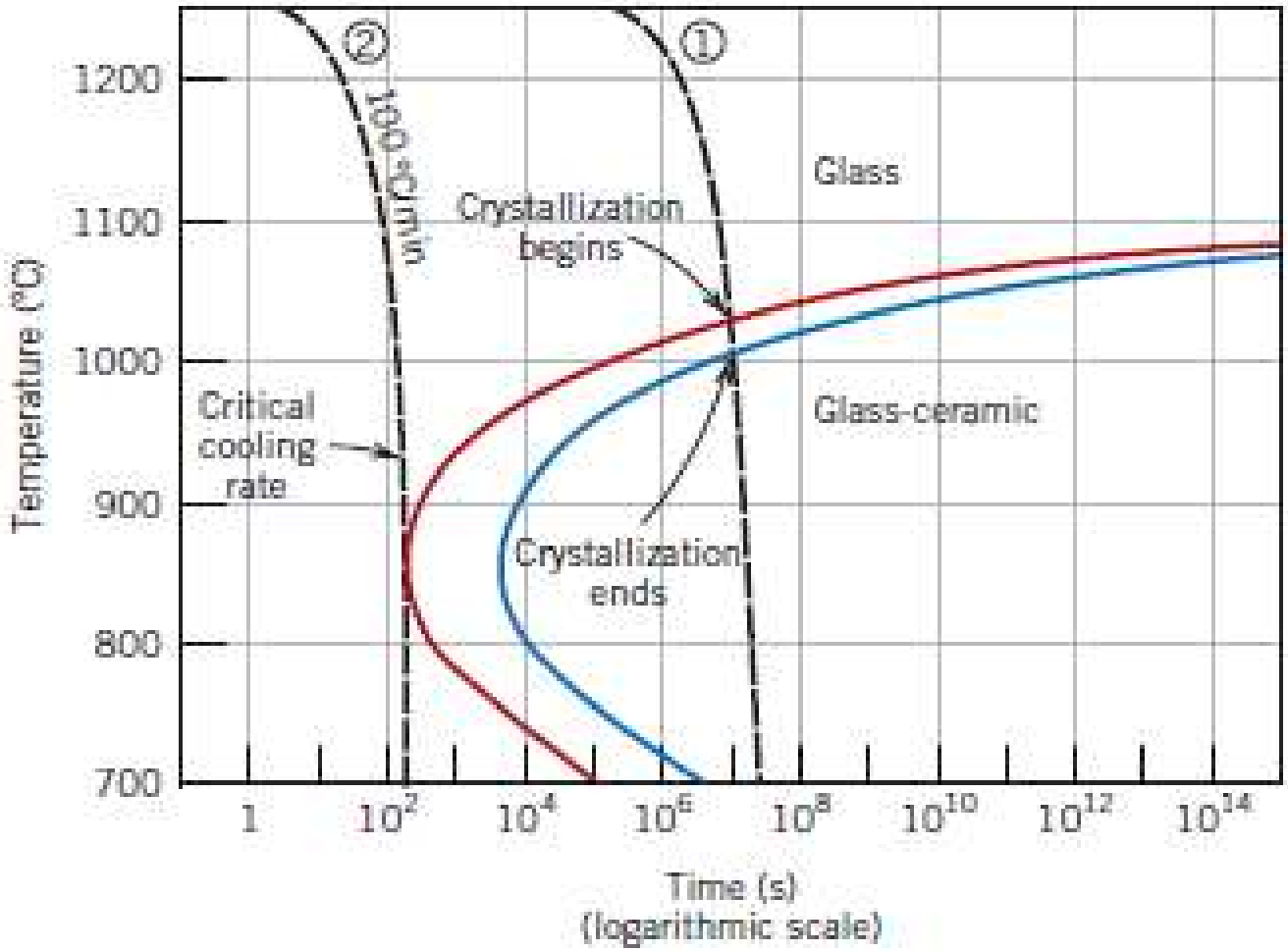


Glasses

- The term glass is used to describe the state of matter known as glassy state, which is obtained when a liquid is cooled without crystallization.
- Glass can be called as super cooled liquid.
- It can be considered as a very viscous liquid when it is solidified.
- It has the physical properties of a solid like brittleness, hardness, transparency and chemical inertness.
- The basic ingredient for the glass is silica sand.
- Compounds like, $CaCO_3$, Na_2CO_3, CaO, Na_2O etc. are also added to make different types of glasses.
- Different combinations of these oxides lead to specific characteristics and hence applications.
- The primary properties of these group of materials are optical transparency and ease of fabrication as compared with other ceramics.
- Glasses are popularly used in construction and engineering applications.
- Glass fibers are used as thermal insulators and as reinforcing materials in plastics.
- Safety glasses used automobiles are sandwich of tough plastic material and two sheets of glass.

Glass-ceramic

- Non-crystalline glass can be subjected to heat treatment to convert them to polycrystalline material.
- This transformation is similar to phase transformation in metallic alloys.
- Glass-ceramics are formed when the cooling rate is more than the critical cooling rate for glass.
- The specific characteristics of glass-ceramics are;
  - Relatively high mechanical strength
  - Low coefficient of thermal expansion
  - High temperature resistance
  - Good dielectric properties
  - Good bio-compatibility
  - Easiness of fabrication
- Applications are; table ware, electrical insulators, oven ware, oven windows, archeological cladding, etc.,


②
①
100 °C/min
Glass
Crystallization begins
Critical cooling rate
Glass-ceramic
Crystallization ends
Temperature (°C)
1200
1100
1000
900
800
700
1
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Time (s)
(logarithmic scale)

Clay ceramics

- One of the most widely used ceramic raw materials is clay.
- This inexpensive ingredient, found naturally in great abundance, often is used as mined without any upgrading of quality.
- Another reason for its popularity lies in the ease with which clay products may be formed; when mixed in the proper proportions, clay and water form a plastic mass that is very responsive to shaping.
- The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.
- Most of the clay-based products fall within two broad classifications: the **structural clay products** and the **whitewares.**
- Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important.
- The **whiteware** ceramics become white after the high-temperature **firing.**
- Included in this group are porcelain, pottery, tableware, and plumbing fixtures (sanitary ware).

Refractory ceramics

- **Refractory ceramics are** materials include the capacity to withstand high temperatures without melting or decomposing, and the capacity to remain unreactive and inert when exposed to severe environments.

Fireclay Refractories

- The primary ingredients for the fireclay refractories are high-purity fireclays, alumina and silica mixtures usually containing between 25 and 45 wt% alumina.
- Fireclay bricks are used principally in furnace construction, to confine hot atmospheres, and to thermally insulate structural members from excessive temperatures.
- For fireclay brick, strength is not ordinarily an important consideration, because support of structural loads is usually not required.

Silica Refractories

- The prime ingredient for silica refractories, sometimes termed acid refractories, is silica.
- These materials, well known for their high-temperature load-bearing capacity, are commonly used in the arched roofs of steel- and glass-making furnaces; for these applications, temperatures as high as 1650°C

Refractory ceramics

Basic Refractories

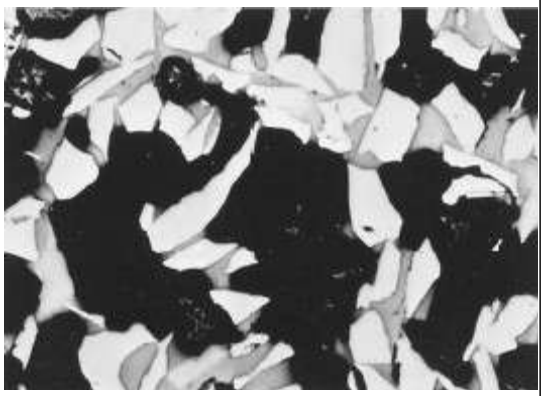
- The refractories that are rich in periclase, or magnesia (MgO), are termed **basic refractories**; they may also contain calcium, chromium, and iron compounds.
- The presence of silica is damaging to the high-temperature performance of basic refractories.
- Basic refractories are especially resistant to attack by slags containing high concentrations of MgO and CaO, and find extensive use in some steel-making open hearth furnaces.

Specialized Refractories

- There are yet other ceramic materials that are used for rather ***specialized refractory*** applications.
- Some of these are relatively high-purity oxide materials, many of which may be produced with very little porosity.
- Included in this group are alumina, silica, magnesia, beryllia (BeO), zirconia (ZrO_2), and mullite ($3Al_2O_3$–$2SiO_2$).
- Others include carbide compounds, in addition to carbon and graphite. Silicon carbide (SiC) has been used for electrical resistance heating elements, as a crucible material, and in internal furnace components.
- Carbon and graphite are very refractory, but find limited application because they are susceptible to oxidation at temperatures in excess of about 800 °C

Abrasives

- **Abrasive ceramics** are used to wear, grind, or cut away other soft materials.
- The primary necessity for this group of materials is hardness or wear resistance; in addition, a high degree of toughness is essential to ensure that the abrasive particles do not easily fracture.
- High temperatures may be produced from abrasive frictional forces, so some refractoriness is also desirable.
- Diamonds, both natural and synthetic, are utilized as abrasives; however, they are relatively expensive. The more common ceramic abrasives include silicon carbide, tungsten carbide (WC), aluminum oxide (or corundum), and silica sand.
- Abrasives are used in several forms—bonded to grinding wheels, as coated abrasives, and as loose grains.
- The abrasive particles are bonded to a wheel by means of a glassy ceramic or an organic resin.
- Coated abrasives are those in which an abrasive powder is coated on some type of paper or cloth material; sandpaper is



the

Cements

- Several familiar ceramic materials are classified as inorganic cements: cement, plaster of paris, and lime, which, as a group, are produced in extremely large quantities.
- The characteristic feature of these materials is that when mixed with water, they form a paste that subsequently sets and hardens.
- Portland cement is consumed in the largest tonnages.
- It is produced by grinding and intimately mixing clay and lime-bearing minerals in the proper proportions, and then heating the mixture to about 1400 °C in a rotary kiln; The process, sometimes called **calcination**.
- The resulting "***clinker***" product is then ground into a very fine powder to which is added a small amount of gypsum ($CaSO_4$–$2H_2O$) to retard the setting process.

Advanced ceramics

- The properties such as; electrical, magnetic, and optical properties and property combinations unique to ceramics have been made use by advanced ceramics.
- Advanced ceramics are utilized in optical fiber communications systems, in microelectromechanical systems (MEMS) and as piezoelectric materials.
- Commonly used piezoelectric ceramics include barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), lead zirconate–titanate (PZT) etc.
- Piezoelectric materials can be utilized as transducers between electrical and mechanical energies.
- It develops voltage across two of its faces, when compressed or changes shape.
- A pyroelectric material develop voltage when there is a temperature difference.
- One of the early uses of piezoelectric ceramics was in sonar, wherein underwater objects (e.g., submarines) are detected and their positions determined using an ultrasonic emitting and receiving system.
- Applications that employ piezoelectric devices are found in the automotive, computer, commercial/consumer, and medical sectors.
- Some of these applications are as follows: automotive-wheel balances, seat belt buzzers, tread-wear indicators, keyless door entry, and airbag sensors; commercial/consumer—ink-jet printing heads, strain gauges, ultrasonic welders, and smoke detectors; medical—insulin pumps, ultrasonic therapy, and ultrasonic cataract-removal devices.

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 latter 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 reduces 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 behavior to guarantee the safe operation of the reactor during its whole lifetime.

Nuclear materials

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 channels 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.
- Aluminium, stainless steel, zirconium and zirconium alloys like zircalloy are being used as cladding materials.
- In general, those materials which are suitable for use as cladding materials are suitable for other structural purposes also.
- 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

Nuclear materials

Structural Materials

- ***Concrete*** is used extensively for building foundations and also as a biological shielding in a number of operating areas.
- ***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 process vessels and piping.
- The advantages of austenitic stainless steels are their inherently high resistance to corrosion in oxidizing media such as nitric acid.
- Nickel alloys are generally used in situations involving high temperatures. ***Inconel*** alloy is suitable for this purpose.
- ***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.
- Smart materials refers to a class of materials that is highly responsive and have the 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).
- “A 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.
- Some 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.

Smart Materials

- **Advantages of smart materials**
- No moving parts.
- High reliability.
- Low power requirements.
- Provide new capabilities that are presently not possible.

Applications of smart materials

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

There are a number of types of smart materials, some of which are already popular. They are piezoelectric, shape memory alloys, Magnetostrictive materials etc.

Smart Materials

Piezoelectric materials:

- These are materials which produce a voltage when stress is applied.
- 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 materials can be operated as both actuators and sensors.
- In ***actuator mode***, elongation (strain) 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 stereospeakers, computer keyboards and

Smart Materials

- ***Shape memory alloys:*** Shape memory alloys (SMA) 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 pre-deformed 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,

Smart Materials

Magnetostrictive materials

- ***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

- ***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

Biomaterials

- 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 man made, 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.

Biomaterials

Uses of Biomaterials

Problem Area.	**Examples**
Replacement of diseased or damaged part	Artificial hip joint, kidney dialysis machine
Assist in healing	Sutures, bone plates, and 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

Biomaterials

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

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

Biomaterials

Polymeric Biomaterials

- The polymeric systems include acrylics, polyamides, polyesters, polyethylene, polysiloxanes, polyurethane and a number of reprocessed biological materials.
- Some of the 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 vessels, artificial skin and sutures.
- Polymeric materials alone and in combination with metals and ceramics are becoming increasingly

Biomaterials

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 corrosion are the disintegration of the implant material and the harmful effect of corrosion products on the surrounding

Biomaterials

Stainless Steels:

- Stainless steels of different types are used successfully. As biomaterials .
- Type 302 stainless steel is stronger and more resistant to corrosion than the vanadium steel.
- The type 316 stainless steel, contains a small percentage of molybdenum to improve the corrosion resistance in chloride solution,
- In the Type 316 L stainless steel, carbon content is reduced from 0.08 to a maximum amount of 0.03%, for better corrosion resistance to chloride solutions.
- The inclusion of molybdenum enhances resistance to pitting corrosion in salt water.
- Even the 316L stainless steels 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.
- Thus, these stainless steels are suitable for use only in temporary implant devices, such as fracture plates, screws, and hip nails.

Biomaterials

CoCr Alloys:

- There are basically two types of cobalt-chromium alloys popularly used as biomaterials:
  - The CoCrMo alloy [Cr (27-30%), Mo (5-7%), Ni (2.5%)) has been used for many decades in dentistry and in making artificial joints
  - The CoNiCrMo alloy (Cr (19-21%), Ni (33-37%), and Mo (9- 1 1%)) has been used for making the sterns of prostheses for heavily loaded joints, such as knee and hip.
- The ASTM lists four types of CoCr alloys, which are recommended for surgical implant applications:
  - CoCrMo alloy [Cr (29-30%), Mo (5-7 %), Ni (2 . 5 %))
  - CoCrWNi alloy (Cr (19 - 21%), W (1 4 - 16 %), Ni (9 - 1 1 %))
  - CoNiCrMo alloy [Ni (3 3 -3 7 %), Cr (19 -2 1 %), Mo (9 - 1 1%)]
  - CoNiCrMoWFe alloy [Ni (15-2 5 %), Cr (18 - 2 2 %), Mo (3 -4 %), W (3 -4 %), Fe (4 - 6 %)]
- The two basic elements of the CoCr alloys form a solid solution of up to 65%Co.
- Molybdenum is added to produce finer grains, which results in higher strengths after casting.
- The chromium 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

- Titanium and its alloys are getting great attention in both medical and dental fields because of
  - 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 Aluminum (5.5-6.5 %) and Vanadium (3.5 - 4.5 %).
- The addition of alloying elements to titanium enables it to have a wide range of properties :
- Aluminum tends to stabilize the α-phase; it increases the transformation temperature from α- to β-phase.
- Vanadium stabilizes the β-phase by lowering the temperature of transformation from α to β.

Biomaterials

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.

Biomaterials

Composite Biomaterials

- By definition, composites contain two or more distinct constituent 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 consist 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 (SiO_2) to make the rubber stronger and tougher.)