

MODULE-I (16 Lectures)

Classification of Engineering Materials, Engineering properties of materials. Characteristic property of metals, bonding in solids, primary bonds like ionic, covalent and metallic bond, crystal systems, common crystal structure of metals, representations of planes and directions in crystals, atomic packing in crystals, calculation of packing density, voids in common crystal structures and imperfections crystals.

Chapter-1

Introduction to Engineering Materials

Introduction

Materials play an important role for our existence, for our day to day needs ,and even for our survival. In the stone age the naturally accessible materials were stone, wood, bone, fur etc *Gold was the 1st metal used by the mankind followed by copper.* In the bronze age Copper and its alloy like bronze was used and in the iron age they discovered Iron (sponge iron & later pig iron).

1960's	Engineering Materials	Metals
Design	Choice of Material	
New Materials	New Products	
Number of Materials	40 – 80,000!	

General Definition of Material

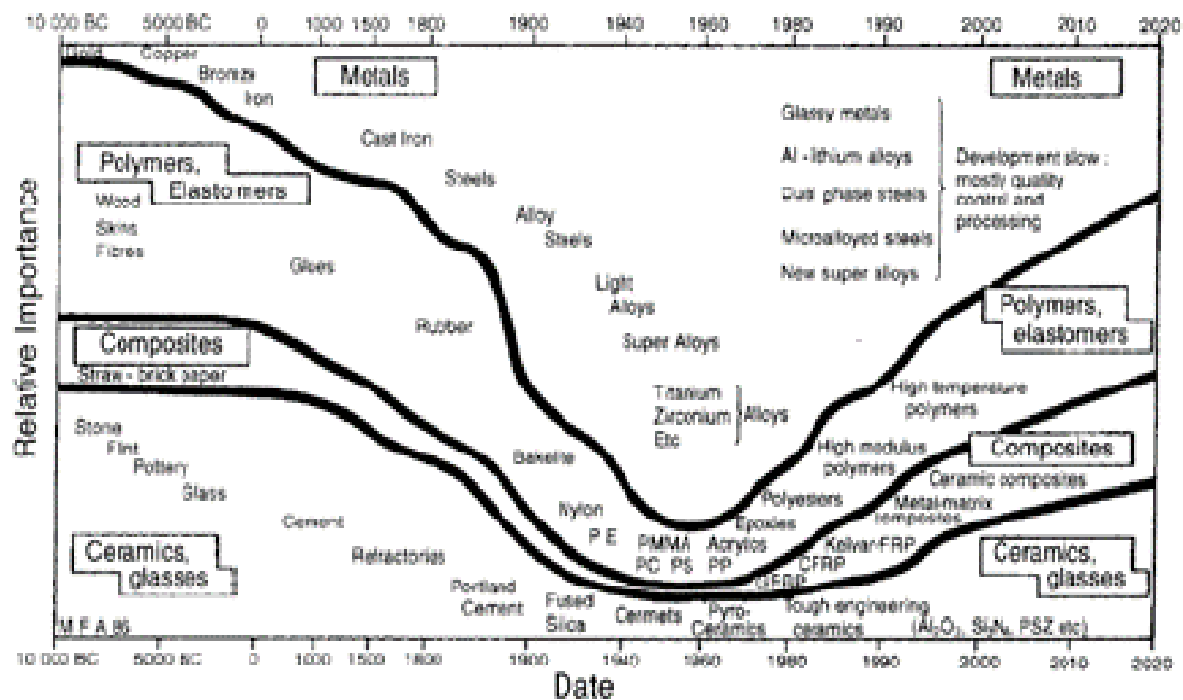
According to Webster's dictionary, materials are defined as '*substances of which something is composed or made*'

Engineering Material: Part of inanimate matter, which is useful to engineer in the practice of his profession (used to produce products according to the needs and demand of society)

Material Science: Primarily concerned with the search for basic knowledge about internal structure, properties and processing of materials and their complex interactions/relationships

Material Engineering: Mainly concerned with the use of fundamental and applied knowledge of materials, so that they may be converted into products, as needed or desired by the society (bridges materials knowledge from basic sciences to engineering disciplines)

Note: Material science is the basic knowledge end of materials knowledge spectrum, where as, material engineering is applied knowledge end and there is no demarcation line between the two subjects of interest



Evolution of Engineering Materials

Why Material Science & Engineering is important to technologists?

Examples:

- Mechanical engineers search for high temp material so that gas turbines, jet engines etc can operate more efficiently and wear resistance materials to manufacture bearing materials
- Electrical engineers search for materials by which electrical devices or machines can be operated at a faster rate with minimum power losses
- Aerospace & automobile engineers search for materials having high strength-to-weight ratio
- Electronic engineers search for material that are useful in the fabrication & miniaturization of electronic devices
- Chemical engineers search for highly corrosion-resistant materials

Note: All these demands may be fulfilled when the internal structure and engineering properties are known to an engineer or technologist

Classification

It is the systematic arrangement or division of materials into groups on the basis of some common characteristic

1. *According to General Properties*

2. *According to Nature of Materials*

3. *According to Applications*

1. According to General Properties

(a). *Metals* (e.g. iron, aluminium, copper, zinc, lead, etc)

Iron as the base metal, and range from plain carbon (> 98 % Fe) to (i). *Ferrous*: high alloy steel (< 50 % alloying elements), e.g. cast iron, wrought iron, steel, alloys like high-speed steel, spring steel, etc

(ii). *Non-Ferrous*: Rest of the all other metals and their alloys, e.g. copper, aluminium, zinc lead, alloys like brass, bronze, duralumin, etc

(b). *Non-Metals* (e.g. leather, rubber, asbestos, plastics, etc)

2. According to Nature of Materials

(a). *Metals*: e.g. Iron & Steel, Alloys & Superalloys, Intermetallic Compounds, etc

(b). *Ceramics*: e.g. Structural Ceramics (high-temperature load bearing), Refractories (corrosion-resistant, insulating), Whitewares (porcelains), Glass, Electrical Ceramics (capacitors, insulators, transducers), Chemically Bonded Ceramics (cement & concrete)

(c). *Polymers*: e.g. Plastics, Liquid Crystals, Adhesives

(d). *Electronic Materials*: e.g. Silicon, Germanium, Photonic materials (solid-state lasers, LEDs)

(e). *Composites*: e.g. Particulate composites (small particles embedded in a different material), Laminate composites (golf club shafts, tennis rackets), Fiber reinforced composites (fiberglass)

(f). *Biomaterials*: e.g. Man-made proteins (artificial bacterium), Biosensors, etc

(g). *Advanced / Smart Materials*: e.g. materials in computers (VCRs, CD Players, etc), fibreoptic systems, spacecrafts, aircrafts, rockets, shape-memory alloys, piezoelectric ceramics, magnetostrictive materials, optical fibres, microelectromechanical (MEMs) devices, electrorheological / magnetorheological fluids, Nanomaterials, etc

3. According to Applications

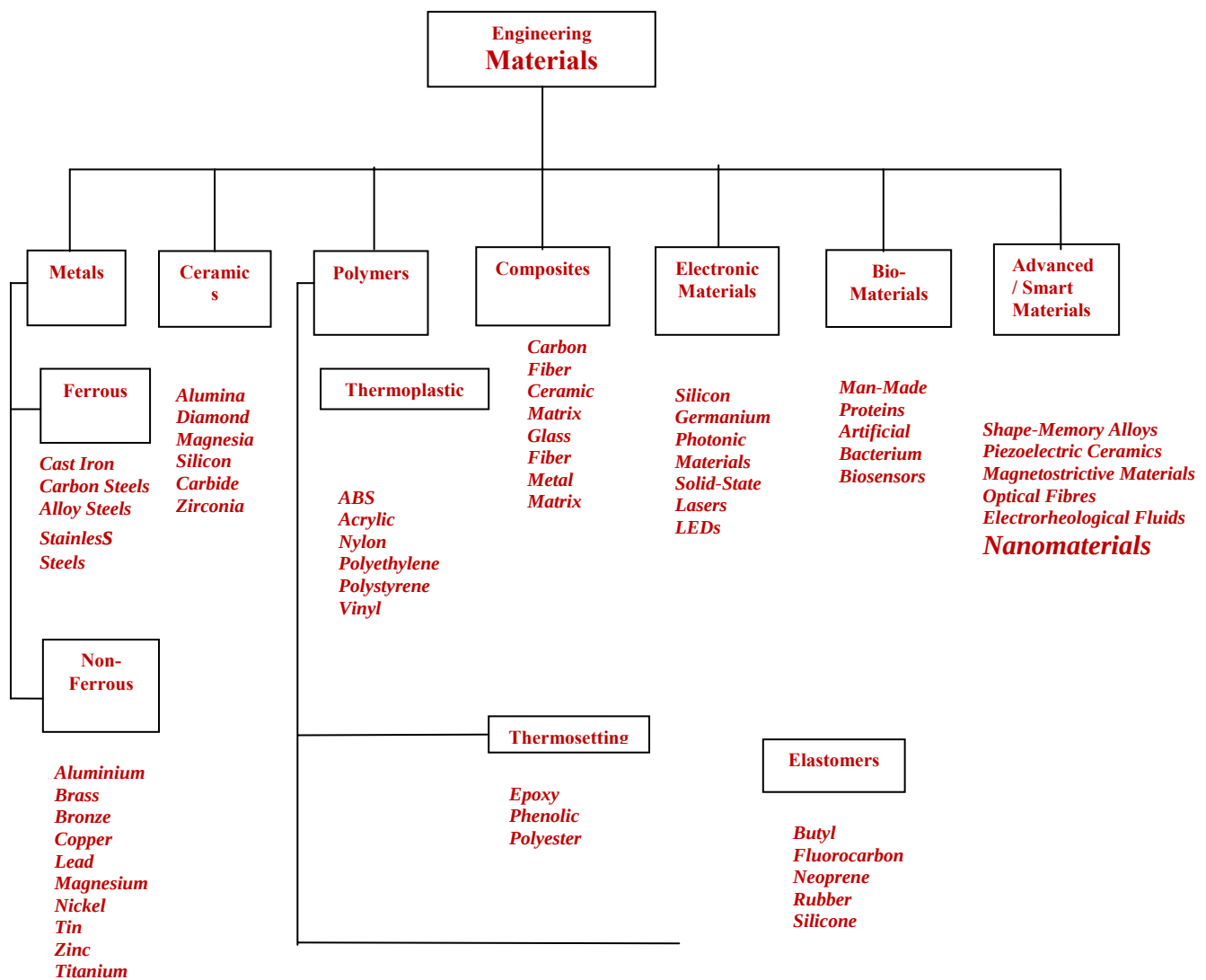
(a). *Electrical Materials*: e.g. conductors, insulators, dielectrics, etc

(b). *Electronic Materials*: e.g. conductors, semi-conductors, etc

(c). *Magnetic Materials*: e.g. ferromagnetic, paramagnetic & diamagnetic materials, etc

(d). *Optical Materials*: e.g. glass, quartz, etc

(e). *Bio Materials*: e.g. man-made proteins, artificial bacterium

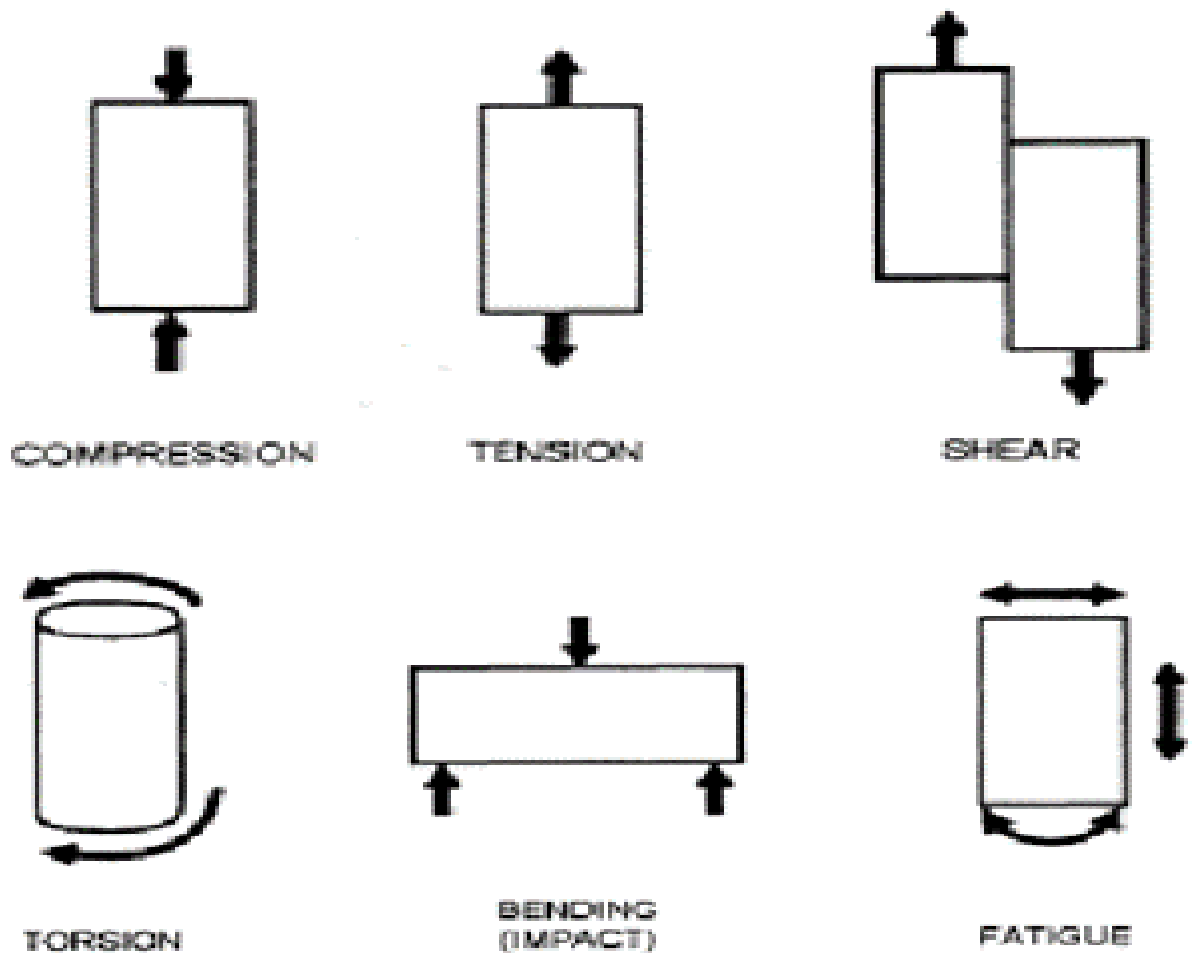


Difference between Metals & Non-Metals

Property	Metals	Non-Metals
Structure	Crystalline	Amorphic
State	Generally solids at room temp.	Gaseous & solid at ordinary temp.
Luster	Metallic luster	No metallic luster (except iodine & graphite)
Conductivity	Good conductors of heat & electricity	Bad conductors
Malleability	Malleable	Not malleable
Ductility	Ductile	Not ductile
Hardness	Generally hard	Hardness varies
Electrolysis	Form anions	Form anions
Excitation of valence electron by e.m.f.	Easy	Difficult
Density	High	Low

1. Material Properties

- *Physical*: e.g. appearance, shape, weight, boiling point, melting point, freezing point, density, glass transition temperature, permeability
- *Mechanical*: e.g. strength (tensile, compressive, shear, torsion, bending), elasticity, plasticity, ductility, malleability, rigidity, toughness, hardness, brittleness, impact, fatigue, creep, strain hardening, Bauschinger effect, strain rate effect, vibration resistance, wear
- *Thermal*: e.g. thermal conductivity, expansion coefficient, resistivity, thermal shock resistance, thermal diffusivity



Types of Force / Stress System

- *Electrical:* e.g. conductivity, resistivity, dielectric strength, thermoelectricity, superconductivity, electric hysteresis
- *Magnetic:* e.g. ferromagnetism, paramagnetism, diamagnetism, magnetic permeability, coercive force, curie temperature, magnetic hysteresis
- *Chemical:* e.g. reactivity, corrosion resistance, polymerization, composition, acidity, alkalinity
- *Optical:* e.g. reflectivity, refractivity, absorptivity, transparency, opaqueness, color, luster

Metallurgical: e.g. grain size, heat treatment done / required, anisotropy, hardenability

Imperfections in Crystals

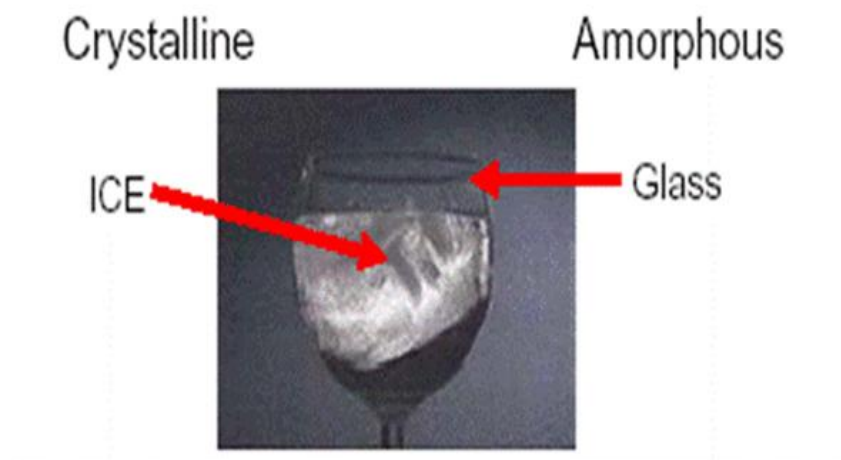
Introduction to Crystal Geometry

- Materials may be classified as Crystalline or Non-Crystalline structures
- Crystalline solid can be either *Single Crystal Solid* (crystal lattice of entire sample is continuous and unbroken to edges of sample with no grain boundary) or *Poly Crystal Solid* (aggregate of many crystals separated by well-defined boundaries)
- Cluster of crystals with identical structure (same crystallographic planes & directions) are known as *Grains* separated by *Grain Boundaries*
- X-ray diffraction analysis shows that atoms in metal crystal are arranged in a regular, repeated 3-D Pattern known as *Crystalline Structure*

Example:

Ceramic: Inorganic non-metallic crystalline (regular internal Structure) materials

Glass: Inorganic non-metallic non-crystalline / amorphous (completely disordered form) material



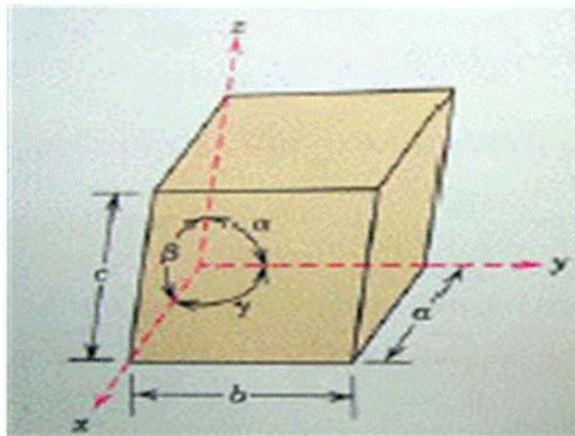
- Arrangement of atoms can be most simply portrayed by *Crystal Lattice*, in which atoms are visualized as, *Hard Balls* located at particular locations
- Space Lattice / Lattice: Periodic arrangement of points in space with respect to three dimensional network of lines
- Each atom in lattice when replaced by a point is called *Lattice Point*, which are the intersections of above network of lines
- Arrangement of such points in 3-D space is called *Lattice Array* and 3-D space is called *Lattice Space*

- Tiny block formed by arrangement of small group of atoms is called *Unit Cell*. It is chosen to represent the symmetry of crystal structure, and may be defined as:
 - Finite representation of infinite lattice
 - Small repeat entity
 - Basic structural unit
 - Building block of crystal structure
 - Can generate entire crystal by translation

Lattice Parameters

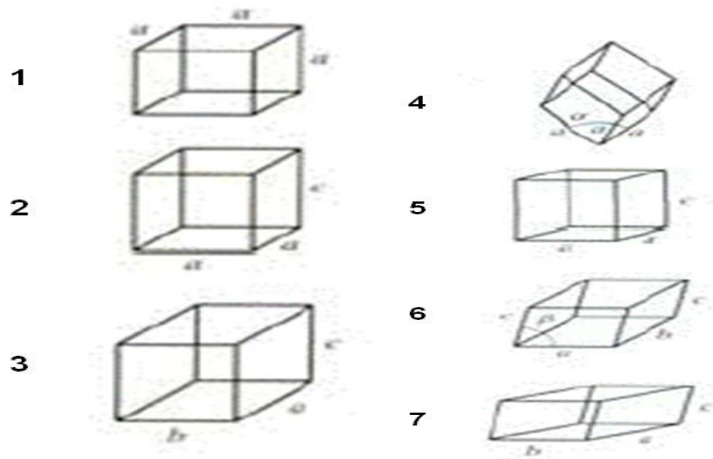
- Six lattice parameters $a, b, c, \alpha, \beta, \gamma$
- Typically in the order of few Angstroms (few tenths of nanometer)
- Example: Cubic structure has following lattice parameters:

$$a = b = c \text{ and } \alpha = \beta = \gamma = 90^\circ$$



Types of Crystal

Cubic, Monoclinic, Triclinic, Tetragonal, Orthorhombic, Rhombohedral and Hexagonal



No.	Crystal Type	Lattice Parameters	Examples
1.	Cubic	$a = b = c, \alpha = \beta = \gamma = 90^\circ$	Fluorite, Garnet, Pyrite
2.	Tetragonal	$a = b \neq c, \alpha = \gamma = 90^\circ = \beta$	Zircon
3.	Orthorhombic	$a \neq b \neq c, \alpha = \gamma = \beta = 90^\circ$	Topaz
4.	Rhombohedral	$a = b = c, \alpha = \beta = \gamma \neq 90^\circ$	Tourmaline
5.	Hexagonal	$a = b \neq c, \alpha = \beta = 90^\circ, \gamma = 120^\circ$	Corundum
6.	Monoclinic	$a \neq b \neq c, \alpha = \gamma = 90^\circ \neq \beta$	Kunzite
7.	Triclinic	$a \neq b \neq c, \alpha \neq \gamma \neq \beta \neq 90^\circ$	Amazonite

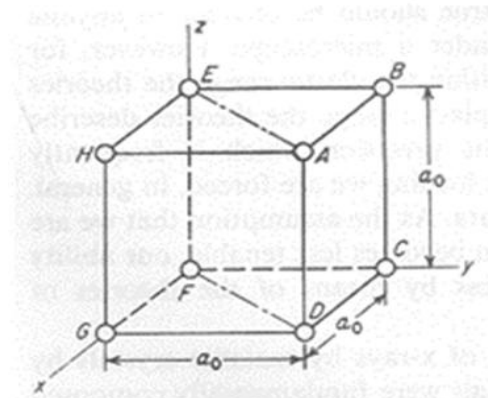
Principal Metal Crystal Structures

- Simple Cubic Lattice Structure
- Body Centered Cubic (BCC) Structure

- *Face Centered Cubic (FCC) Structure*

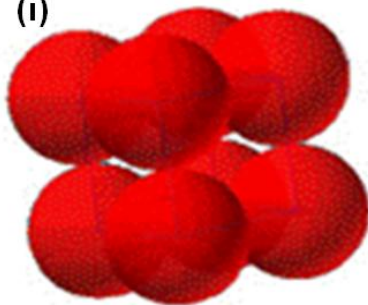
Simple Cubic Lattice

- Most elementary crystal structure with three mutually perpendicular axes arbitrarily placed through one of the corners of a cell
- Each corners occupied with one atom
- Example: alpha polonium

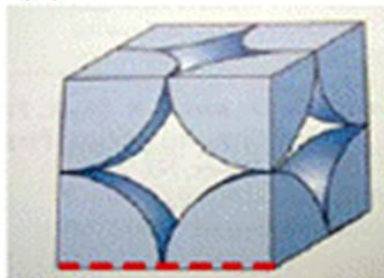


SC Structure

(i)



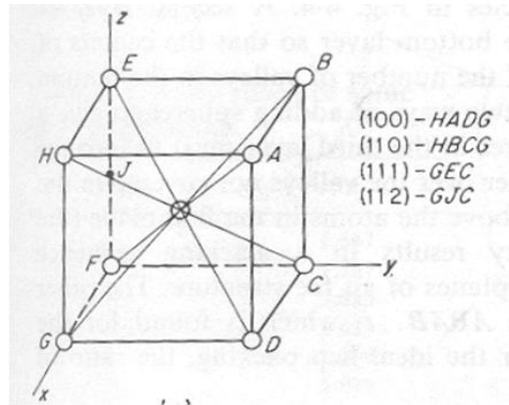
(ii)



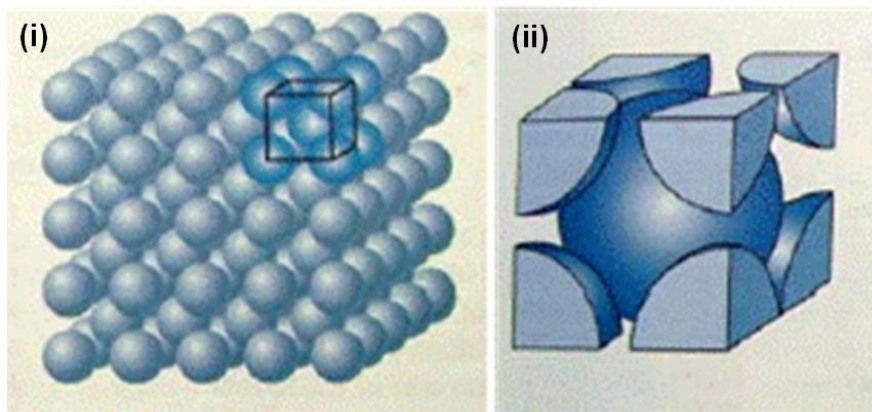
(i). Aggregate of atoms (ii). Hard Sphere Unit Cell

Body Centered Cubic (BCC) Structure

- BCC cell has an atom at each corner and another atom at body center of cube
- Each atom at corner is surrounded by eight adjacent atoms
- Example: alpha iron, chromium, molybdenum & tungsten



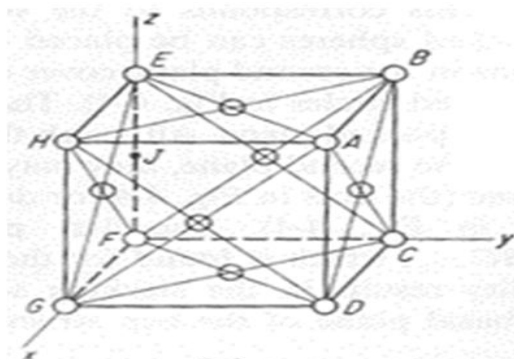
BCC Structure



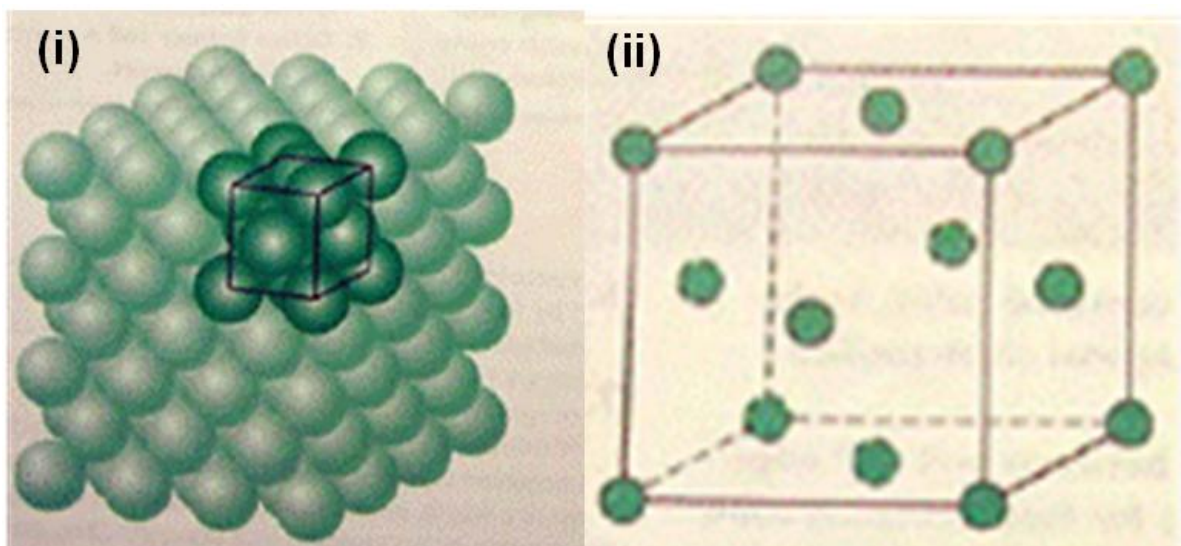
i). Aggregate of atoms (ii). Hard Sphere Unit Cell

Face Centered Cubic (FCC) Structure

- Atoms at each corner of cube, and in addition there is an atom at the center of each cube's face
- Example: aluminium, copper, gold, lead, silver and nickel



FCC Structure

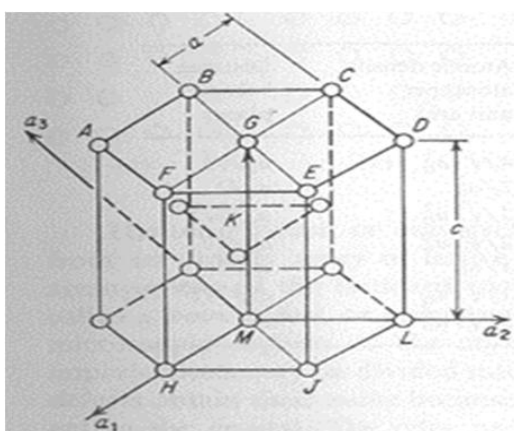


(i). Aggregate of atoms

(ii). Hard Sphere Unit Cell

Hexagonal Close-packed (HCP) Structure

- Unit cell has an atom at each of twelve corners of hexagonal prism, with one atom at centre of each of two hexagonal faces and three atoms in body of cell
- Example: zinc, lithium, magnesium, beryllium



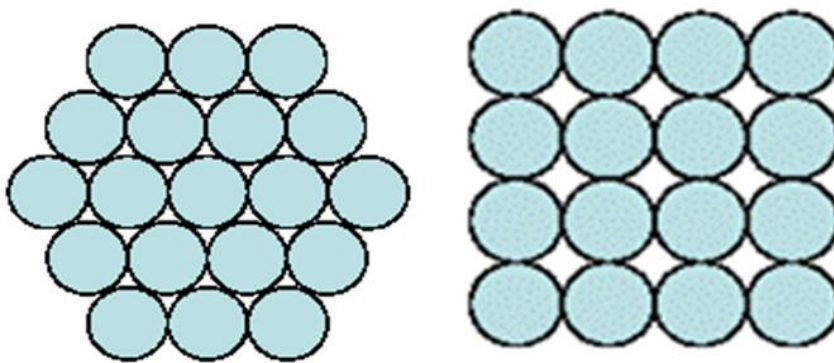
Comparison

Sl. No.	APF (Atomic Packing Factor) (Ratio of vol . of atoms in unit cell to unit cell vol.)	Co-ordination Number (No. of nearest neighbor atoms)
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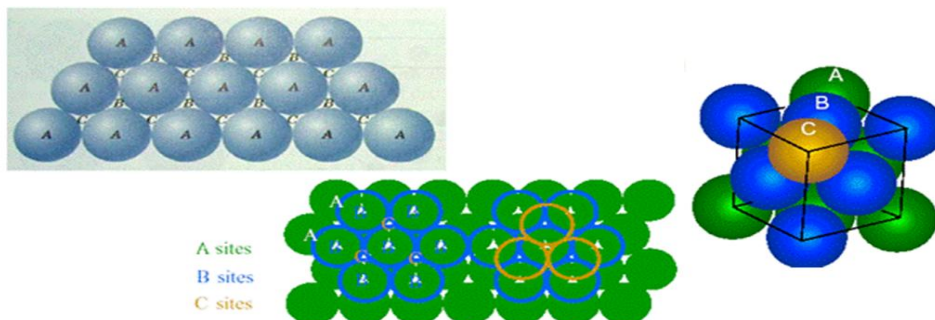
SC	0.52	6
BCC	0.68	8
FCC	0.72	12

Close-Packed Structures

- How can metal atoms be stacked to fill empty spaces in the lattice?
- Can these 2-D layers be stacked to make 3-D structures

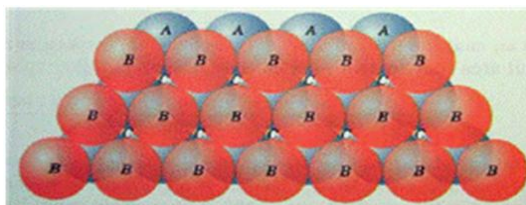


Example: Close-Packed FCC Structure

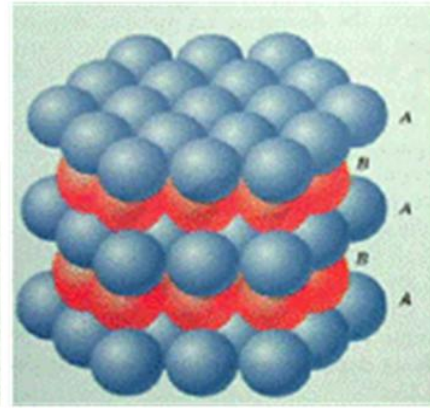
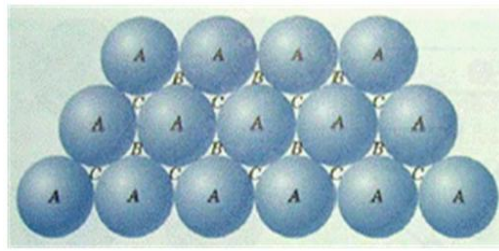


ABC Stacking Sequence

Example: Close-Packed HCP Structure



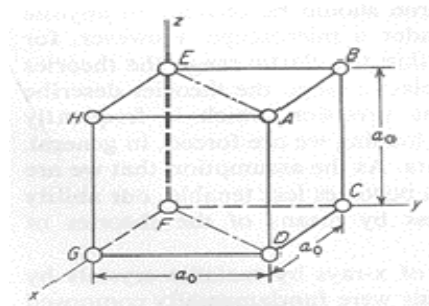
AB Stacking Sequence



ABC Stacking Sequence

Crystallographic Planes & Directions

- *Crystallographic Planes & Directions* are specified with respect to the reference axes in terms of '*Miller Indices*', which is the system of notation of planes within a crystal of space lattice
- Example: SC structure is chosen for understanding



- *Crystallographic Plane* is specified in terms of length of its intercepts on three mutually perpendicular axes. To simplify it, reciprocals of these intercepts reduced to lowest common denominator (LCM) are used as miller indices,
e.g. plane ABCD in figure is parallel to x and z axes and intersects y-axis at one interatomic distance ' a_0 ', therefore miller indices of the plane are $1/\infty$, $1/a_0$, $1/\infty$ or $(hkl) = (010)$

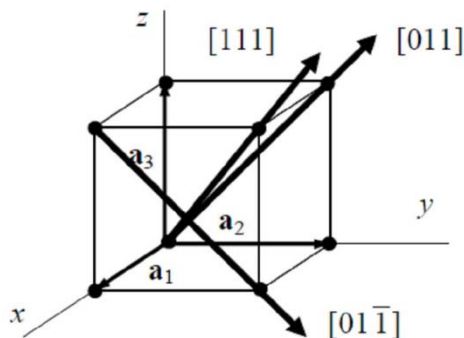
- Plane EBCF is designated as $(\bar{0}0)$ plane, where bar indicates that plane intersects the axis in negative direction
- *Crystallographic Directions* are indicated by integers in brackets like $[uvw]$, where reciprocals are never used, e.g. direction 'FD' is obtained by moving out from origin, a distance ' a_0 ' along positive x-axis and moving same distance along positive y-axis also, therefore, the crystallographic direction will be given as $[110]$
- Example: Ionic crystals like NaCl, LiF (not for metals)

Note: For simple cubic lattice only, direction is always perpendicular the plane having same indices

Index system for crystal directions and planes

Crystal directions:

The direction is specified by the three integers $[n_1n_2n_3]$. If the numbers $n_1n_2n_3$ have a common factor, this factor is removed. For example, $[111]$ is used rather than $[222]$, or $[100]$, rather than $[400]$. When we speak about directions, we mean a whole set of parallel lines, which are equivalent due to transnational symmetry. Opposite orientation is denoted by the negative sign over a number. For example:



Crystal planes: The orientation of a plane in a lattice is specified by *Miller indices*. They are defined as follows. We find intercept of the plane with the axes along the primitive translation

vectors a_1 , a_2 and a_3 . Let's these intercepts be x , y , and z , so that x is fractional multiple of a_1 , y is a

fractional multiple of a_2 and z is a fractional multiple of a_3 . Therefore we can measure x , y , and z in

units a_1 , a_2 and a_3 respectively. We have then a triplet of integers $(x y z)$. Then we invert it $(1/x 1/y$

$1/z)$ and reduce this set to a similar one having the smallest integers by multiplying by a common

factor. This set is called Miller indices of the plane (hkl) . For example, if the plane intercepts x , y ,

and z in points 1, 3, and 1, the index of this plane will be (313) .

The orientation of a crystal plane is determined by three points in the plane, provided they are not

collinear. If each point lay on a different crystal axis, the plane could be specified by giving the coordinates

of the points in terms of the lattice constants a , b , c . A notation conventionally used to describe lattice points (sites), directions and planes is known as Miller Indices.

A crystal lattice may be considered as an assembly of equidistant parallel planes passing through the

lattice points and are called lattice planes. In order to specify the orientation one employs the so called Miller indices.

Crystal direction is the direction (line) of axes or line from the origin and denoted as $[111]$, $[100]$, $[010]$ etc.

How to find Miller Indices:

To determine the indices for the plane p in Figure 2,

-first we have to find the intercepts with the axes along the basis vector

be x, y, z . We form the fractional triplet Let these intercepts

-Take reciprocal to this set.

-Then reduce this set to a similar one having the smallest integers multiplying by common factor.

To determine the Miller indices:

(i) Find the intercepts on the axes along the basis vector

$\rightarrow \rightarrow \rightarrow$

cba ,, in terms of the lattice constants a, b

and c . The axes may be those of a primitive or nonprimitive cell.

Let these intercepts be x, y, z . We form the fractional triplet

.

(ii) Take the reciprocals of these numbers.

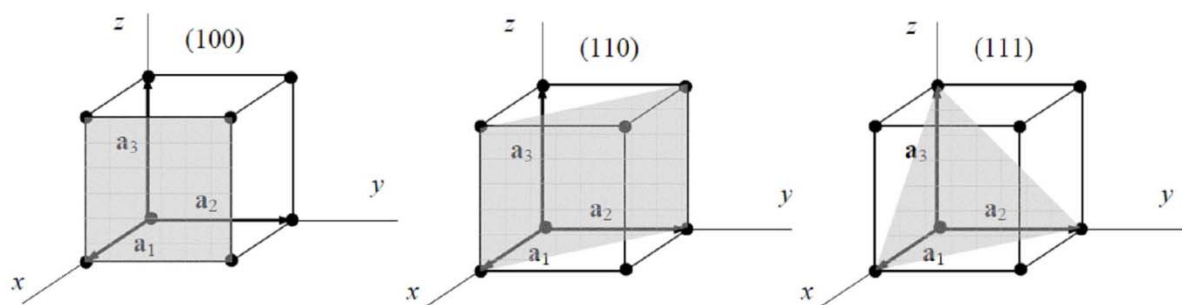
(iii) Reduce the numbers to three smallest integers by multiplying the numbers with the same integral multipliers.

This last set is enclosed in parentheses $(h\ k\ l)$, is called the index of the plane or Miller Indices.

The Miller indices specify not just one plane but an infinite set of equivalent planes. Note that for

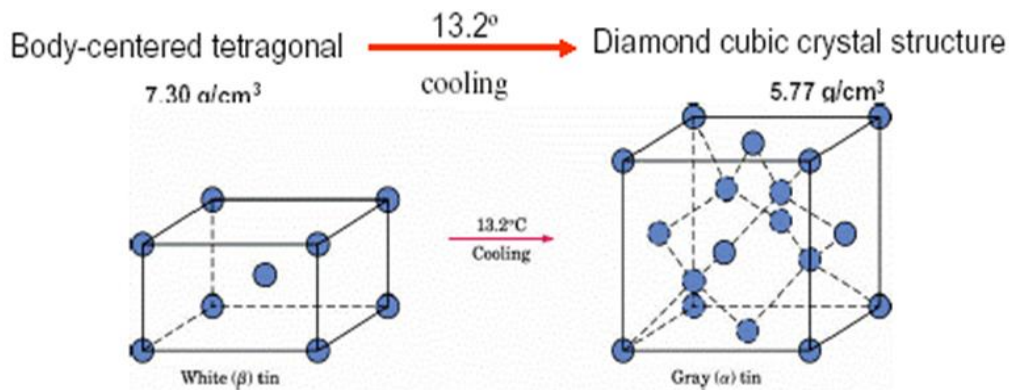
cubic crystals the direction $[hkl]$ is perpendicular to a plane (hkl) having the same indices, but this is

not generally true for other crystal systems. Examples of the planes in a cubic system:



Allotropy / Polymorphism

- Two or more distinct crystal structures for the same material at different temperature & pressure
- Examples: iron (α -iron & γ -iron), carbon (graphite & diamond), tin (α -tin & β -tin)



Imperfection / Defects In Crystals

In actual crystals, imperfection or defects are always present, which are important to understand, as they influence the properties of material

Classifications of Defects

(i). Point Defects (Zero Dimensional Defects)

- (a). Vacancy
- (b). Schottky Imperfections
- (c). Interstitialcy
- (d). Frenkel Defect
- (e). Compositional Defect
 - Substitutional Defect
 - Interstitial Impurity
- (f). Electronic Defect

(ii). Line Defects / Dislocations (One Dimensional Defects)

- (a). Edge Dislocations
- (b). Screw Dislocations

(iii). Surface / Plane Defects (Two Dimensional Defects)

(a). External Defects

(b). Internal Defects

- Grain Boundary Defect
- Tilt Boundary Defect
- Twin Boundary Defect
- Stacking Fault

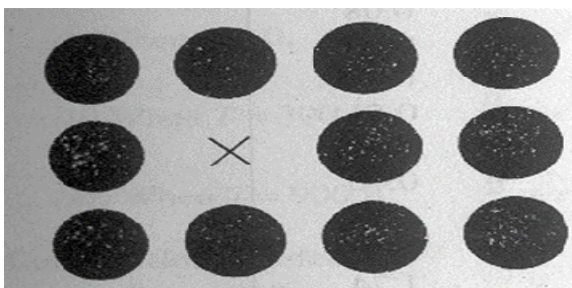
(iv). Volume Defects (Three Dimensional Defects)

(I). Point Defects (Zero Dimensional Defects)

- Imperfect point like regions in crystal (size is one or two atomic diameter)
- Completely local in effect, i.e. vacant lattice site
- Always present in crystals
- Created by thermal fluctuations, quenching (high rate of cooling), severe deformation of crystal lattice (hammering or rolling) or external bombardment by atoms / high energy particles

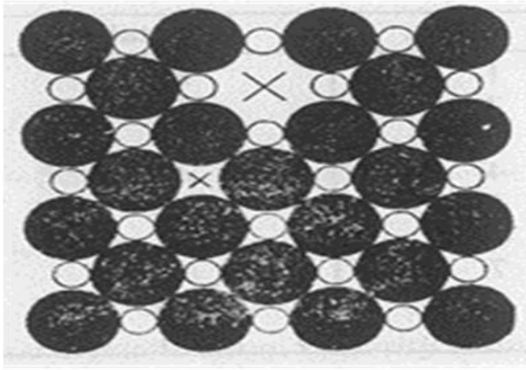
(a). Vacancy

- Simplest type of point defect involving a missing atom within crystal lattice of metal, which results due to imperfect packing during original crystallization process or by thermal vibrations of atoms at very high temperature



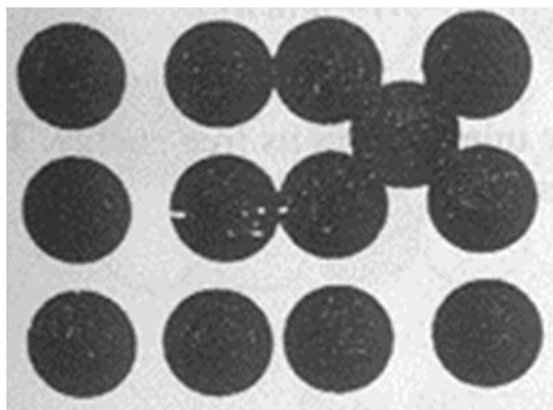
(b). Schottky Imperfections

Involve vacancies in pair of ions having opposite charges and are found in compounds, which maintain charge balance, e.g. alkali halides



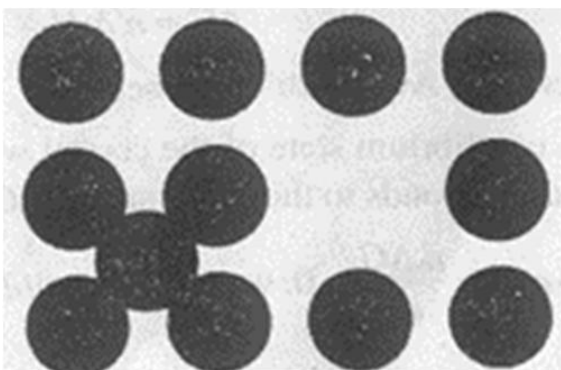
(C). Interstitialcy

Addition of an extra atom in the crystal lattice, when atomic packing density / factor is low and the foreign atom may be an impurity or alloying atom (generally very less in number as additional energy is required to force atom / ion to occupy new position)



(d). Frenkel Defect

Ion dislodged from its crystal lattice into an interstitial site (generally very less in number as additional energy is required to force the atom / ion to occupy the new position)



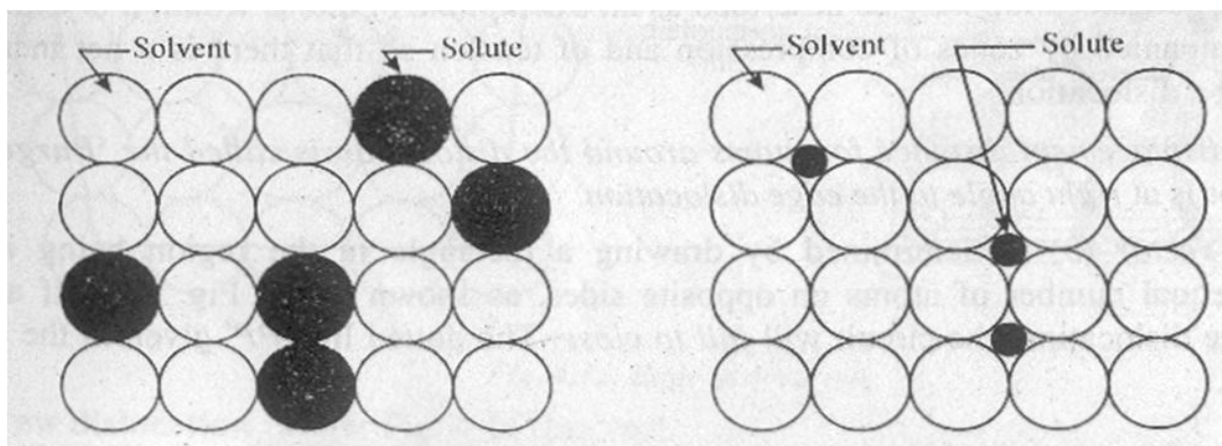
(e). Compositional Defect

Arises due to presence of impurity atom in crystal lattice of metal during original crystallization process (responsible for functioning of semi-conductor devices)

- Substitutional Defect: Original parent atom from its lattice is replaced
- Interstitial Impurity: Small impurity occupies interstitial spaces in lattice

(f). Electronic Defect

Errors in charge distribution in solids, e.g. diodes and transistors devices, where charges diffuse in opposite regions leading to change of their concentration in that region



Substitutional Defect

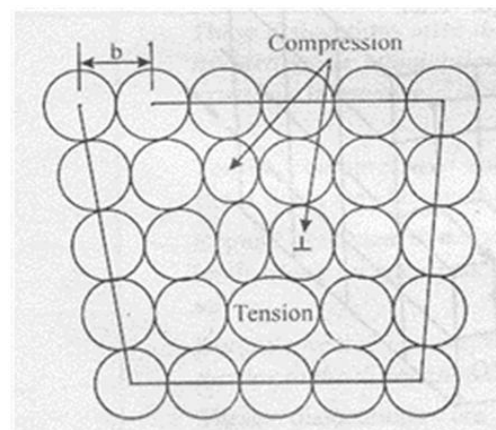
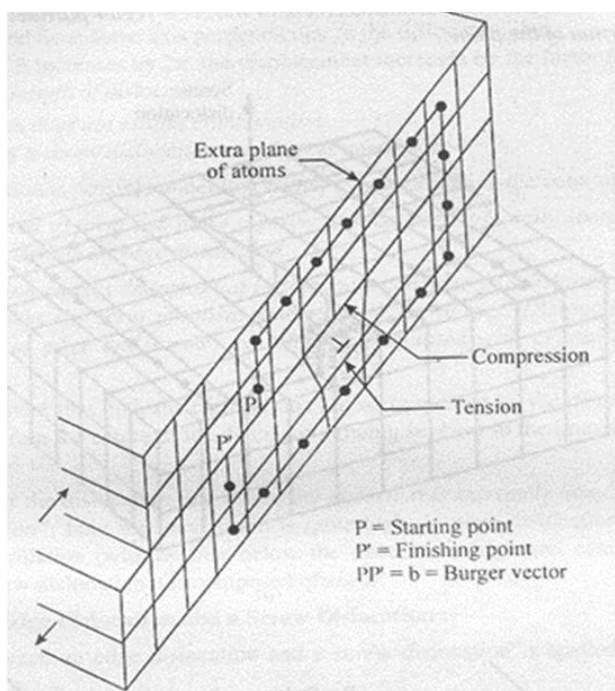
Interstitial Defect

(ii). Line Defects (One Dimensional Defects)

- Linear disturbance of atomic arrangement, which can move very easily on slip plane through crystal
- Occurs during recrystallization process or during slip
- Created along a line, which is also boundary between slipped and unslipped regions of crystals
- Defect is known as 'dislocation' and boundary is known as 'Dislocation Line'
- Region near dislocation, where distortion is extremely large is called 'Core of Dislocation' (very high local strain)

(a). Edge Dislocation

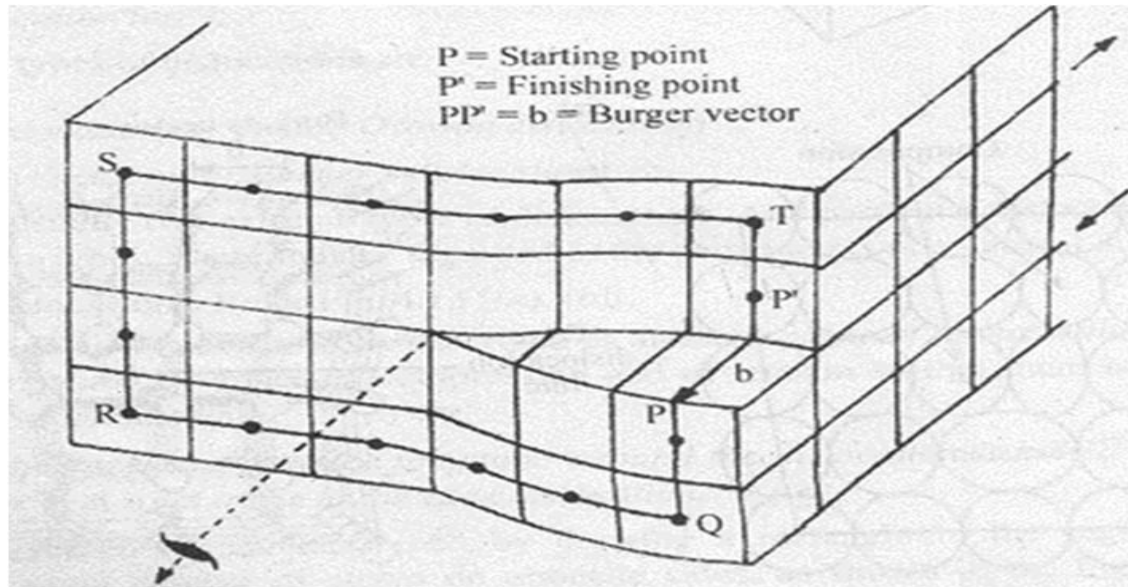
- Any extra plane of atoms within a crystal structure is edge dislocation
- Accompanied by zones of compression and tension and there is a net increase in energy along dislocation
- Displacement distance for atoms around dislocation is called '*Burger Vector*', which is at right angle to edge dislocation
- Burger vector is determined by drawing a rectangle in region by connecting an equal number of atoms on opposite sides (circuit fails to complete), i.e. PP' as shown in figure



Edge Dislocation

(b). Screw Dislocation

- Originate from partial slipping of a section of crystal plane
- Shear stresses are associated with adjacent atoms and extra energy is involved along the dislocation
- Successive atom planes are transformed into the *Surface of Helix of Screw* (plane is distorted), which accounts for its name as screw dislocation
- Displacement vector is parallel to the line defect

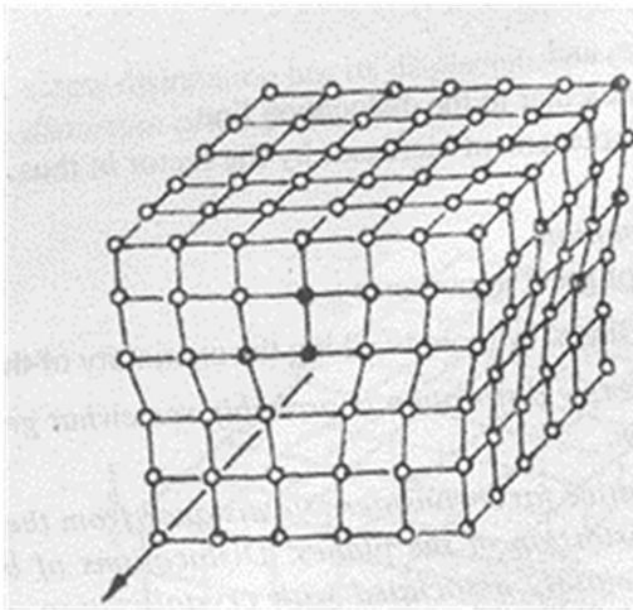


SCREW DISLOCATION

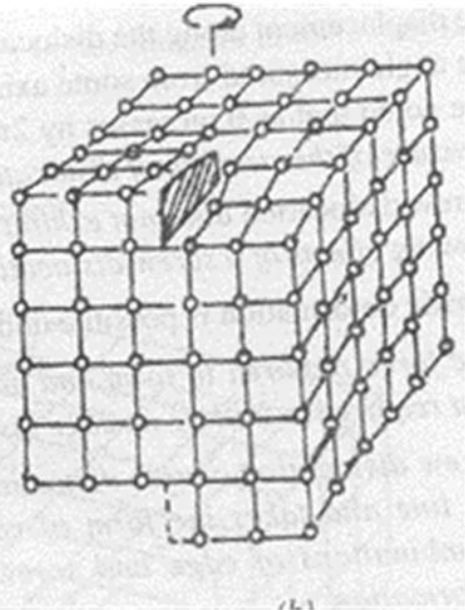
Comparison

Edge Dislocation	Screw Dislocation
Arise due to introduction or elimination of an extra row of atoms	Arise due to partial slipping of section of crystal where planes of atoms are transformed into surface helix of screw
Tensile, compressive or shear stress field may be present	Only shear stress field is present
Lattice disturbance extends along an edge inside crystal	Lattice disturbance extends into two separate regions at right angles to each other
Burger's vector is always perpendicular to dislocation line	Burger's vector is parallel to dislocation line

Dislocations can climb and glide	Dislocation can only glide
Force required is less as compared to that for screw dislocation	Force required is more as compared to that of edge dislocation

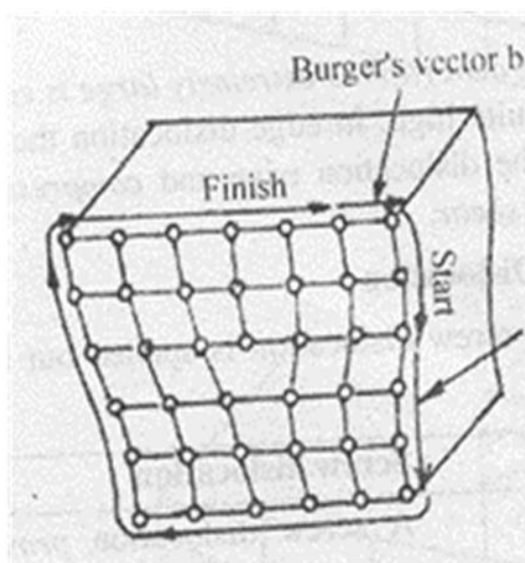


Edge Dislocation

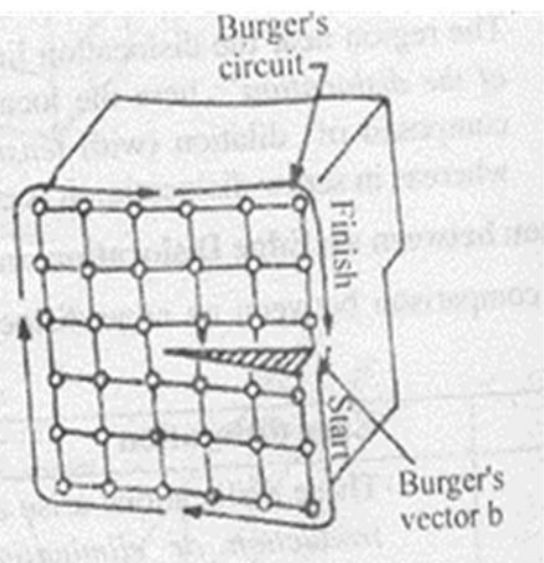


Screw Dislocation

Geometry of Dislocation

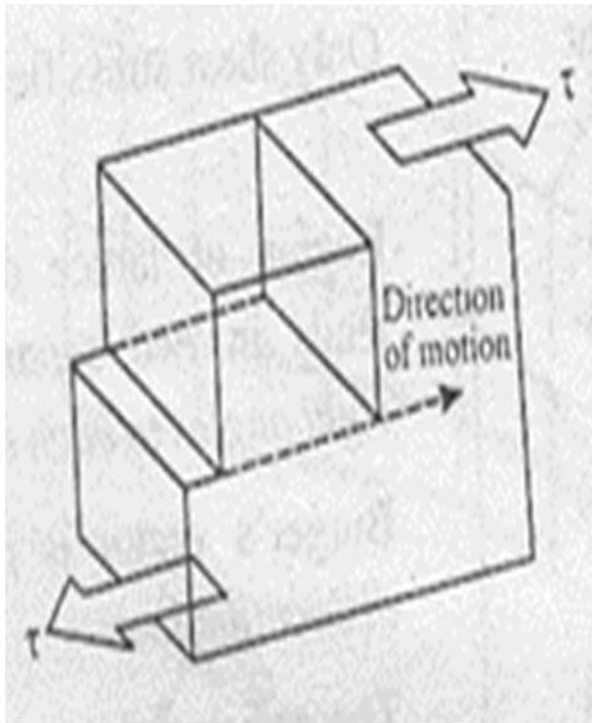


Edge Dislocation

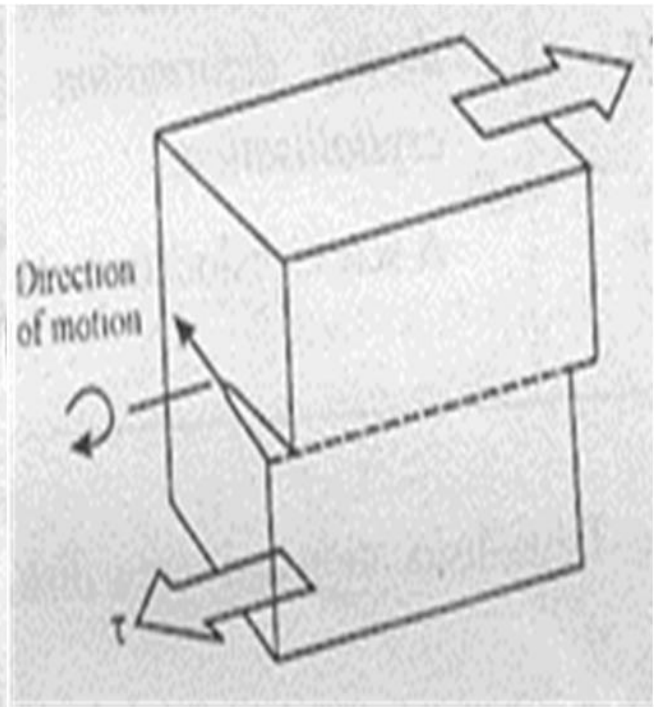


Screw

Burdaer's Vector



Edge Dislocation



Screw Dislocation

Formation of Step on Crystal Surface

(iii). Surface / Plane Defects (Two Dimensional Defects)

- Two-dimensional regions in crystal and arise from change in stacking of atomic planes on or across boundary

(a). External Defects

- Defects or imperfections represented by a boundary
- External surface of material itself is an imperfection because atomic bonds do not extend beyond it
- Surface atoms do not have neighboring atoms on one side (as compared to atoms inside the material) and thus, have high energy (in the order of 1 J/m²)

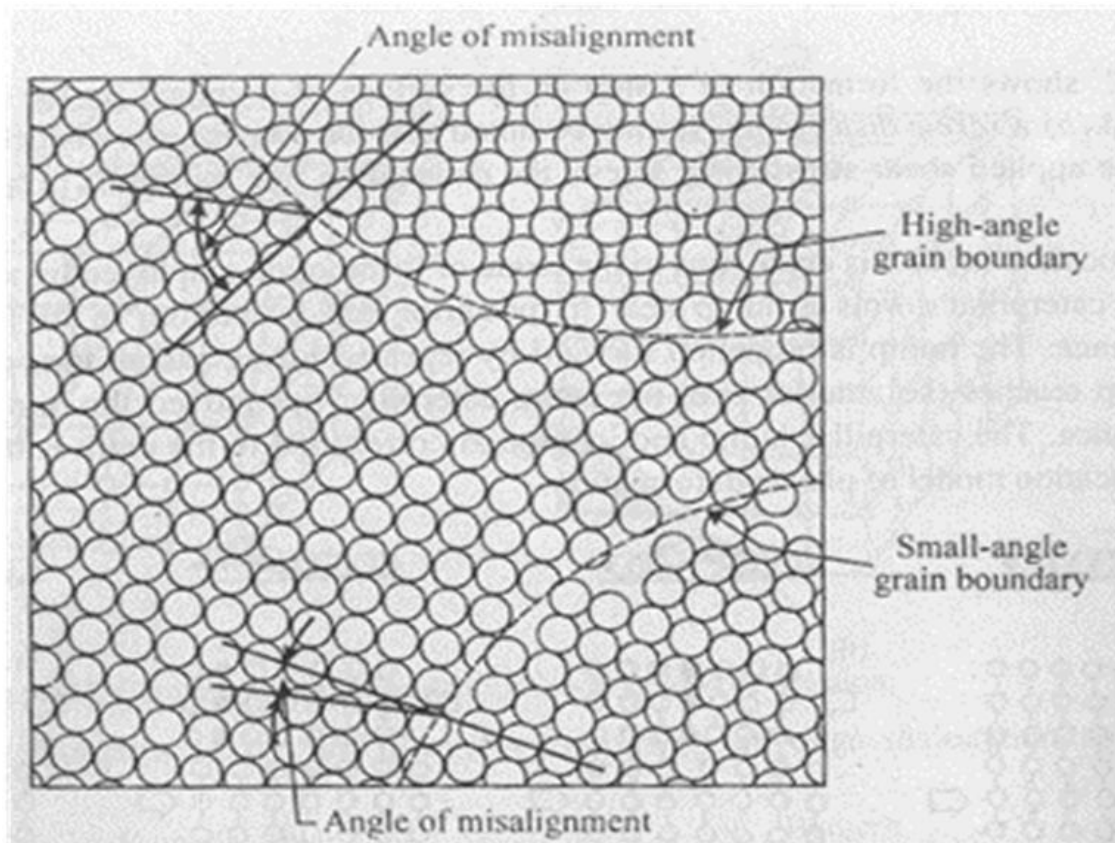
(b). Internal Defects

- **Grain Boundary Defect**
- Imperfections, which separate crystals or grains of different orientation in polycrystalline aggregation during nucleation or crystallization

- Individual crystals with different orientation are called as '*Grains*', and boundary separating grains are called as '*Interface / Interface Boundary*'

Example: copper metal

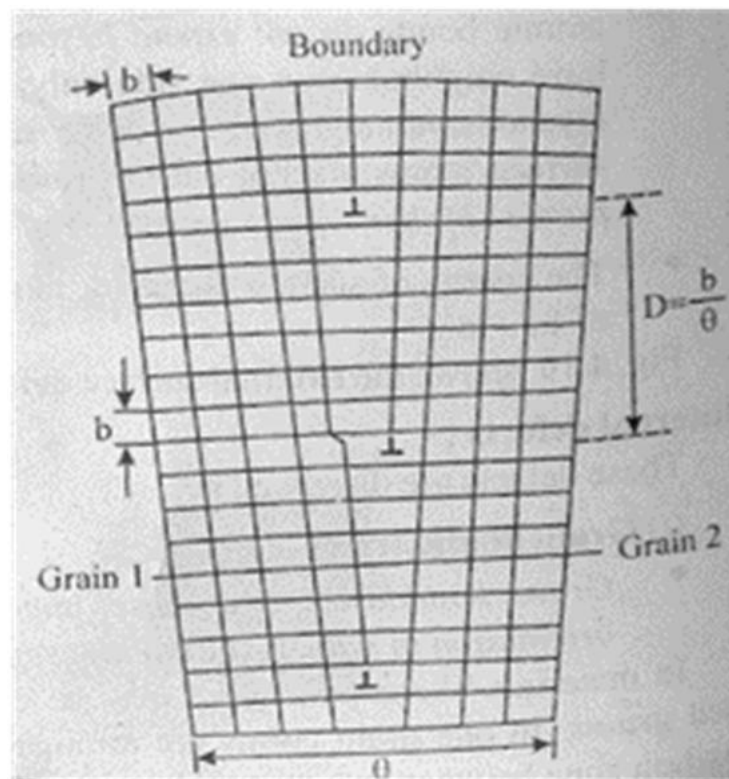
- Atoms within a grain are arranged with one orientation and pattern, which does not aligns with orientation of atoms in neighboring grains
- Misalignment between adjacent grains may be of various degrees (small or high angle grain boundaries)
- Always a transition zones between two neighboring grains
- Leads to less efficient packing of atoms at boundary and thus, atoms at boundary have higher energy as compared to those at inside of grain boundaries



Grain Boundary Defect

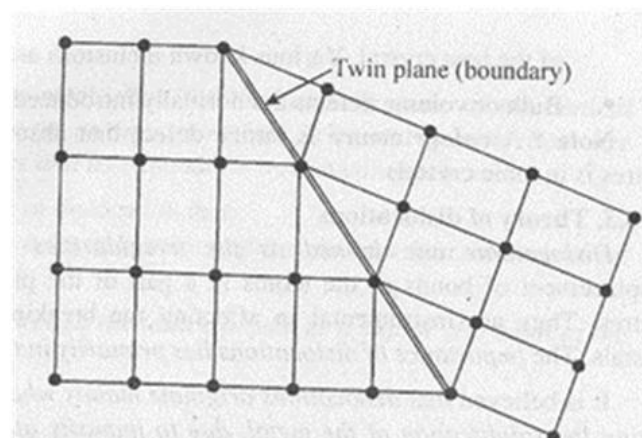
- **Tilt Boundary Defect**
 - Series of aligned dislocations, which tend to anchor (fasten) dislocation movements normally contributing to plastic deformation

- Associated with little energy
- Orientation difference between two neighboring grains is less than 10° , thus, it may be called as small / low angle grain boundary



Tilt Boundary Defect

- **Twin Boundary Defect**
 - Special type of grain boundary across which, there is specific mirror lattice of symmetry, i.e. atoms on one side of boundary are located in mirror-image positions of atoms on other side
 - Region of material between these boundaries is called as 'Twin', which results due to basic twinning



▪

Stacking Fault

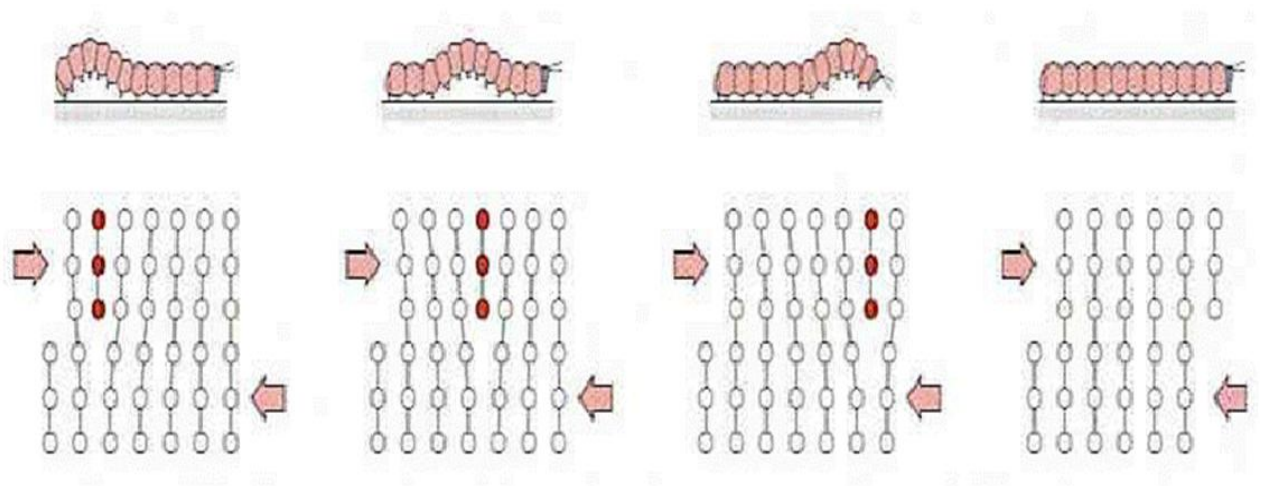
- Arise due to stacking of one atomic plane out of sequence on another, while lattice on either side of fault is perfect, i.e. one or more than one atomic plane may be missing from usual conventional style of stacking

(iv). Volume Defects (Three Dimensional Defects)

- Bulk defects, which includes pores, cracks, foreign inclusions or other phases

Slip by Dislocation Motion

- Slip is plastic deformation process produced by dislocation motion (Note: Dislocations Can Move)
- Dislocation motion is analogous to the mode of locomotion employed by caterpillar
- Caterpillar forms a hump near its posterior (later) end by pulling in its pair of legs unit leg distance and then this hump is propelled forward by repeating lifting and shifting of leg pairs
- When a hump moves forward, entire caterpillar moves forward by leg separation distance corresponding to extra half plane of atoms in its dislocation model of plastic deformation



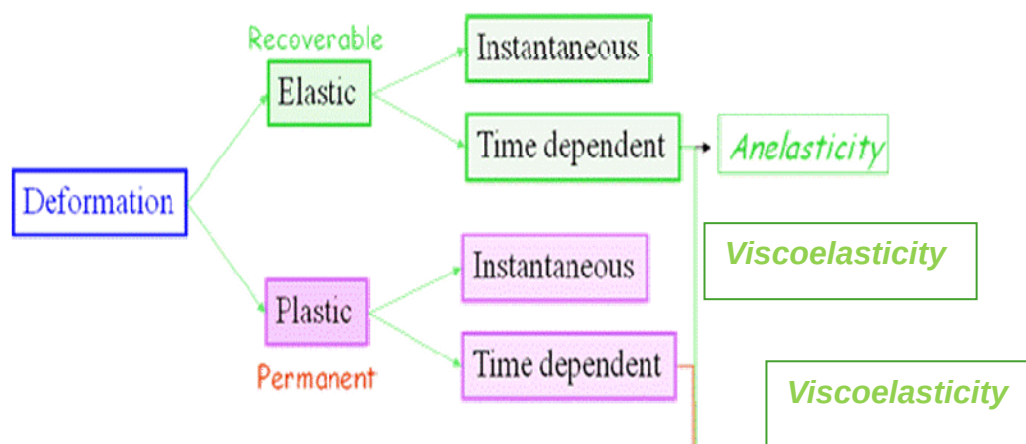
Analogy between Caterpillar & Dislocation

Concept of Elastic & Plastic Deformation

Introduction:

- Change in dimensions of material under action of applied forces
- Caused by mechanical action or by various physical and physio-chemical processes
- Deformed components are superior to cast components in performance
- Types: Elastic & Plastic deformations

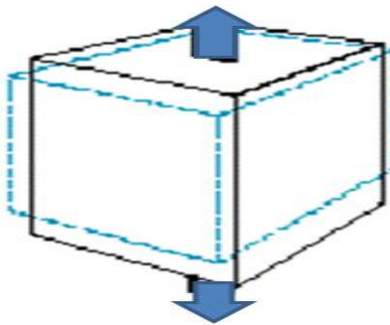
Classification of Deformation



Elastic Deformation

- Disappears, when load is removed & takes place before plastic deformation
- Strain is proportional to stress (*Hooke's Law*)
- Ratio of stress to strain is *Young's Modulus of Elasticity (E)*, which is a material characteristic (magnitude depends upon force of attraction between atoms of metal)
- Shear stress produces shear strains and ratio of shear stress to shear strain is *Shear Modulus of Rigidity (G)*
- Ratio of volumetric stress to volumetric strain is *Bulk Modulus of Elasticity (K)*
- Perfect elastic material is one which regains back its original shape and size completely, after deforming force is removed
- During elastic deformation, material stores energy (strain or elastic energy), which is recovered, when load is removed
- Elastic strain energy is area under stress-strain curve (up to elastic limit)

- Materials subjected to tension shrink laterally & those subjected to compression, bulge
- Ratio of lateral and axial strains is called the Poisson's ratio (ν), which is a dimensionless quantity (sign shows that lateral strain is in opposite sense to longitudinal strain)
- Theoretical value is 0.25 & maximum value is 0.50 (typical value lies in between 0.24 to 0.30)

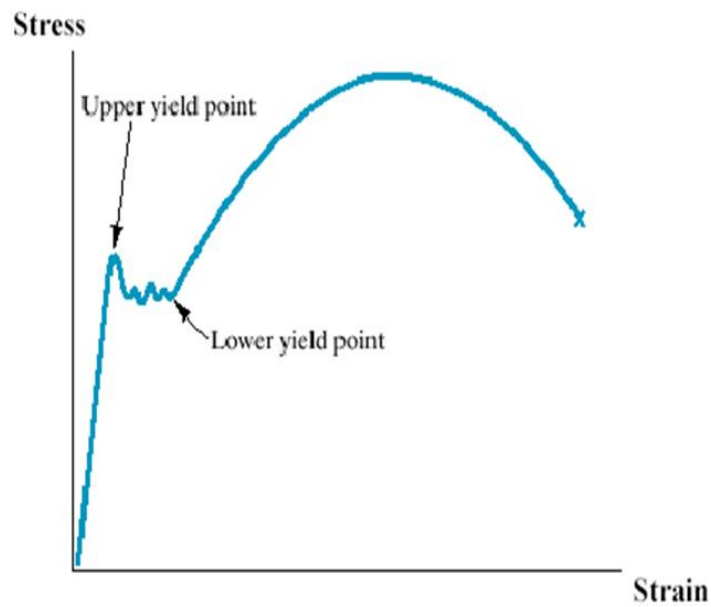
$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$


Plastic Deformation

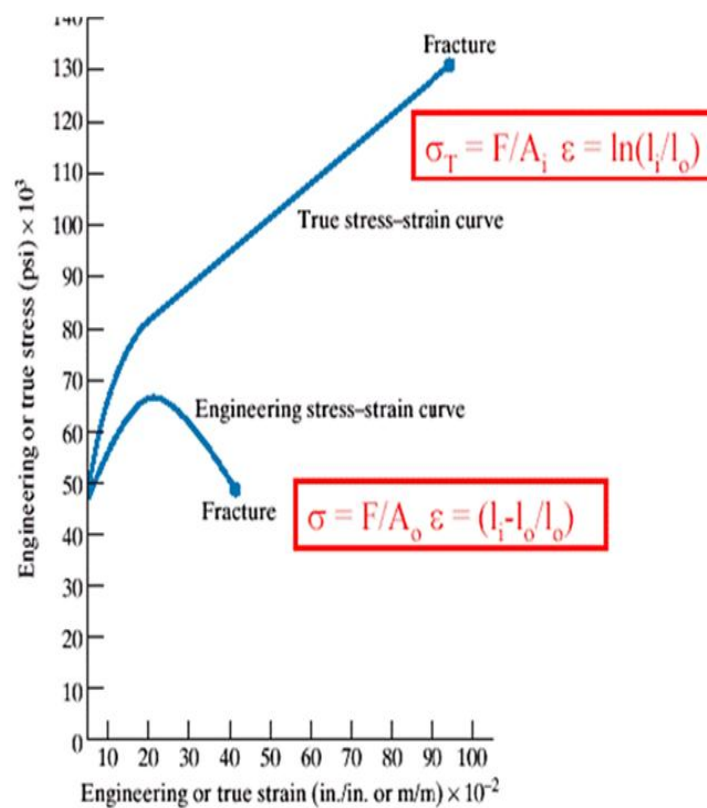
- Permanent deformation, which persists even when deforming load is removed (function of stress, temperature & rate of straining)
- Caused by loads exceeding elastic limit & occurs after elastic deformation
- Non-linear relation between stress and strain (nature varies with material & deformation condition)
- Exhibit yield point phenomenon (yield stress)
- Continued plastic deformation leads to fracture (instantaneous fracture for brittle material & necking followed by fracture for ductile material)

Yield Point Phenomenon

- Yielding starts at 1st higher point known as *UpperYieldPoint* and 2nd lower point is known as *LowerYieldPoint*
- Stress required to deform metal after yield point is always higher due to strain hardening, which causes curve to gradually rise upwards uptill ultimate tensile point (corresponding stress known as *Ultimate Tensile Strength*). After this specimen fails by fracture



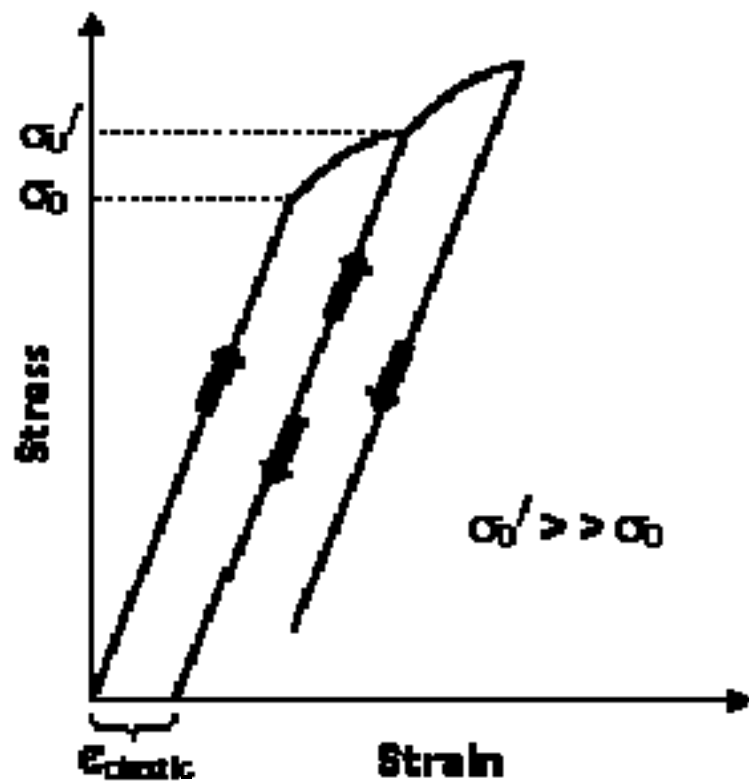
Stress-Strain curve for Mild Steel



True & Engineering Stress-Strain

Strain Hardening

- Increase in yield stress of material when loaded subsequently in same direction again and again below recrystallization temperature
- When material is loaded in any direction (say tensile direction), it experiences linear elastic deformation till elastic limit. If load is removed, material comes back to its original shape and size and curve will retrace back loading path
- If material is further loaded (beyond yield stress ' σ_0 '), slight plastic deformation occurs leading to small permanent deformation. Now, if load is removed, material will retain this small plastic / permanent deformation and curve will not retrace original path, but will follow path parallel to original loading path

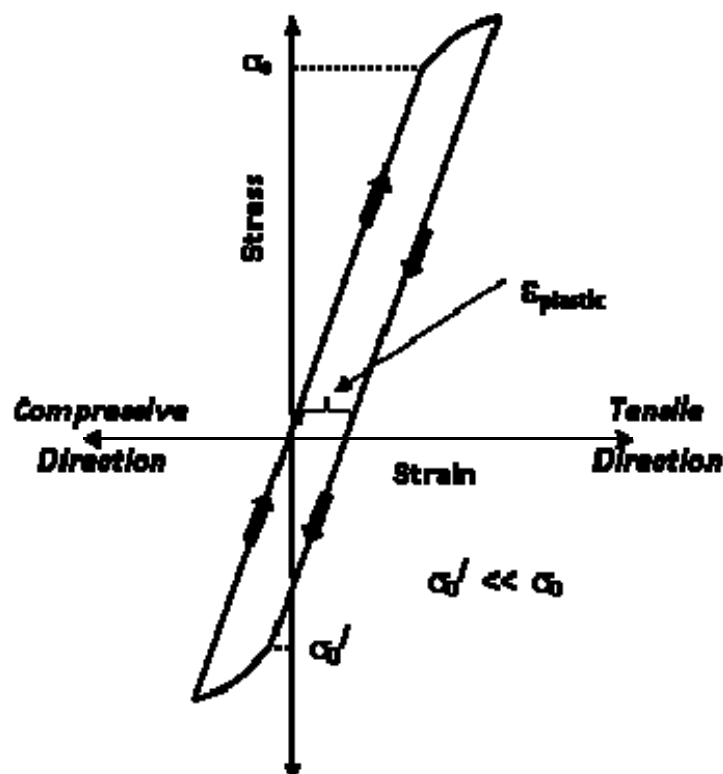


Strain Hardening

- If same material is loaded in same (tensile) direction again, it will start yielding at new yield stress ' σ_0' ', which will be higher than initial yield stress of material ' σ_0 '.
- This is because material becomes harder during plastic deformation by storing strain energy (some % of total deformation energy)
- Reduces ductility and plasticity of material
- At micro level, dislocation piles up during plastic deformation at slip planes, which interact with each other and create barriers to further motion / movement of dislocations through crystal lattice

Bauschinger Effect / Elastic Hysteresis

- Decrease in yield stress of material when loaded initially in one direction (tensile) and then subsequently in opposite direction (compressive) below recrystallization temperature
- When a material is loaded in any direction (say tensile direction), it experiences linear elastic deformation till elastic limit. If it is further loaded (beyond yield stress ' σ_0 '), slight plastic deformation will occur leading to small permanent deformation
- Now, even if load is removed, material will retain this small plastic / permanent deformation and curve will not retrace original path, but will follow path parallel to original loading path



Bauschinger Effect

- Further, loaded in opposite direction (compressive), it will start yielding at new yield stress ' σ_0' ', which will be very less than initial yield stress of material ' σ_0 '.
- This is because residual tensile stress stored in material during tensile loading need to be removed / compensated before elastic deformation in reversal (compressive) direction starts
- At micro level, dislocations piles up during tensile loading along at slip planes, which can be easily moved in opposite direction (compressive loading) by residual stresses

Anelasticity:

Time-dependent, recoverable low strain with linear behavior and relatively low damping

Viscoelasticity:

Time-dependent, recoverable higher strains with nonlinear behavior and higher damping

Viscoplasticity:

Time-dependent, non-recoverable strain with nonlinear behavior and higher damping