

The Text books by Callister and Raghavan and others have been referred.

Module 1 Structure of Materials

Subject: Material Science and Engineering

Subject Code: BME303

Syllabus

Structure of Materials Introduction: Classification of materials, crystalline and non-crystalline solids, atomic bonding: Ionic Bonding and Metallic bonding.

Crystal Structure: Crystal Lattice, Unit Cell, Planes and directions in a lattice, Planar Atomic Density, Coordination number, atomic Packing Factor of all the Cubic structures and Hexa Close Packed structure. Classification and Coordination of voids, Bragg's Law.

Imperfections in Solids: Types of imperfections, Point defects: vacancies, interstitials, line defects, 2-D and 3D-defects, Concept of free volume in amorphous solids. Slip, Twinning.

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Introduction:

When we say 'materials' we think of nearly all materials known to science and in all states of matter like solid, liquid & gaseous.

But material science concern itself basically with the nature & behaviour of only solid materials.

'Solid engineering materials' are those which helps engineers to build machines, structures, automobiles, and air craft.

Classifications of engineering materials:

- (i) Metals & alloys: Ex: cast iron, steels, aluminium, copper, silver, gold, brass & bronze
- (ii) Ceramics & glasses : Ex: MgO, ZnO, SiC, concrete & cement
- (iii) Polymers: plastics, polyethylene, PVC, nylon, cotton & rubber
- (iv) Composites: metal-matrix composites

Each of above group of materials has their own set of properties. Some of the most engineering materials as follow:

- ✓ Mechanical: strength, hardness, ductility, malleability, toughness, resilience & fatigue
- ✓ Physical: shape, size, density, porosity & colour
- ✓ Chemical: acidity, alkalinity, composition, corrosion resistance, atomic number & molecular weight
- ✓ Electrical: conductivity, resistivity, dielectric constant, dielectric strength & power factor
- ✓ Thermal: Specific heat, refractoriness & conductivity

- ✓ Aesthetic: feel, texture, appearance, lustre

The above properties of the materials which guide us in the selection of the materials for specific operations. Ex: (i) an aircraft structure has to be built with materials having low density but high strength, (ii) a steel melting furnace has to be lined with refractory materials to with stand high temperature, (III) buildings & structures have to be built with materials having high compressive strength to with stand heavy loads.

Crystalline and non-crystalline solids:

1. Crystalline solids,
2. Non- Crystalline solids

Crystalline solids	Non- Crystalline solids/ amorphous solids
1. The basic structural unit is a crystal [a solid whose constituent molecules or atoms are arranged in a systematic geometric pattern.	The basic structural unit is a molecule & chains of these molecule come together to form an amorphous solids
2. Each crystal [also called as a grain] is made up of a number of respective blocks called unit cells[the smallest group of atoms possessing the symmetry of the crystal] which are arranged neatly in relation to each other	The chains of molecules are random within the solid & occur in no particular relation to each other. They are irregular & lack symmetry
3. Compare crystalline solid with a military parade where all soldiers are arranged in order with respect to each other.	In this, crowd where people are random & not arranged in order with respect to each other.
4. A crystalline solid therefore is made up of millions of unit cells orderly arranged. Each unit cell is itself made up of atoms & the number of atoms depends on the type of unit cell.	In this it is made up of millions of molecules disorderly arranged
5. Metals, alloys, some salts like NaCl, KCl, many oxides & ceramics, non metals like diamond, Gem stones	Glass, polymers, rubber & plastics
6. Density of crystalline solids is generally high. They have higher melting point & strength	Generally low because molecules cannot be compacted. They have lower melting point & strength

7. Structures are stable & materials are stronger	Structures are unstable & materials are less stronger
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Aggregates: some materials are obtained both in crystal as well as amorphous. Ex: silicate can occur as crystalline solid [quartz] or a Non- Crystalline solids/ amorphous solids [silicate glass]. Aggregates type of materials which have short range order but no long-range order. Ex: concrete, rocks & minerals.

Atomic bonding

In a substance atom of interact with each by forming bonds to create molecules and macroscopic materials. There are three basic ways that the outer electrons of atoms can form bonds:

Ionic bond -Electrons can be transferred from one atom to another

Covalent bond Electrons can be shared between neighbouring atoms

metallic bond-Electrons can be shared with all atoms in a material

Secondary Bonding

Ionic bond: Ionic bonding forms between two oppositely-charged ions which are produced by the transfer of electrons from one atom to another. Electropositive elements such as the alkali metals have small ionization potentials. Electronegative elements such as halogens have large electron affinities. Hence ionic bonds form most readily between electropositive and electronegative elements.

Ex: Consider as an example an atom of sodium, which has one electron in its outermost orbit, coming near an atom of chlorine, which has seven. Because it takes eight electrons to fill the outermost shell of these atoms, the chlorine atom can be thought of as missing one electron. The sodium atom donates its single valence electron to fill the hole in the chlorine shell, forming a sodium chloride system at a lower total energy level.

The ionic bond is **nondirectional** because the electron transfer results in the inert gas configuration around both the nuclei and has spherical symmetry of the electron probability cloud. Therefore, the bonding force between the ions is the same in all directions.

Metallic bond: In metallic bonding the sharing of electrons between neighbouring atoms now becomes delocalised as there are not enough electrons to produce the inert gas configuration around each atom. The metallic sharing changes with time and the bonding electrons resonate between different atoms. The metallic state can be visualized as an array of positive ions, with a common pool of electrons to which all the metal atoms have contributed their outer electrons. This common pool is called the free electron cloud or the free electron gas. These electrons have freedom to move anywhere within the crystal and act like an all-pervasive, mobile glue holding the ion cores together. The electron freedom in metallic bonding makes the metallic bonds **nondirectional**.

Ex: Cu, Ag etc.

Crystal Structure

Refers to the manner in which atoms, ions, or molecules are spatially arranged

Space lattice is defined as an infinite array of points in three dimensions in which every point has surroundings identical to that of every other point in the array

Unit cell: it is the smallest repeatable unit of a crystalline solid. In other words every unit cell is a crystalline solid consists of a group of atoms arranged in a definite order.

Crystal Lattice: crystal lattice is the symmetrical three-dimensional structural arrangements of atoms, ions or molecules (constituent particle) inside a crystalline solid as points.

Planes and directions in a lattice:

Crystal directions are obtained using the system devised by Miller. Consider the figure below the vector $\mathbf{r}$, passing through the origin o to a lattice point, can be expressed in terms of the fundamental translation vectors $\mathbf{a}$, $\mathbf{b}$ and $\mathbf{c}$, which form the crystal axes, as $\mathbf{r} = r_1\mathbf{a} + r_2\mathbf{b} + r_3\mathbf{c}$, where r_1 , r_2 and r_3 are integers. The $\mathbf{c}$ -axis is not shown in the figure as $\mathbf{r}$ is assumed to lie on the $\mathbf{ab}$ plane. The components of $\mathbf{r}$ along the three axes are: $r_1 = 2$, $r_2 = 3$ and $r_3 = 0$. Then the crystal direction denoted by $\mathbf{r}$ is written as $[230]$ in the Miller notation, with square brackets enclosing the indices.

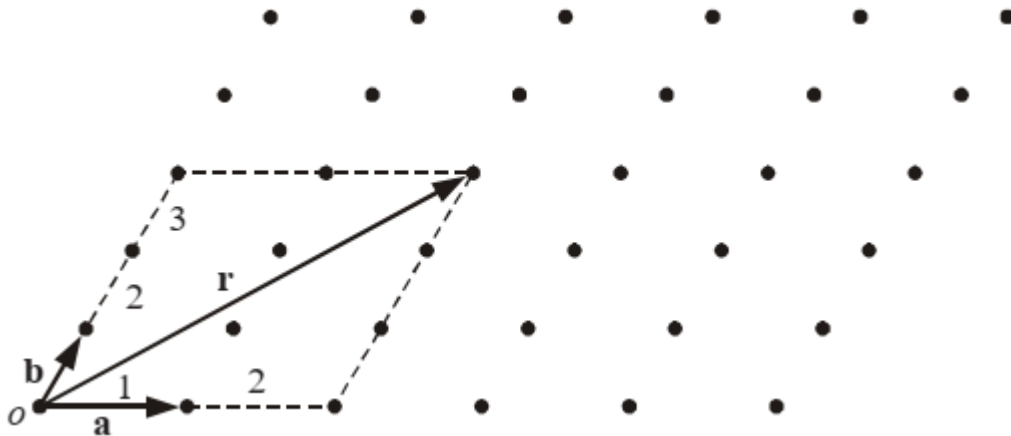
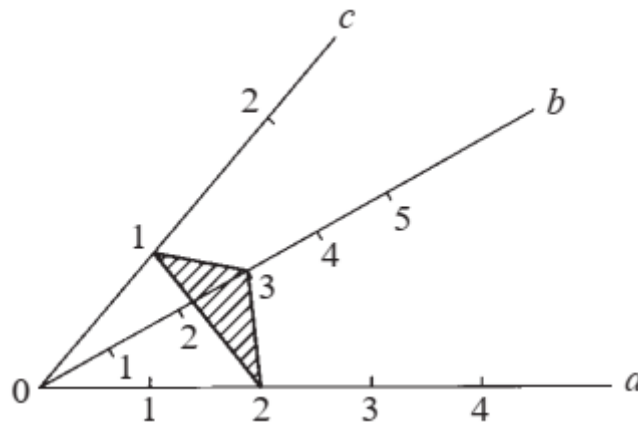


Figure: The Miller indices of the crystal direction denoted by vector $\mathbf{r}$ are $[230]$

If there is a negative component along a crystal axis such as -2 , it is written as $\bar{2}$ and read as bar 2. A family of directions is obtained by all possible combinations of the indices, both positive and negative. The family $[230]$, $[\bar{2}03]$, $[203]$, $[30\bar{2}]$, $[\bar{3}20]$, etc., is represented by $\langle 230 \rangle$, where the *angular brackets* $\langle \rangle$ denote the entire family.

The crystal directions $[230]$, $[460]$ and $[1\frac{1}{2}0]$ all have the same direction, but different magnitudes. Since Miller indices for directions are usually specified as the smallest possible integers, the differences in magnitude for the above three directions are indicated using the following convention: $[230]$, $2[230]$ and $\frac{1}{2}[230]$

The Miller indices of a crystal plane are determined as follows. Referring to the plane shown:



A crystal plane making intercepts 2, 3 and 1 on the crystal axes a, b and c. Its Miller indices are (326).

<i>Step 1</i>	Find the intercepts of the plane along the axes a, b and c (the intercepts are measured as multiples of the fundamental vectors)	2 3 1
<i>Step 2</i>	Take reciprocals of the intercepts [#]	$\frac{1}{2}$ $\frac{1}{3}$ 1
<i>Step 3</i>	Convert into smallest integers in the same ratio	3 2 6
<i>Step 4</i>	Enclose in <i>parentheses</i>	(326)

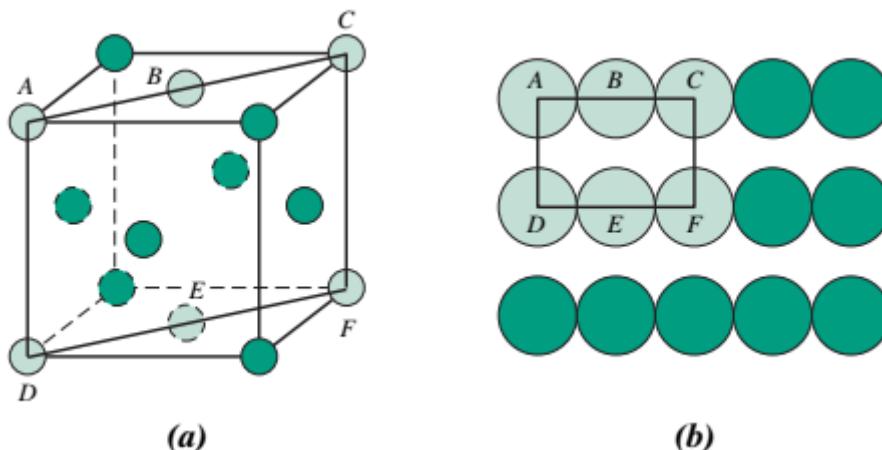
The factor that results in converting the reciprocals to integers may be indicated outside the brackets, but it is usually omitted. The family of planes with members (236), (263), ($3\bar{6}2$), ($3\bar{2}6$), ($\bar{6}32$); etc., is denoted by {326}, the curly brackets { } standing for the family.

Planar Atomic Density

planar density (PD) is taken as the number of atoms per unit area that are centered on a particular crystallographic plane.

$$\text{PD} = \frac{\text{number of atoms centered on a plane}}{\text{area of plane}}$$

The units for planar density are reciprocal area (e.g., nm⁻², m⁻²)



(a) Reduced-sphere FCC unit cell with the (110) plane. (b) Atomic packing of an FCC (110) plane. Corresponding atom positions from (a) are indicated

Consider the section of a (110) plane within an FCC unit cell. Although six atoms have centers that lie on this plane (Figure *b*), only one-quarter of each of atoms *A*, *C*, *D*, and *F* and one-half of atoms *B* and *E*, for a total equivalence of just 2 atoms, are on that plane. Furthermore, the area of this rectangular section is equal to the product of its length and width. From Figure *b*, the length (horizontal dimension) is equal to $4R$, whereas the width (vertical dimension) is equal to $2R\sqrt{2}$ because it corresponds to the FCC unit cell edge length (Equation 3.1). Thus, the area of this planar region is $(4R)(2R\sqrt{2}) = 8R^2\sqrt{2}$, and the planar density is determined as follows:

$$PD_{110}(FCC) = \frac{1}{4R^2\sqrt{2}}$$

Atomic packing factor:

It is the ratio of the volume of atoms contained in each unit cell to the volume of the unit cell itself OR the APF represents the percentage of space within each unit cell of a crystal structure which is packed with atoms.

- ✓ It also gives us information on the free space available within the unit cell.
- ✓ APF basically affects the density of the material.

$$APF = \frac{\text{Volume of atoms}}{\text{Volume of unit cell}}$$

APF of SC-0.52

APF of BCC-0.68

APF of FCC and HCP-0.74

Packing of atoms

FCC and HCP may be described in terms of stacking of the atoms in the close-packed planes of atoms. A portion of one such plane is illustrated in Figure *a* below. The two crystal structures may be generated by the stacking of these close-packed planes on top of one another; depending on the stacking sequence.

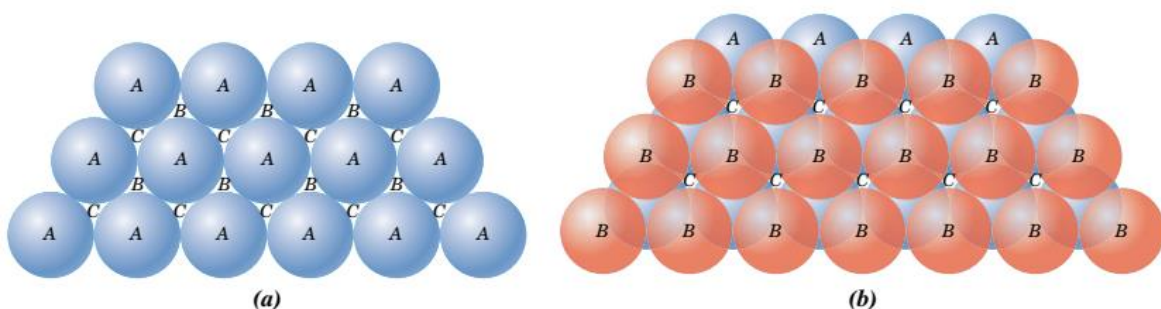


Figure: (a) A portion of a close-packed plane of atoms; A, B, and C positions are indicated. (b) The AB stacking sequence for close-packed atomic planes.

In the Figure *a* the sites having the triangle vertex pointing up are arbitrarily designated as B positions, whereas the remaining depressions are those with the down vertices, which are marked C. A second close-packed plane may be positioned with the centers of its atoms over either B or C sites; at this point both are equivalent. Suppose that the B positions are arbitrarily

chosen; the stacking sequence is termed AB, as shown in Figure b. This stacking sequence, ABABAB.. results in HCP. In the FCC case the after the B positions, atoms occupy C position then the sequence will be ABCABCABC. .

Classification and Coordination of voids

What are Voids?

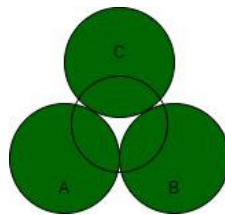
In close packing of spheres, some hollows or voids are left blank. These vacancies in the crystal are called **interstitial Voids** or **interstitial sites** or simply, voids. The two essential interstitial voids are Tetrahedral Voids and Octahedral Voids.

Packing of spheres consisting of two types of blanks after arranging the two layers. The void is formed by four spheres is called tetrahedral void, and the void formed by the six spheres is called the octahedral void.

Tetrahedral voids

A sphere in the second layer is placed on top of three spheres touching each other in the first layer. The centres of these spheres lie at the top of a tetrahedron. It is likely that the shape of the void is not tetrahedral, but that the arrangement around this void is **tetrahedral**. The space between four spheres having a tetrahedral arrangement is called a tetrahedral void or a tetrahedral space. A crystal has two tetrahedral voids per atom.

The number of Tetrahedral Voids in a lattice can be easily calculated. The number of voids will be twice as much as the number of spheres (i.e. unit cells) in this case. As a result, there will be “2n” tetrahedral voids.



Tetrahedral voids

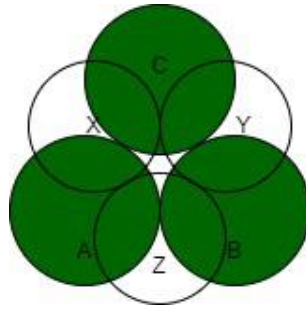
Ex: in the FCC unit cell, the centres of the tetrahedral voids lie quarter-way and three-quarter-way along the four nonparallel body diagonals of the cube. There are thus eight tetrahedral voids in the unit cell

Octahedral void

The octahedral space is a type of space or void that forms at the centre of six circles. It is visible in the diagram that each octahedral void is formed by the combination of triangular voids of the first and second layers. The void formed by the vertices on opposite sides by two equilateral triangles is called octahedron al void or octahedral site. Therefore, this void is surrounded by 6 spheres at the vertices of a regular octahedral. A crystal has one octahedral void per atom.

As a result, an octahedral void is formed when the first layer's tetrahedral void and the second layer's tetrahedral void align. A void forms in the centre of six spheres here. So an octahedral void has a coordination number of six.

If the number of spheres in a structure is “n,” the number of octahedral voids will be the same. “n” is a good example.



Octahedral void

Ex: in the FCC unit cell, the centres of the octahedral voids fall at the body centre and at the middle of the 12 cube edges. The effective number of octahedral voids per unit cell is then $1 + 12 \times \frac{1}{4} = 4$. This is equal to the effective number of atoms in the unit cell.

Difference between tetrahedral and octahedral voids

Tetrahedral voids	Octahedral voids
Tetrahedral voids are unoccupied empty spaces present in substances having a tetrahedral crystal system.	Octahedral voids are unoccupied empty spaces present in substances having an octahedral crystal system.
It can be found in substances having a tetrahedral arrangement in their crystal system.	It can be found in substances having an octahedral arrangement in their crystal system
Tetrahedral voids can be observed in the edges of the unit cell.	Octahedral voids can be observed in the center of the unit cell.
Four is the coordination number of the tetrahedral void.	Six is the coordination number of the Octahedral void.
In the space lattice, there are two tetrahedral voids per sphere.	There are two octahedral voids per sphere in the crystal lattice
Tetrahedral voids are smaller.	Octahedral voids are larger as compared to tetrahedral voids.

$$\text{Voids per atom} = 8/4 = 2$$

$$V_{\text{tetrahedron}} = \frac{1}{24} V_{\text{cell}}$$

$$r_{\text{void}} / r_{\text{atom}} = 0.225$$

$$\text{Voids per atom} = 4/4 = 1$$

$$V_{\text{octahedron}} = \frac{1}{6} V_{\text{cell}}$$

$$r_{\text{void}} / r_{\text{atom}} = 0.4142$$

Brag's Law

Consider the two parallel planes of atoms $A-A'$ and $B-B'$ in the below Figure, which have the same h , k , and l Miller indices and are separated by the interplanar spacing d_{hkl} . Now assume

that a parallel, monochromatic, and coherent (in-phase) beam of x-rays of wavelength λ is incident on these two planes at an angle θ . Two rays in this beam, labelled 1 and 2, are scattered by atoms P and Q . Constructive interference of the scattered rays 1' and 2' occurs also at an angle θ to the planes if the path length difference between 1– P –1' and 2– Q –2' (i.e., $\overline{SQ} + \overline{QT}$) is equal to a whole number, n , of wavelengths. That is, the condition for diffraction is

$$n\lambda = \overline{SQ} + \overline{QT}$$

or

$$\begin{aligned} n\lambda &= d_{hkl} \sin \theta + d_{hkl} \sin \theta \\ &= 2d_{hkl} \sin \theta \end{aligned}$$

Eq (1)

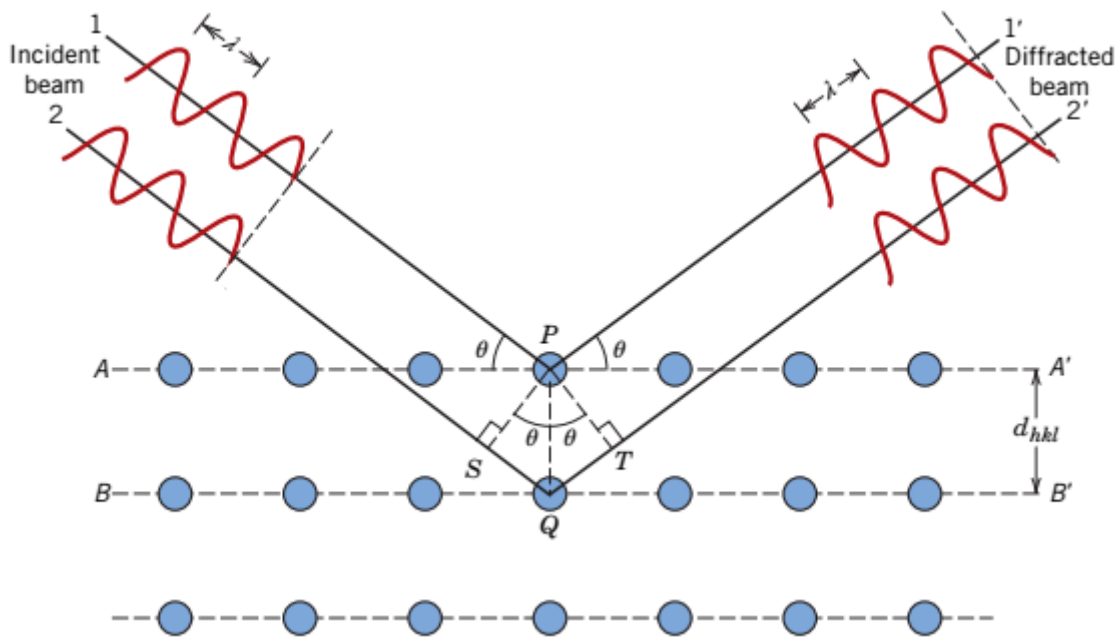


Figure: Diffraction of x-rays by planes of atoms (A–A' and B–B')

Eq (1) is known as **Bragg's law**; n is the order of reflection, which may be any integer (1, 2, 3, . . .) consistent with $\sin \theta$ not exceeding unity. Thus, we have a simple expression relating the x-ray wavelength and interatomic spacing to the angle of the diffracted beam. If Bragg's law is not satisfied, then the interference will be nonconstructive so as to yield a very low-intensity diffracted beam.

Imperfections in Solids:

All the different types of crystal structures with their arrangement of atoms are true only under ideal conditions. This means that all real crystals generally have imperfections among their unit cells. These are important because they affect many structure-sensitive properties of the material. Ex: tensile strength, shear strengths of materials.

Crystal imperfections can be broadly classified as

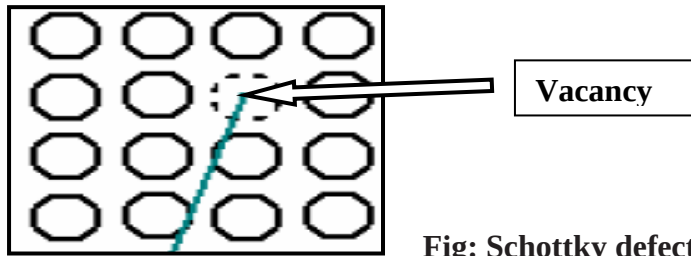
1] Point imperfections, 2] Line imperfections, 3] Surface imperfections, 4] Volume imperfections

1] Point imperfections: There are 4 types:

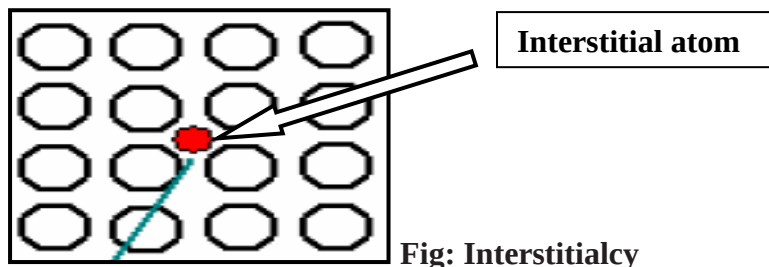
1] Vacancies, 2] Interstitialcies, 3] Substitutional impurities, 4] Electronic defects

1] Vacancy: A vacancy refers to an atomic site from where the atom is missing. This may be due to imperfect packing during original crystallization or from thermal vibration of the atom.

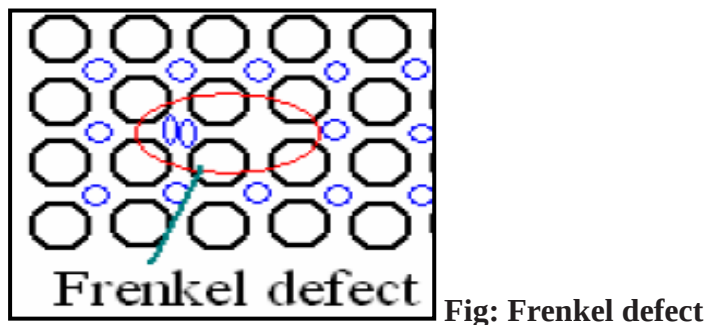
SCHOTTKY DEFECT: If two ions of opposite charges are missing but are found elsewhere in the same crystal, called as '*SCHOTTKY DEFECT*'.



2] Interstitialcy: Here, a small sized foreign atom occupies the space in between the atoms of a crystal without dislodging any of the parent atoms. This interstitial atom is usually of much smaller size than the atoms among which it is present. Ex: Carbon in iron.



3] Frenkel defect: When an ion of the same crystal tries to occupy an interstitial position jumping from another site, then it is called 'Frenkel defect'.



4] Substitutional impurity: This impurity is created when a foreign atom substitutes a parent atom in the lattice structure. Ex: a Zinc atom replaces a Copper atom in the FCC structure of Copper.

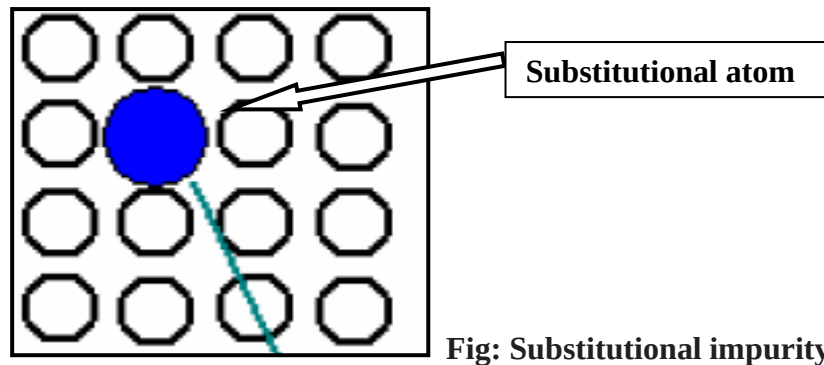


Fig: Substitutional impurity

5] Electronic defects: Electronic defects are the results of errors in the charge distribution in solid. For ex: An impurity atom whether interstitial or Substitutional may have a charge quite different from that of the host atoms & hence may produce local electronic disturbances. These are called electronic imperfections & are necessary to explain electrical conductivity & related phenomenon in solids.

(ii). Line imperfections: Line imperfections are called dislocations. A dislocation is a line defect where a uniform alignment of atoms is broken to form a discontinuity or a localised distortion in the crystal. The dislocations are responsible for the phenomenon of slip, by which most metals plastically deform.

There are two basic types of dislocations:

(1) Edge dislocation, (2) Screw dislocation or cross slip

1. Edge dislocation:

- Consider a perfect crystal fig: (a) to be made up of a number of vertical planes of atoms. If one of these vertical does not extend from to bottom.
- But ends at only a part of the way within the crystal as shown in fig: (b), an edge dislocation is present.

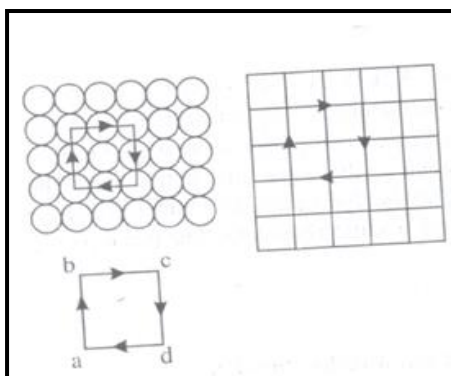


Fig (a): Ideal crystal

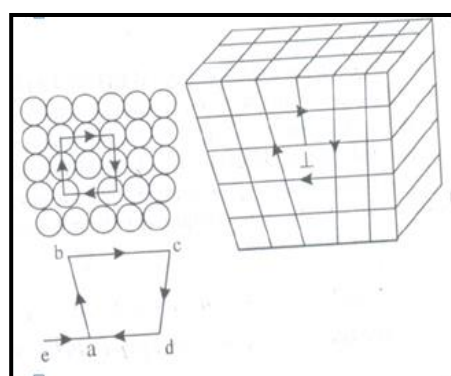


Fig (b): Crystal with edge dislocation

- In the perfect crystal, the atoms are in equilibrium positions & all the bond lengths are of equilibrium value.
- Where as in an imperfect crystal the atoms do not occupy equilibrium positions & the bond lengths are either compressed or pulled apart. Dislocations are denoted by the symbol $\perp$.

Burger's Vector

The magnitude & direction of the displacement of atoms in a dislocation is defined by a vector called the *Burger's Vector*.

From fig (b): Burger's Vector = $\vec{EA} = b$

The Burger's Vector is always **perpendicular** to the edge dislocation line.

2. Screw dislocation or cross slip:

Consider the shaded area AFED on the plane ABCD. Let top part of the crystal over the shaded area be placed by one inter atomic distance to the left with respect to the bottom part as shown in fig:(b), just like in a *Rubik's cube*.

Now there is said to be a screw dislocation about the line EF which is known as the screw dislocation line. The atomic bonds in this region immediately surrounding the dislocation line undergo a shear distortion. Also the forces required to form a screw dislocation is greater than that required for an edge dislocation.

From fig :(b), the Burger's Vector, $b = xy$

The Burger's Vector is always **parallel** to the screw dislocation line.

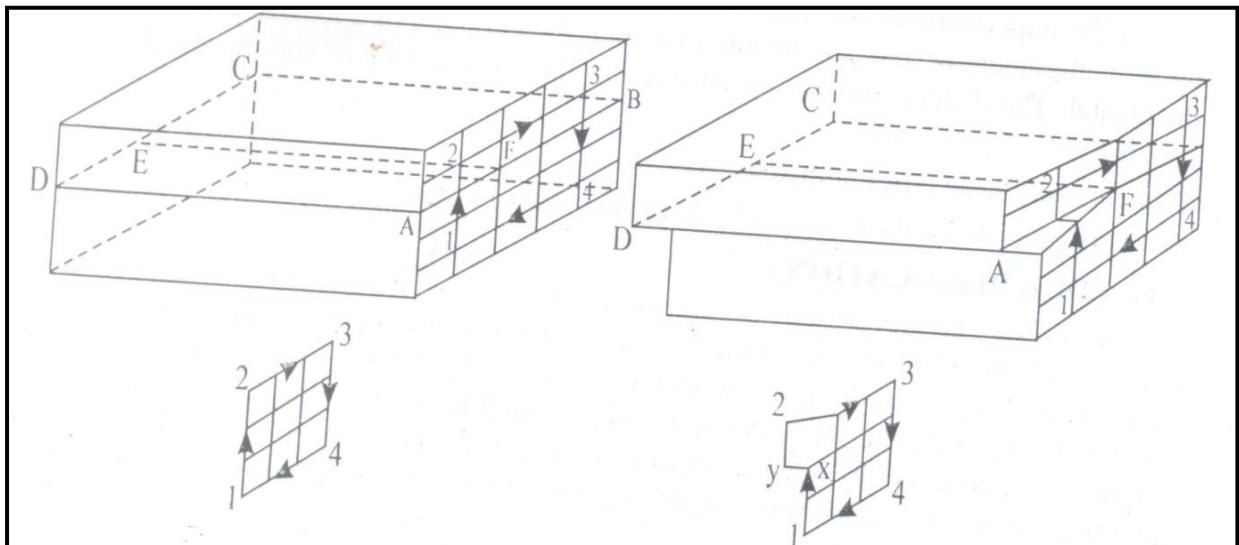
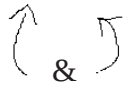


Fig: (a) Ideal Crystal

Fig: (b) Crystal with screw dislocation

Edge dislocation	Screw dislocation
1] An edge dislocation is a line defect where there is a discontinuity in a line of atoms. The discontinuous line of atoms can also be considered as an extra plane of atoms.	1] A Screw dislocation is also a line defect formed when a part of the crystal displaces angularly over the remaining part. The plane of atoms converts into a helical surface, or a screw.

2] Edge dislocation are symbolically represented as $\perp$ & $\top$, which are positive & negative dislocations respectively	2] Screw dislocation are shown as  & are reference to as 'clockwise' & 'anticlockwise' or positive & negative Screw dislocations respectively.
3] Burger's Vector 'b' is always perpendicular to edge dislocation line.	3] Burger's Vector 'b' is always parallel to screw dislocation respectively
4] Atomic bonds around a dislocation line undergo tensile & compressive stresses.	4] Burger's Vector 'b' is always parallel to screw dislocation line
5] Force required to form edge dislocation is less.	5] Atomic bonds around a dislocation line undergo shear distortion.
6] Edge dislocation travel faster (≈ 50 times) under load.	6] Force required to form screw dislocation is more. Screw dislocations travel slowly under load.

2D defects

(iii) Surface imperfections:

There are 4 types:

1. Grain boundaries, 2. Tilt boundaries, 3. Twin boundaries, 4. Stacking faults

1. Grain boundaries:

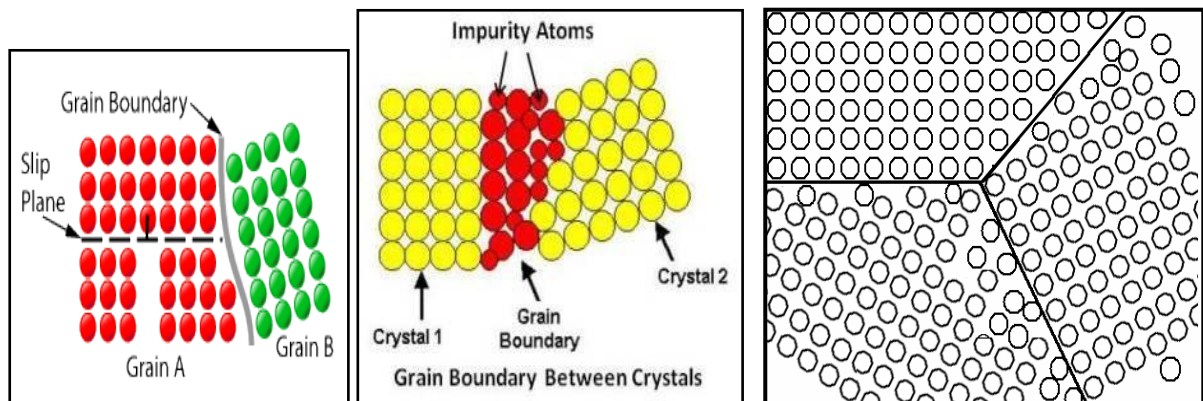
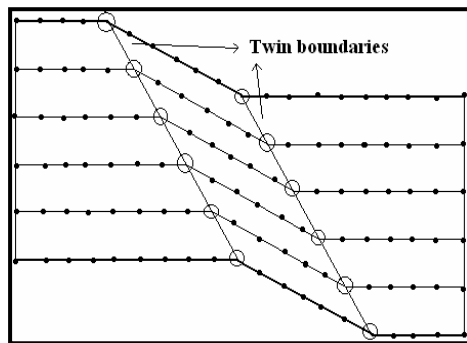


Figure : Schematic presentation of grain boundaries

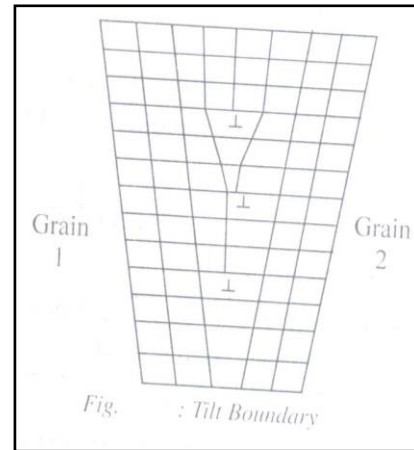
- ✓ Grain boundaries are those regions which separate crystals of different conditions. A Grain boundary is formed when two adjoining growing crystals (grains) meet at their surfaces.
- ✓ The thickness of these regions is only a few atomic diameters.
- ✓ The atoms in these regions are highly distorted & are caught between the two crystals & pulled apart by each to its own configuration.

1. Tilt / Twin boundaries:

- ✓ It is a type of low angle grain boundary where the orientation difference between two neighbouring crystals is less than 10° .
- ✓ The distortion in the boundary is less, & is limited to a few edge dislocations, located one below the other.



Twin boundary



Tilt boundary

3) Twin boundaries:

- ✓ In this type the atomic arrangement on one side of the twin boundary is a mirror reflection of the arrangement on the other side.
- ✓ Twin boundaries occur in pairs so that change in orientation of two grains introduced by one boundary is restored by the other grain boundary.
- ✓ Twins are generally formed during annealing or mechanical working of metals.

4) Stacking faults: They are surface imperfections created by an error in the stacking sequence of atomic planes in the crystals. Consider the stacking arrangement in an FCC crystal.

.....ABC ABC (A) BC ABC.....

If suppose the plane within the bracket is missing, then the stacking becomes

.....ABC ABC (BC) ABC.....

The two planes BC found in the middle of FCC stacking in then termed as a stacking fault. In other words stacking faults can be called as discrepancies in the packing sequence of the layers of the crystal structure.

3D defects

Volume defects: Volume imperfections are those defects like blow holes, cracks, foreign inclusions etc. Which are 3 dimensional & are much larger than other types of imperfections. They are normally introduced into solids during processing & fabrication techniques & have a considerable effect on the properties of materials.

Concept of free volume in amorphous solids

Free volume in a polymer can be defined as the volume of the total mass, that is not occupied by polymer chains themselves and hence diffusing molecules can be situated there. It can

generally be said to the gap or pores occupied between the chains of polymers as shown in the Figure.

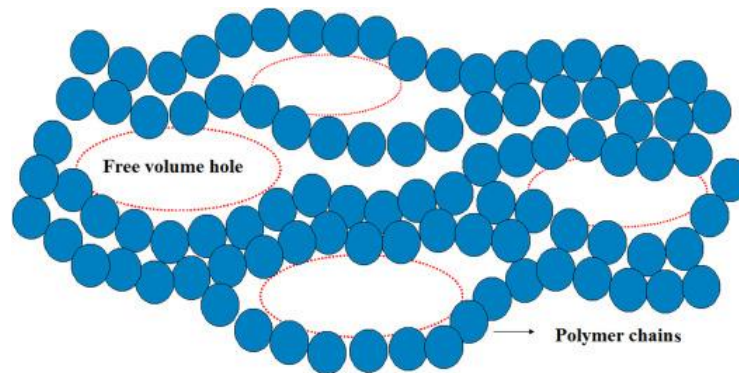


Figure: Schematic representation of the free volume in a polymer.

Similarly in the case of glass and gel the atoms do not have long range order and possesses space between the molecules/atoms which constitute to free volume.

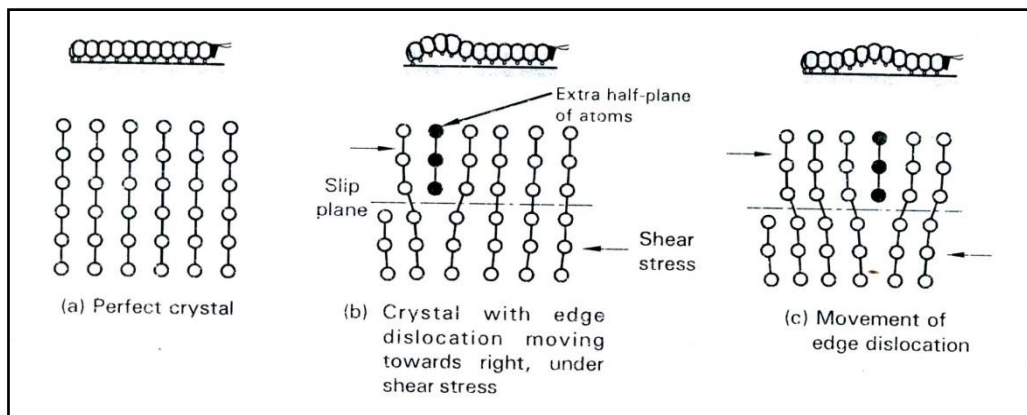
Plastic Deformation:

Plastic deformation in a single crystal occurs by:

- Slip
- Twinning, or
- Combination of slip and twinning

1. Plastic Deformation by Slip:

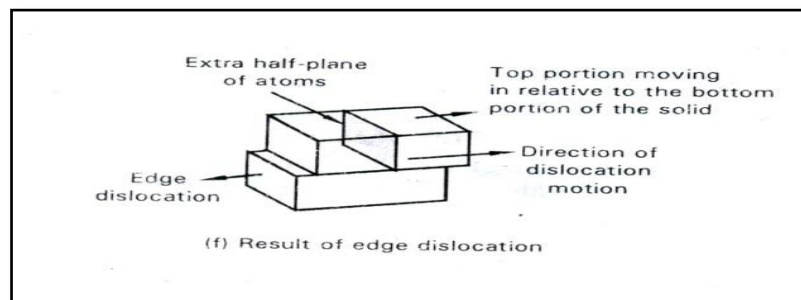
The process by which plastic deformation is produced by the motion of a large number of dislocations is termed as slip.



- ▶ Figure shows **an edge dislocation**, which helps in explaining slip under the action of shear stress. The figure illustrates how an edge dislocation gets glided along the slip plane under the action of shear stress, and how the slip is caused by the movement of edge dislocation.
- ▶ The dislocation motion is analogous to the movement of a caterpillar, which is also shown in figure above the crystal lattice for clear understanding. The caterpillar would have to exert a large force to move its entire body at once. Instead, it moves the rear

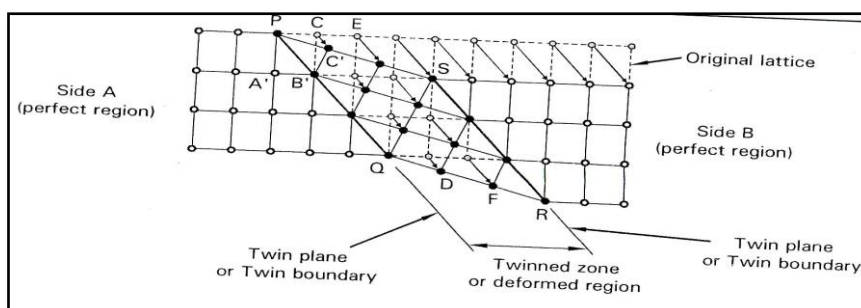
portion of its body forward by a small amount and creates a hump. The hump then moves forward, and eventually moves all of the body forward by a small amount.

- ▶ Under the influence of shear stress, the dislocation in a crystal structure moves similarly by a small amount as that of a caterpillar. It can be seen in figure that, the dislocation in the top half of the crystal is slipping one plane at a time as it moves to the right from its initial position as is shown in figure (a), figure (b), and finally (c). In the process of slipping, the dislocation propagates across the crystal.
- ▶ The movement of the dislocation across the plane eventually causes the top half of the crystal to move with respect to the bottom half. Due to the actual movement of the atomic blocks, no return to the original lattice shape is possible, even after withdrawal of the straining force. This results in permanent deformation, which is clear from figure (e) when compared to figure (a)
- ▶ Figure (f) shows the 3-D view of the formation of a step on the surface of the crystal due to the motion of an edge dislocation



2. Plastic Deformation by Twinning:

Twinning is the movement of atoms in the lattice resulting in a division of lattice into two parts: twinned region and untwinned region, which are symmetrical, but differently oriented. Twinning occurs when a material is permanently or plastically deformed, or during the heat treatment of certain metals. As shown in figure, PQ and RS are called twin boundaries or twin planes, which separate the un-deformed and the deformed parts of the metal lattice. The region PQRS is known as twinned zone or twinned region.



- ▶ The part of the atomic lattice deformed in the twinned region is a mirror image of the un-deformed lattice. The mechanism of twinning may thus be **described as the simple sliding of one plane of atoms over the next**; the extent of the movement of each plane

in the twinned region being proportional to its distance from the twinning plane. For example, the first plane CD moves one-third of an inter-atomic distance, the second plane EF moves two-thirds of the inter-atomic distance, and the third plane SR moves an entire spacing. Notice that the atom C gets displaced to C' exactly the same distance from either side of the twin plane, i.e., $B'C' = B'A'$.

- ▶ In simple words, PC'B' in the twinned region is mirror image of PA'B' in the undeformed region. Similar is the case with respect to other atoms in the twinned region.
- ▶ Twin boundaries interfere with the slip process, and increase the strength of the metal. Movement of twin boundaries causes a metal to deform. Twinning is observed as wide bands under the microscope, and is shown in figure above.

Difference between slip and twinning

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|---|---|
| <ol style="list-style-type: none">1. All atom in one block move over same distance2. Slip appear in thin lines3. There is little change in lattice orientation4. Requires lower shear stress5. More pronounced at high temperature and gradual loadings6. Occurs in metals having more number of slip systems. Eg. Cu (FCC) (12 slip system) | <ol style="list-style-type: none">1. Different planes of atoms moves fractional distance2. They appear in broad lines3. Lattice orientation change in the twinned region4. Require higher shear stress5. More pronounced at low temperature and impact loadings.6. Occurs in metals having less number of slip systems. Eg. Zn (HCP) (3 slip system) |
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