

MATERIAL SCIENCE & METALLURGY.

Introduction.

Material is something that consists of matter. However in the phrase "Materials science and Engg.", material does not refer to all matter in the universe. To be more specific and define materials as that part of inanimate matter which is useful to the engineer in the practice of his profession.

The word 'science' refers to the physical sciences in particular to chemistry and physics. As we mainly deal with solids in material science, the subject is related to solid state physics and solid state chemistry. The engineering usefulness of the matter under study is always kept in mind.

Therefore, material science refers to that branch of applied science concerned with investigating the relationship existing between the structure of materials and their properties and it concerns with the inter-disciplinary study of materials for entirely practical purposes.

Metallurgy: Metallurgy is defined as an art and science of extraction of metals from their ores, ^{refining them} and subsequent combination of two or more metals to form an alloy. In broad sense, the term metallurgy also includes the forming of metals and conferring the desired properties on the products by suitable heat-treatment.

In brief, metallurgy may be defined as the art and science of procuring and adapting metals and alloys to satisfy human needs.

History and Importance of the study of Metallurgy:

— O.P. Khanna. (Peter)

Classification of Metallurgy:

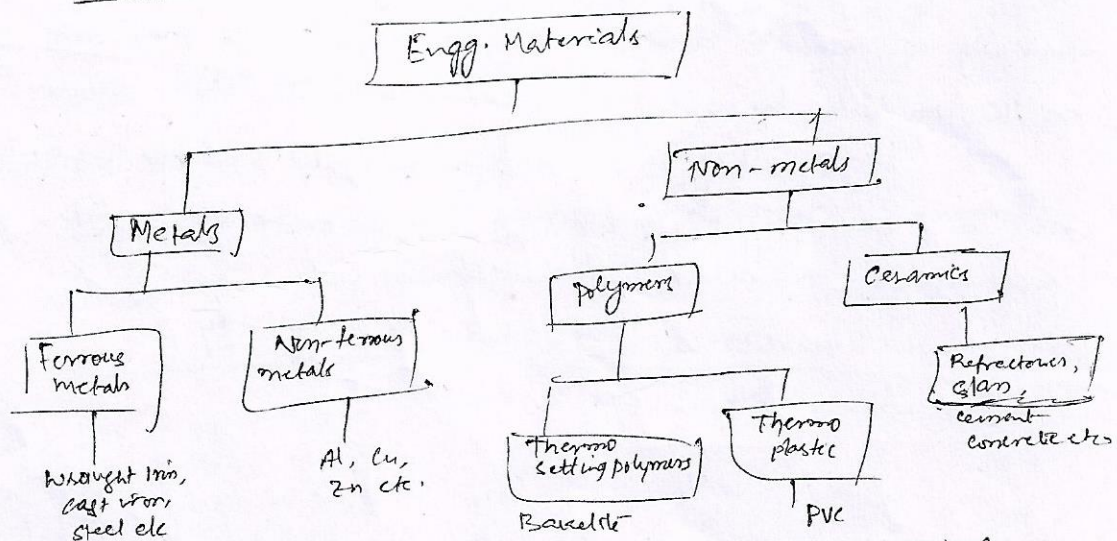
The metallurgical field may be divided into two large groups.

1) Process or Extractive (Chemical) Metallurgy: It is the science of obtaining metals from their ores, including mining, concentration, extraction and refining metals and alloys.

2) Physical Metallurgy - It is the science concerned with the study of physical and mechanical characteristics of metals and alloys. This field studies the properties of metals and alloys as affected by

- Chemical composition - the chemical constituents of the alloy
- Mechanical treatment - any operations that cause a change in shape such as rolling, drawing, stamping, machining, welding etc.
- Thermal or heat treatment - the effect of temp and rate of heating and cooling.

Classification of Engg. Materials.



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 5, 8, 9, 10, 12, 13, 14, 18, 19,
 20, 21, 23, 24, 25, 26, 28, 29,
 30, 32, 34, 35, 36, 37, 40, 41,
 43, 45, 46, 47, 51, 54, 58,
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2.

Levels of structure: The internal structure of a material, or simply called structure can be studied at various levels of observation. The magnification and the resolution of the physical aid used are ~~the~~ a measure of the level of observation. The higher is the magnification the finer is the level. The details disclosed at some level ~~are~~ of observation are generally different from the details disclosed at some other level.

Depending on the level, the structure of materials can be classified as

- Macrostructure,
- Microstructure
- Substructure
- Crystal structure
- Electronic structure and
- Nuclear structure.

Macrostructure - is examined with naked eye or under a low magnification.

Microstructure - structure as observed under the optical microscope. The microscope can magnify a structure upto about 1500 times linear, without loss of resolution details.

Substructure - refers to the structure obtained by using a microscope with a much higher magnification and resolution than the optical microscope. Electron microscope (of magnification of 100000 times linear) normally used to refer substructure to get information on very fine particles or on crystal imperfections etc.

Crystal structure - tells us the details of the atomic arrangement within a crystal. The main technique employed for determining the crystal structure is the X-ray diffraction.

Electronic structure: - usually refers to the electrons

in the outermost orbitals of individual atoms that constitute the solid. Spectroscopic techniques are very useful in determining the ~~crysta~~ electronic structure.

Nuclear structure - studied by nuclear spectroscopic techniques, such as nuclear magnetic resonance (NMR).

Structure - property Relationship in Materials:

To design and fabricate any engineering part, the engineer must select the material which possesses such properties as will permit the component part to perform its functions successfully. Since it is obviously impossible for an engineer to have detailed knowledge of the many thousands of materials already available as well as to think about new developments, he must have a firm grasp of the underlying principles that govern the properties of all materials.

The principle that is of most value to engineers is that properties of a material originate from the internal structures of that material. The internal structures of materials comprise atoms associated with ~~their~~ molecules & microstructures.

The gross composition of material is important in determining its structure. Yet for a given gross composition, radical changes in the structure and properties can be brought about by subtle changes in the concentration and distribution of minute quantities of impurities. The same may also be possible by a thermal or a mech. treatment that involves no change in the overall composition of the material.

Engg. Requirements of materials - Engg. requirements of a material mean as what is expected of from the matl. so that the same can be successfully used for making an engg. component. The main engg. requirements are: (1) Fabrication requirements. (2) Service requirements. (3) Economic requirements.

Atomic Structure - (A Revision) :

All matter is composed of unit substances known as chemical elements. The elements are composed of atoms, which have a distinct structure characteristic of each element. The difference in atomic structure that gives the element its characteristic properties.

Atom is a compose of three elementary particles.

- i) Electrons - tiny particles of negative electricity.
- ii) protons - particles of positive electricity. and
- iii) neutrons - electrically neutral particles.

Almost the entire mass of the atom is concentrated in the nucleus, which contains the protons and neutrons.

Since the electron and proton have equal but opposite electrical charge, the neutral atom must contain an equal no. of electrons and protons.

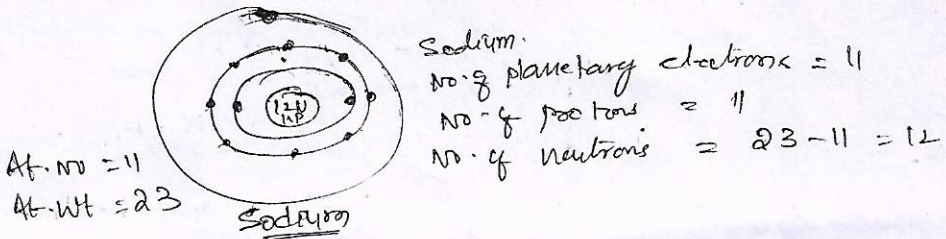
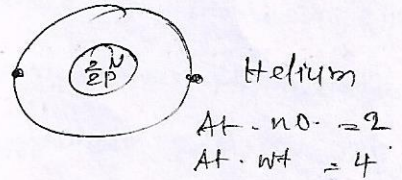
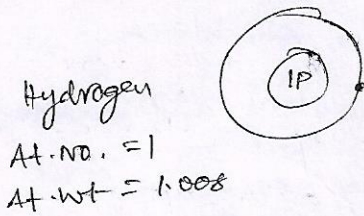
As the mass of the electron is negligible compared to that of protons and neutrons, the mass of the atom depends mainly on the no. of protons and neutrons in the nucleus.

The electrons surrounding the nucleus in an atom occupy different orbitals. The position and the momentum of an electron cannot be specified precisely. We cannot visualize an electron orbital to be a discrete path around the nucleus. Instead, the orbital may be considered as an electron probability density cloud surrounding the nucleus. Each electron orbital is called a quantum state with a set of quantum numbers n, l, m_l & m_s assigned to it.

An electron can be excited from a lower

energy state to a higher energy state by the supply of energy from an external source.

Atomic structure of some atoms:-



Atomic Number :- no. of protons or electrons in an atom.
The no. of protons present in an atomic nucleus of any element is called its atomic number.

Atomic weight :- The mass of the nucleus is directly proportional to the total no. of protons plus neutrons. This is known as atomic weight of the element.

Isotopes - The ^{atoms of} elements having same atomic number but different atomic weights are called isotopes. The chemical properties of isotopes ^{of an atom} will remain same.

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Bonds in Solids :-

All solids are composed of a very large no. of atoms that are bonded together in some manner. Atoms occupy relatively fixed positions with regard to one another. Atoms are held in the solid state by relatively ~~fixed~~ strong interatomic forces which are generally function of temp. & pr. The equilibrium spacing of ~~the~~ atoms in a solid is obtained when the opposing forces are balanced at a particular temp. & pr.

- Solids offer resistance to applied force, due to interatomic forces that hold atoms together. When the applied force exceeds the interatomic force, then ~~the~~ solids tend to get deformed.

Various properties i.e. physical, chemical & electrical properties depend upon these interatomic forces.

Types of Bonds: According to the strength, chemical bonds are classified as

a) primary bonds (interatomic bonds)

- Ionic bonds
- Covalent bonds
- Metallic bonds

b) Secondary bond — Vander ~~waal~~ weak bond (molecular bond).
(intramolecular bond)

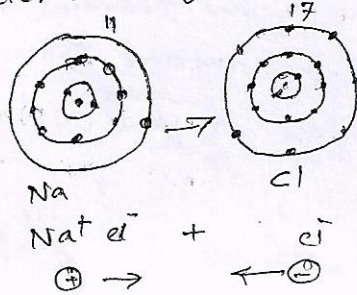
The attractive forces in primary bonds are directly associated with the valence electrons. The outer shell which contains the valence electrons, is in a high energy state and is relatively unstable. A primary bond is formed only if there is lowering of the energies of the electrons involved during the formation of the bond. primary bonds are stronger and more stable than the secondary bond.

Ionic bond:- This bond is formed between two oppositely charged ions, which are produced by the transfer of electrons from one atom to another. It is the

attractive force existing between a positive and negative ion when they are brought into close proximity. These ions are formed when the atoms involved lose or gain electrons in order to stabilize their outer shell electron configuration.

Ex: Sodium & Chlorine. \rightarrow Sodium chloride.

The sodium atom has a single electron in its outer shell and this transfers to join the seven electrons in the outer shell of the chlorine atom to form sodium chloride.



This type of atomic interaction involves outright transfer of one electron from one atom to another leads to the formation of +ve and -ve ions, which are held together by electrostatic forces.

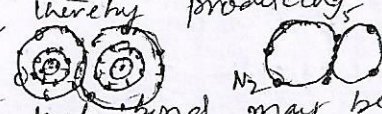
Characteristics of ionic bond

- 1) No fixed direction of force of attraction in ionic crystals i.e. force of attraction is equal in all directions.
- 2) The crystal planes strongly resist any tendency to slip past each other.
- 3) Strong and brittle.
- 4) Low ductility.
- 5) High melting points.

Covalent Bond: The electronic structure of an atom is relatively stable if it has eight electrons in its outer valence shell. Sometimes atoms of some elements may attain stable electron structure by sharing (and not transferred) one or more electrons with adjacent atoms, and thus covalent bond is formed.

Stable covalent bonds are formed between many non-metallic elements since the atoms of these elements usually possess half-filled outer electron shells which resist the direct electron transfer required for the formation of an ionic bond. Ex: Chlorine molecule,

The outer shell of each ^{chlorine} atom possesses seven electrons, 5
Each chlorine atom would like to gain an electron,
and thus forms a stable atom. This can be done
by sharing of two electrons between pairs of
chlorine atoms, thereby producing stable diatomic
molecules.


The covalent bond may be considered to be
regions of high electron density existing between two
atoms. This can be found in hydrogen molecule. When
two hydrogen atoms are very far apart, they do not
interact. When the two atoms brought together, the
two electron-density distribution clouds start to overlap.
The electron of one atom comes under the influence
of the +ve charge of the nucleus of the other and
vice-versa.

Since pairs of electrons are shared in covalent
bonds, there is some degree of orbital overlap between
the bonded atoms. The greater the degree of orbital
overlap the stronger the bond since extensive overlap
means greatly lowered energy levels of the bond
electrons.

Covalent bond — between same or different elements.

~~the~~
characteristics of covalent bond

- 1) Crystals are strong, hard and have high melting points
and low electrical conductivity.
- 2) Have fixed direction.

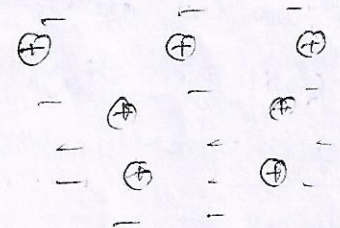
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Metallic Bond: This bond exists due to electrostatic force of attraction between the electron cloud of valency electrons and positive ions of the same or different metals.

- Metallic bond is characteristic of the elements having small no. of valency electrons, which are loosely held, so that they can be released to the common pool forming electron cloud.
- The valence electrons which hold the atoms together, are non-bound to individual atoms or pairs of atoms but move freely throughout the whole metal.
- The metallic ions are held together by mutual attraction ~~between~~ for the electron cloud.

- This bond appears in most metals & alloys.
characteristics ① Good thermal & electrical conductivity.
② soft, ductile & malleable



Vanderwaals Bond:-

Intermolecular or Vanderwaals forces are weak forces that account for mutual interaction between molecules of ~~most~~ most atoms.

Intermolecular bonds do not involve the transfer or sharing of electrons between atoms, however weak attractive force is existed ~~due~~ due to unsymmetrical electrical charges in electrically neutral atoms or molecules. This type of bonding is so weak that the crystals produced by this bonding are unstable, soft and possess low melting points.

ex: Melting, CO₂ and most organic compounds.

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Secondary bonds or Intermolecular bonds

The forces that hold molecules together to form a solid are relatively weaker than atomic bonds and are called secondary bonds. There are no free electrons, hence electrical conductivity is not favoured. They are also called **vander walls bonds (forces)**. *The bonds are weak and do not involve transfer or sharing of electrons between atoms.* There are three types of intermolecular bonds.

(i) Dispersion bond (ii) Dipole bond (iii) Hydrogen bond.

(i) **Dispersion bond** : When the electrons rotate around the nuclei they try to keep in phase as shown in fig. 1.4 for a hydrogen molecule. The result is that the molecule has a small fluctuating net charge on each end. The hydrogen molecule is instantaneously charged negative on the right and positive on the left. This fluctuating charge on one molecule tries to interact with the fluctuating charge on a neighbouring molecule causing a net attraction and thus gives rise to dispersion bonds. Inert gas molecules are held together by dispersion bonds when gases solidify.

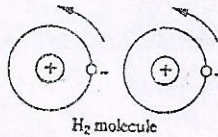


Fig. 1.4

(ii) **Dipole bond** : They are caused due to permanent electrical dipoles formed between molecules. The permanent dipoles are due to unequal sharing of electrons between two atoms.

Dipole bonds are present in HCl, SO₂ and HBr. Consider the formation of hydrogen fluoride molecule by electron sharing. The hydrogen atom has one electron in its outermost shell and fluorine atom has 7 electrons at its outer most shell. The hydrogen atom requires one extra electron to become stable and similarly fluorine require one extra electron to become stable, both hydrogen and fluorine share a pair of electrons and form a covalent bond and results in the formation of hydrogen fluoride molecule. In this bond the fluorine atom has a greater affinity than the hydrogen atom, thus the shared electron pair shifts towards the fluorine atom, this shift of electrons produce an electric dipole.

Similar dipoles are also formed in adjacent molecules. The adjacent hydrogen fluoride molecules attract each other by electrostatic attraction between their oppositely charged ends and the dipole bond is formed.

Dipole bonds are weaker than primary bonds but stronger than dispersion bonds. Since no valance electrons are available they are good insulators.

(iii) Hydrogen bond or bridge : A hydrogen bond is a particular type of dipole bond in which one of the atom is a hydrogen atom. The other atom has a high affinity to attract electron from the hydrogen atom. Thus it is a special type of dipole bond made between similar molecules, each molecule has one end as a hydrogen atom converted into a positive ion by a strong electronegative adjacent atom in the same molecule.

The bond that is formed between ice and water molecules due to attraction between the positively-charged hydrogen end of a molecule and the negatively charged oxygen end of another molecule is called the hydrogen bond.

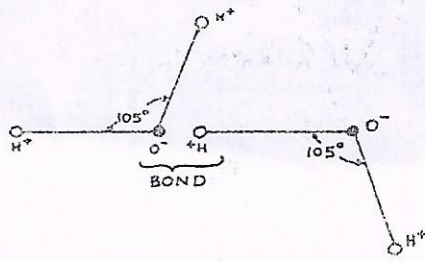


Fig. 1.5: Hydrogen bond between water (ice) molecules

One electron in the hydrogen atom is loosely held and when the adjacent atom in the molecule such as oxygen is strongly electronegative it tries to keep all the electrons around itself leaving the hydrogen atom as a positive ion. A strong permanent dipole is created that bonds the atom.

1.3 INTERATOMIC DISTANCES, IONIC RADII AND BOND LENGTH

Interatomic Distances

The attraction force between two atoms or ions is a function of the interatomic distance between them. The interatomic distance or distance of separation is r as shown in fig. 1.6.

When two atoms are positioned at infinite distance away from each other then their potential energy of interaction is assumed to be zero. When the atoms come closer together, there is a force of attraction between them which increases steadily as they come closer. The potential energy drops as shown in fig. 1.6, this occurs because work is done by the atoms as they come closer together under the force of attraction.

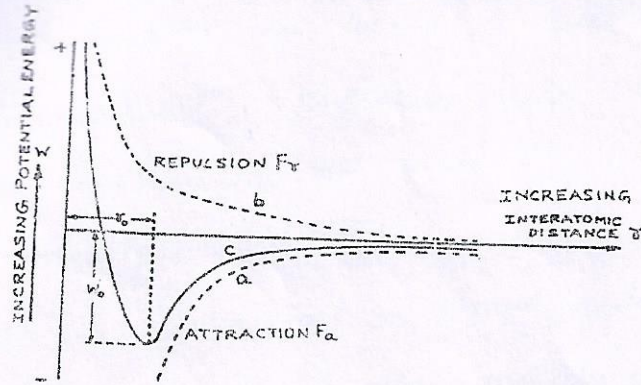


Fig. 1.6

When the atoms get very close over a short range (r_0 , critical spacing), a force of repulsion builds up and this tends to balance the force of attraction, at this stage the potential energy steadily increases because the atoms are pulled together.

In fig. 1.6 the potential energy due to forces of attraction is curve 'a', force of repulsion is curve 'b' and the resultant is curve 'c'.

The potential energy is a minimum (W_0) at the equilibrium position r_0 , which is the *bond length*. W_0 (potential well) represents the work required to separate the atoms completely. The magnitude of the minimum energy W_0 is called *bond energy*. Depending on the bond energy a bond may be strong or weak. Primary bonds have bond energy in the range of (100 – 1000 KJ/mole). Covalent bond, ionic bond and metallic bonds are primary bonds, among them covalent and ionic bonds are stronger.

Secondary bonds have bond energies that range from 1 – 50 KJ/mole. Hydrogen bond, dipole bond and dispersion bonds are examples. The figure 1.7 shows the graph for a strong bond and a weak bond.



Fig. 1.7

Properties of materials (Review)

property means the quality that defines a specific characteristic of material. Properties helps us in predicting the behaviour of materials under different and varying conditions.

Material properties :- Mechanical - strength, elasticity etc.

Electrical - conductivity, Resistivity, dielectric const etc

Magnetic - reluctance, relative permeability, hysteresis etc.

Thermal - Specific heat, thermal capacity, thermal expansion, thermal conductivity etc.

Chemical - corrosion resistance, atomic wt., molecular wt, acidity, alkalinity etc

physical - shape, size, finish, density etc.

Optical - colour, light transmission, light reflection etc

properties depend fundamentally on the nature of that particular material, ~~also~~ ^{also} conditions of use, environment and the state of material. Ex: Mech. strength differs for tensile, compressive, shear and fatigue.

Mechanical properties of materials:

- Describe the behaviour of materials under mech. usage.

Most imp. mech. properties:

① Elasticity - Regaining original shape after removal of external load.

Ex: steel, rubber.

② Plasticity - Retaining the deformed shape even after removal of external load.

ex: Al, lead, clay

- ✓ ⑤ Ductility - plastic deformation under tensile load.
 Ductility of matls. can be measured by the percentage of elongation and the percentage of reduction of area.
 ex: Gold, platinum, silver, Iron, Cu, Al, Ni, Zn etc
- ⑥ Brittleness: - NO or little plastic deformation.
 - lack of ductility.
 ex: cast iron - glass.
- ⑦ Hardness - Resist abrasion, indentation or scratching.
 - Decreases by heating
- ⑧ Hardenability - Degree of hardness that can be imparted to a metal.
 Hardenability can be increased by addition of alloying elements.
- ⑨ Toughness - enables the matl. to be twisted, bent or stretched, under a high stress before rupture.
- ⑩ Stiffness - Resisting deformation.
- ⑪ Resilience - Amount of energy that can be stored per unit volume, after being stressed.
- ⑫ Proof resilience - max. energy stored.
- ⑬ Creep - The slow and progressive deformation of metals material with time at const. stress is called creep.

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1, 2, 5, 8, 9, 10, 16, 17, 18,
 20, 21, 23, 23, 24, 25, 29, 35,
 36, 37, 40, 41, 43, 44, 46, 47
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Crystal structure

Structure — Arrangement of atoms with in a crystal.

Crystal — is a solid whose atoms or molecules are arranged in a systematic geometric pattern.

or
A crystal is an orderly array of atoms in space.

The atoms in the solid are not stationary but are vibrating around fixed points, giving rise to the orderly arrangement of crystal structures.

Solids $\left\{ \begin{array}{l} \rightarrow \text{Crystalline solids} \\ \rightarrow \text{Amorphous solids} \end{array} \right.$

Crystalline solids — built up of a no. of crystals. These crystals may be of similar or varying sizes.

Crystalline solids $\left\{ \begin{array}{l} \rightarrow \text{Metallic crystals} \\ \rightarrow \text{Non-metallic crystals} \end{array} \right.$

Metallic crystals — the ions are connected through the free electrons surrounding them. There are no directional properties involved in the metallic bond and each atom attracts as many neighbouring atoms as it can.

Non-metallic crystals — These crystals have covalent or ionic bonding. ~~or any~~ Atoms of two or more kinds are frequently involved in these bonds.
ex: crystal carbon, crystallized plastic or polymers.

Amorphous solids: These are the materials in which the molecule is the basic structural solid and have no regular structure. In these solids, the elementary particles are mixed together in a disorderly manner. An amorphous structure does not generally possess elasticity but only plasticity (an exception to this statement is rubber). ex: glass, polymers (plastics & rubbers).

Polycrystalline Materials. - Most crystalline solids are built up of no. of small crystals. These solids are called polycrystalline materials. Each crystal or grain in polycrystalline material is connected to neighbouring crystals or grains by grain boundaries.

- Orientation of crystal axes in different grains is usually ~~random~~ random. For the sake of simplicity, polycrystalline materials are often considered as isotropic (isotropic means having same properties in all directions). This is due to random orientation of individual crystals.

Crystallography: - It is the branch of science in which the internal structure of crystals and their properties are studied.

Crystallization (Solidification) of metals: - When a metal is in molten condition, its atoms move freely & rapidly. The atoms lose speed as the liquid cools and arrange themselves in a systematic or definite pattern when it solidifies. The formation ^{& growth} of crystals during solidification of metals from liquid to solid state is called crystallization.

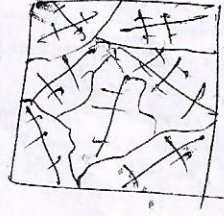
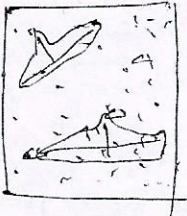
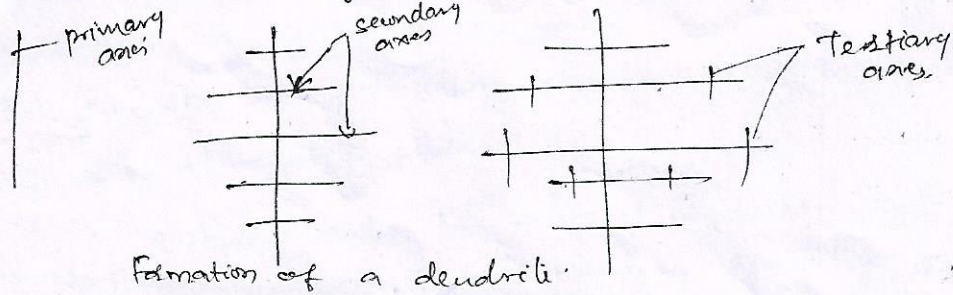
Crystallization consists of two ~~processes~~ stages.

- (1) Formation of crystals.
- (2) Growth of crystals.

Formation of crystal centres or nuclei takes place in several different places ~~depending~~ where the chilling effect is more. This process depends on rate of solidification. High rate of solidification means more no. of crystals are formed ~~and~~ and if the metal solidifies slowly there will be less no. of grains or crystals in a given vol. of metal.

(2) Growth of crystals: once crystal centres are formed, additional atoms in the liquid attach themselves

to the initial crystals.



crystallization process.

Each crystal nucleus grows into the liquid in a dendritic pattern, (structure that have a tree like appearance is called dendrites) which have a primary axis, secondary and tertiary axes. Crystals growing towards each other will eventually meet, but will be unable to assume their usual shape because they are growing at diff. angles. Therefore their external boundaries will be irregular.

Crystal Symmetry: the internal structure of a crystal is due to a definite, ordered arrangement of atoms or molecules. the molecular structure is in general symmetrical. a definite pattern is repeated over and over again in definite directions in space.

The crystal symmetry depends on the internal structure. It is not concerned with the geometrical symmetry except in the perfect crystal, since the crystal may have developed certain faces developed to a greater extent than others.

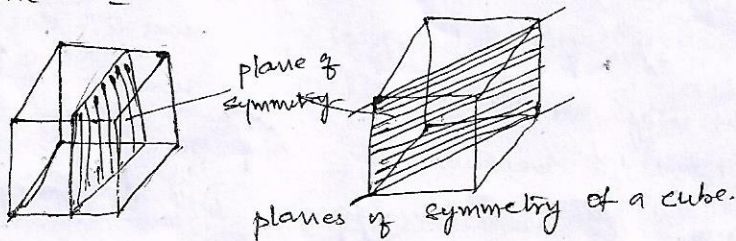
The regularities in the positions of the similar faces, edges etc. will determine the symmetry of a crystal form.

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52, 55, 6.

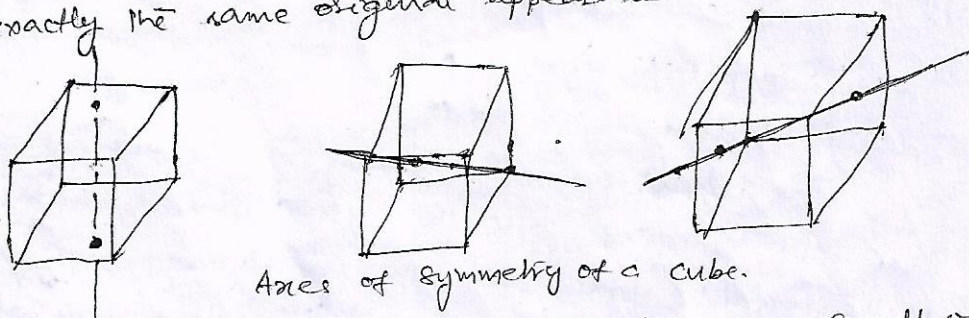
Elements of symmetry: The most important elements of external symmetry are

- ① plane of symmetry
- ② Axis of symmetry and
- ③ Centre of symmetry.

① Plane of symmetry: When a plane divides the crystal into two equal parts such that each part is a mirror image of the other, then the crystal is said to have a symmetry to that plane. ex: A cube has 9 planes of symmetry.



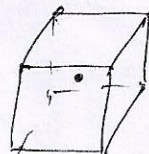
② Axis of symmetry: It is a line passing thru' the crystal so that definite angular rotations of the crystal produces exactly the same original appearance.



If the original appearance is repeated as a result of rotation thru' 180° , the axis is said to be two-fold symmetry. Other possibilities are three, four and six repetitions of the initial appearance, that is after rotation of 120° , 90° & 60° , respectively for three-fold, four fold and six-fold axis of symmetry.

③ Centre of symmetry: It is a point in a crystal such that any line drawn through it, will intersect at the surface of the crystal at equal distances on either side.

A crystal may have one or more



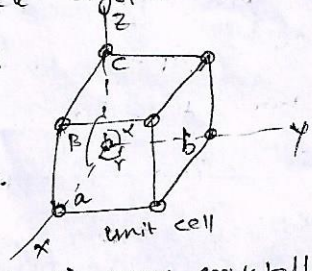
planes, and one or more axes of symmetry but never more than one centre of symmetry.
 Many crystals are not centre-symmetrical since they develop differently at opposite ends.

A perfect cube has a ^{highest} total of twenty-three elements of symmetry. 9 planes of symmetry, 3 three-fold, ~~axes~~ 4 three-fold and 6 two-fold axes of symmetry and one (1) centre of symmetry.

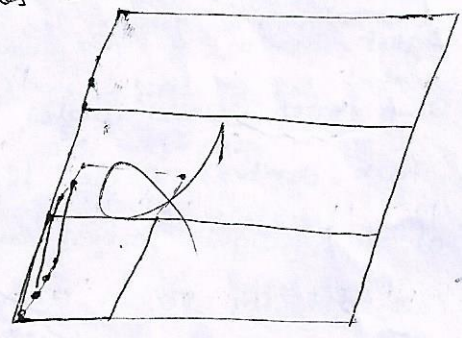
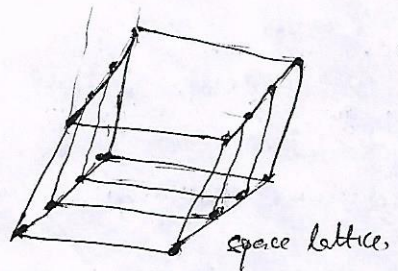
Unit Cell: A unit cell is the smallest geometric figure, the repetition of which in three dimensions will give the actual crystal structure.

These unit cells are containing complete representation of unit of the crystal pattern. The entire crystal structure is formed by packing these unit cells side by side in three dimensional space.

Unit cell can also be defined as the smallest volume of the crystal which represents the arrangement and position of atoms in a complete crystal. Unit cell can be specified by means of three edges (a, b & c) and three angles (α, β & γ) between the axes.

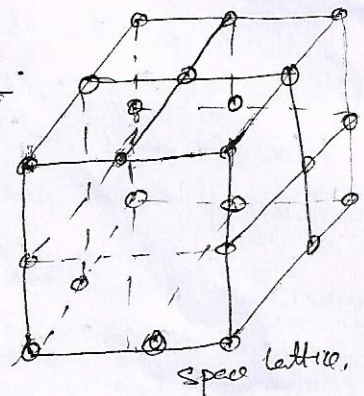


Space Lattice: The atoms present in any crystalline material are arranged in a regular three dimensional repeating pattern in space. This three-dimensional pattern present in a crystalline material is known as crystal lattice or space lattice. Hence space lattice is the three-dimensional network of imaginary lines connecting the atoms.



An important characteristic of a space lattice is that every point has identical surroundings.

There are fourteen space lattices, that is not more than fourteen ways can be possible in which points can be arranged in space.



These 14 space lattices are known as Bravais space lattices after the name Bravais who mathematically demonstrated that only fourteen are possible. ~~Any~~ All crystal structures are based on these fourteen arrangements. All 14 possible crystal lattices are fall into ~~the~~ seven crystal systems.

Bravais Lattices:

The fourteen distinguishable three dimensional space lattices that can be generated by repeated translation of three non-coplanar vectors a, b and c of a unit cell in three dimensional space, are known as Bravais lattices, named after their originator.

Fig. Shows conventional unit cells of 14 Bravais lattices.

1. Simple cubic lattice: It possesses lattice points at the eight corners of the unit cell. It has vectors $a=b=c$, and inter axial angles $\alpha=\beta=\gamma=90^\circ$
2. Face centred cubic lattice: It possesses lattice points at the eight corners and at the face centres of the unit cell. It has vectors $a=b=c$ and inter axial angles $\alpha=\beta=\gamma=90^\circ$
3. Body centred cubic lattice: It possesses lattice points at the eight corners and at the body centre. It has vectors $a=b=c$ and inter axial angles $\alpha=\beta=\gamma=90^\circ$.
4. Simple Tetragonal lattice: It possesses lattice points at

corners of the unit cell. It has vectors $a = b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$.

5. Body centred Tetragonal lattice. It possesses lattice points at the eight corners and at the body centre. It has vectors $a = b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$

6. Simple Rhombohedral lattice. It possesses lattice points at the eight corners of the unit cell. It has vectors $a = b = c$, and inter axial angles $\alpha = \beta = \gamma \neq 90^\circ$.

7. Simple Hexagonal lattice. It possesses lattice points at the twelve corners of the hexagonal prism and at the centres of the two hexagonal faces of the unit cell. It has vectors $a = b \neq c$, and inter axial angles $\alpha = \beta = 90^\circ$ and $\gamma = 120^\circ$

8. Simple Orthorhombic lattice. It possesses lattice points at the eight corners of the unit cell. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$

9. End centred Orthorhombic lattice. It possesses lattice points at the eight corners and at two face centres opposite to each other. This lattice is also known as side centred or base centred Orthorhombic lattice. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$.

10. Face Centred Orthorhombic lattice. It possesses lattice points at the eight corners and at the six face centres of the unit cell. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$.

11. Body centred Orthorhombic lattice. It possesses lattice points at the eight corners and at the body centre. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = \gamma = 90^\circ$

6

12. Simple monoclinic lattice. It possesses lattice points at the eight corners of the unit cell. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = 90^\circ \neq \gamma$.

13. End centred monoclinic lattice. It possesses lattice points at the eight corners and at two face centres opposite to each other. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha = \beta = 90^\circ \neq \gamma$.

14. Simple Triclinic lattice. It possesses lattice points at the eight corners of the unit cell. It has vectors $a \neq b \neq c$, and inter axial angles $\alpha \neq \beta \neq \gamma \neq 90^\circ$.

Lattice parameters of a Unit cell:

The three edges of a unit cell is drawn from the reference axes and is called as crystallographic axes.

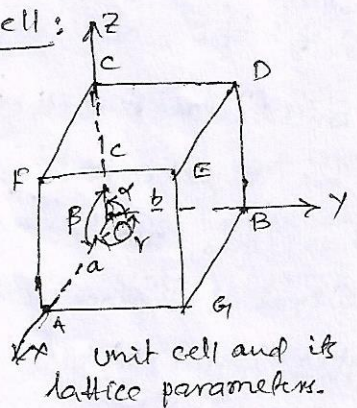
The three vectors a, b & c are called as lattice vectors or fundamental translation vectors.

The angles between them are called as interfacial angles.

The lattice parameters of unit cell are nothing but its characteristic intercepts (a, b & c) and interfacial angles (α, β & γ)

Primitive cell :- It is defined as a unit cell which contains lattice points at corners only. It is the simplest type of unit cell.

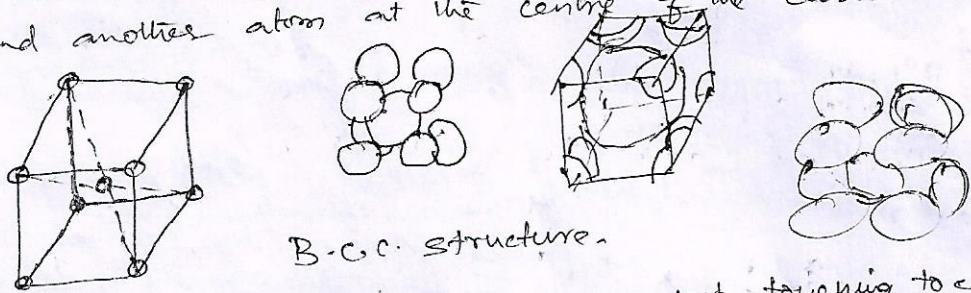
A primitive cell can also be defined as a simple cell which always contains equivalent of one complete unit of pattern i.e., at atom or ion.



Crystal structure of metals:- As per Bravais lattices, there are 14 possible types of space lattices and they fall into seven crystal systems. However, most of the important metals crystallize in either the cubic or hexagonal systems, and only three types of space lattices are commonly found. They are,

- 1) Body-centred cubic structure (B.C.C.):
- 2) Face-centred cubic (F.C.C) structure and
- 3) close-packed hexagonal (C.P.H or h.c.p) structure.

1) B.C.C. structure: In this type of metallic structure, a unit cell has one atom at each corner of the cube and another atom at the centre of the cube.



B.C.C. structure.

In this case, the corner atoms are not touching to each other but the central atom is touching the eight corner atoms.

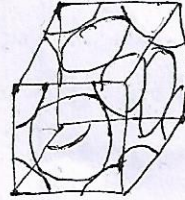
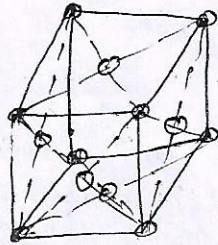
∴ The unit cell of B.C.C. structure contains,

8 atoms at the corner $\times \frac{1}{8}$	= 1 atom
1 centre atom	= 1 "
Total = 2 atoms.	

∴ The effective atoms per unit cell = 2.

~~Ex~~ Many metals crystallize in b.c.c. structure
 Ex: Vanadium, molybdenum, tungsten, α -iron, chromium, barium etc.
 or properties - moderate ductility.

2) F.C.C. structure:- The unit cell of f.c.c. structure contains one atom at each corner of the cube and also one atom at the centre of each face. The corner atoms are in touch with the atom at the centre of the face. Each face atom is shared by two adjacent faces of cube.



properties: Very highly ductile

f.c.c. structure.

Hence the effective no. of atoms per unit cell

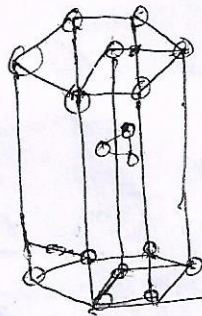
$$= 8 \times \frac{1}{8} + 6 \times \frac{1}{2} = 1 + 3 = 4 \text{ atoms.}$$

ex: copper, silver, gold, Al, lead, Ni, Zn, nickel, Co, platinum etc.

③ Close-packed hexagonal (C.P.H or H.C.P) Structure:

A hexagonal close packed structure has one atom at each corner of the hexagon, one atom at the centre of the two hexagonal faces and one atom at the ~~center~~ ~~of the line~~ connecting the geometric centre of ~~the~~ each of the three alternative triangular prisms.

This type of structure is found in Mg, Zn, Cadmium, beryllium, Zirconium, titanium etc.



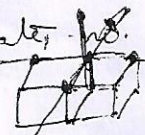
- properties - too lack of ductility, brittle.

- effective no. of atoms = $12 \times \frac{1}{6} + 2 \times \frac{1}{2} = 2 + 1 = 3$

Hcp structure

Co-ordination number: - It is defined as the no. of nearest ^{equidistant} atoms which are directly surrounding a given atom.

For simple structure: Any corner atom has four nearest neighbours in the same plane plus two nearest neighbours one exactly above and the other exactly below of that corner atom. Hence the ~~coordination no.~~ ^{coordination no.} of simple cubic structure is $4 + 2 = 6$.



On b.c.c. structure: In this structure there are 8 atoms one each at the corners of a unit cell and one atom

the centre of the cube. For any corner atom, the nearest atoms are the body centred atoms. For each corner atom of a unit cell, there are 8 unit cells in neighbours, which are having 8 body centred atoms. Hence coordination no. of b.c.c. structure is 8.

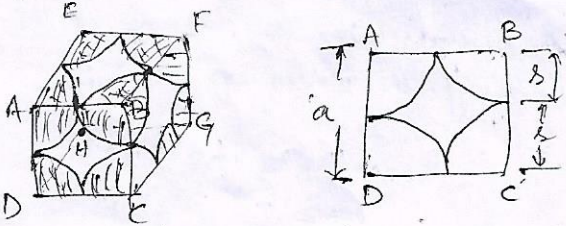
f.c.c. structure - In this structure, for any corner atom, the nearest atoms are the face centred atoms. There are 4 face centred atoms of the surrounding unit cells in its own plane, 4 face-centred atoms below this plane and 4 above this plane. Hence coordination no. of f.c.c. structure is $4 + 4 + 4 = 12$.

Atomic packing factor :-

The atomic packing factor or density of packing has been defined as the ratio of the volume of the atoms per unit cell to the total volume occupied by the unit cell.

$$\therefore \text{A.P.F} = \frac{\text{vol. of atoms per unit cell}}{\text{vol. of the unit cell.}} = \frac{v}{V}$$

For simple cubic structure: In this structure, the atoms are arranged to be placed in such a way that any two adjacent atoms touch each other.

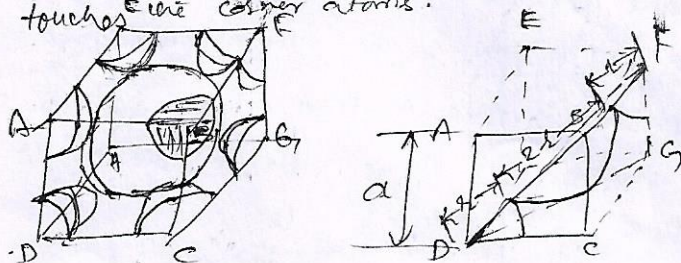


If a = lattice parameter
 r = radius of atoms,
 from fig. $a = 2r$

$$\therefore \text{APF} = \frac{\text{Average no. of atoms/unit cell} \times \text{Volume of an atom}}{\text{Volume of the unit cell}}$$

$$= \frac{1 \times \frac{4}{3} \pi r^3}{a^3} = \frac{4/3 \pi r^3}{(2r)^3} = \underline{\underline{0.52}}$$

B.C.C. structure :- In b.c.c. structures, the centre atom touches ^{the} corner atoms.



if a = lattice parameter
 r = radius of atoms

$$DF^2 = DG^2 + GF^2 \quad ; \quad DG^2 = DE^2 + EG^2$$

$$(4r)^2 = a^2 + a^2 + a^2 = 3a^2$$

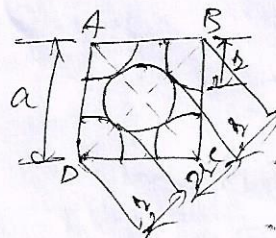
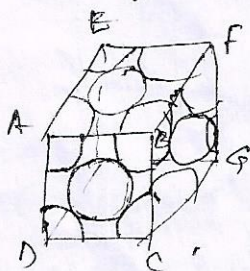
$$a = \frac{4r\sqrt{3}}{4}$$

$$\therefore \text{APF} = \frac{\text{Average no. of atoms per unit cell} \times \text{Vol. of an atom}}{\text{Vol. of the unit cell}}$$

$$= \frac{2 \times \frac{4}{3} \pi r^3}{a^3} = \frac{2 \times 4 \times \pi \times \left(\frac{a\sqrt{3}}{4}\right)^3}{a^3}$$

$$= \underline{\underline{0.68}}$$

FCC structures :- In fcc structures, the atoms at the centre of faces, are touching the corner atoms.



$$DB^2 = DC^2 + CB^2$$

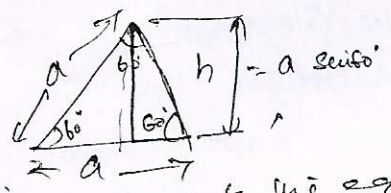
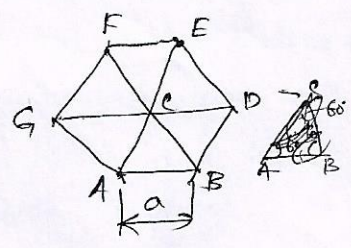
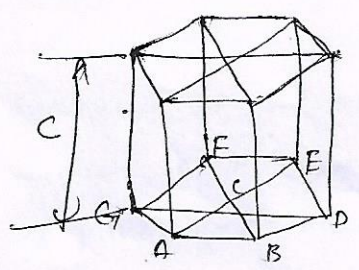
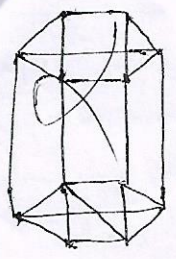
$$(4r)^2 = a^2 + a^2$$

$$r = \frac{a}{2\sqrt{2}}$$

$$\therefore \text{APF} = \frac{4 \times \frac{4}{3} \pi r^3}{a^3} = \frac{4 \times \frac{4}{3} \times \pi \left(\frac{a}{2\sqrt{2}}\right)^3}{a^3}$$

$$= \underline{\underline{0.74}}$$

HCP structure :- The vol. of the unit cell can be found out by finding out the area of the base plane and multiplying this by its height.



The area of the equilateral triangle $ABC = \frac{1}{2} a \times a \sqrt{3}$

\therefore Total area of $ABDEFG = 6 \times \frac{1}{2} a^2 \sqrt{3} = 3a^2 \sqrt{3}$

\therefore Vol. of unit cell = $3a^2 \sqrt{3} \times c$

for hcp structures, the corner atoms are touching to the centre atom on top as well as bottom faces i.e., atoms at $ABDEFG$ are touching the atom at C .

$\therefore a = 2r \Rightarrow r = \frac{a}{2}$

$$APF = \frac{6 \times \frac{4}{3} \pi r^3}{3a^2 \sqrt{3} \times c} = \frac{6 \times \frac{4}{3} \pi \left(\frac{a}{2}\right)^3}{3a^2 \sqrt{3} \times c}$$

$$= \frac{\pi a}{3c \sqrt{3}}$$

The $\frac{c}{a}$ ratio for an ideal hcp crystal structure is $= 1.633$

$$\therefore APF = \frac{\pi}{3 \times 1.633 \times \sqrt{3}} = 0.74$$

22/2/2 74-81
 4, 7, 13, 25, 49, 85,
 4, 17, 4, 6

Miller Indices (of planes)

The orientation of atomic planes in a space lattice are usually specified by Miller indices. The method of marking the planes symbolically was made popular by the English crystallographer Miller and hence the indices of the planes are called Miller Indices.

Miller indices are the reciprocals of the fractional intercepts which the plane makes with the crystallographic axes. These reciprocals of fractional intercepts are converted to whole numbers by their LCM, and are enclosed in brackets (parentheses). ex: (111). Negative indices are written with a bar over the number.

All the symmetrical planes called planes of a form and are represented by the indices of one of them enclosed in a curly brackets. ~~ex: {100}~~

For ex: the six faces of a cube which have indices (100), (010), (001) & $\bar{1}00$, $0\bar{1}0$, $00\bar{1}$ are the planes of a form and are indicated by $\{100\}$.

procedure of finding Miller indices of any plane:

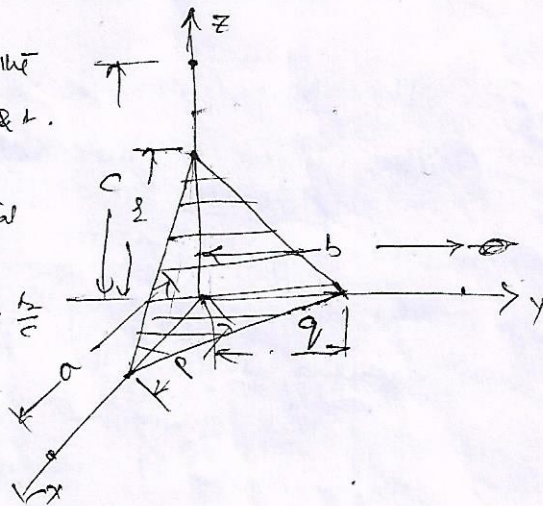
① Find out the intercepts made by the planes on three axes. $p, q, & r$.

② Convert these into fractional intercepts. If a, b, c are axial lengths, fractional intercepts are $\frac{p}{a}, \frac{q}{b}, \frac{r}{c}$.

③ Find out the reciprocals of these fractional intercepts. i.e. $\frac{a}{p}, \frac{b}{q}, \frac{c}{r}$.

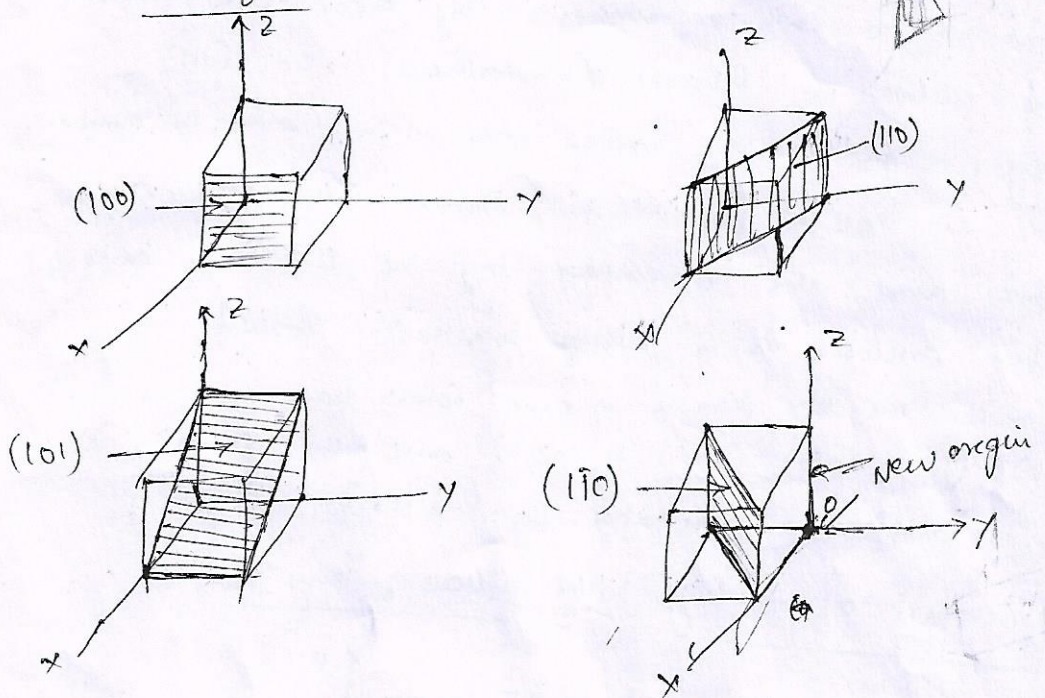
④ Convert these reciprocals to the whole numbers by dividing with their LCM. say these are $h, k, & l$.

⑤ Enclose these numbers in parenthesis. (hkl).



If the plane passes thru' the origin, the origin has to be shifted for drawing the plane.

Some of the examples:

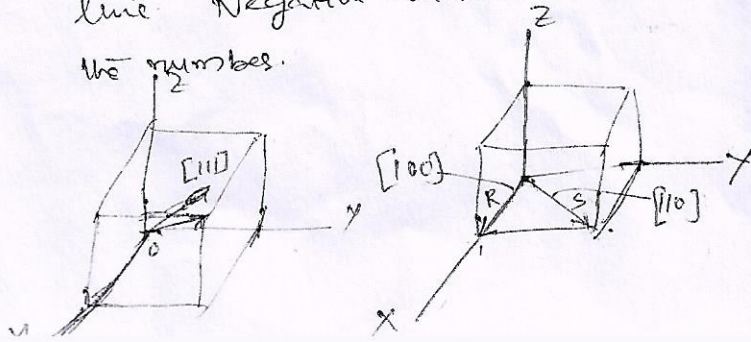


The procedure for drawing a plane from the given Miller indices is the reverse of the above.

Exercise: Draw $(1\bar{1}0)$, (112) , (210)

Indexing of Lattice Directions:

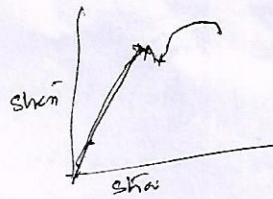
The direction of any line in a lattice is described by first drawing a line thru' the origin parallel to the given line and then getting the coordinates of any point on this line. These coordinates in square bracket indicates the direction of that line. These will be converted into smallest integers and are ^{enclosed} kept in square bracket, which indicates the direction of that line or ~~parallel~~ any line parallel to that line. Negative indices are written with a bar over the numbers.



Crystal Imperfections: - Crystal imperfections are the defects in crystals. Any real crystal always has defects in its structure. In metal crystals, it is observed that the yield stress causing slip is much lower than the theoretical estimate of the shear cohesion because every crystal contains imperfections from which slip can start at a low stress. These defects in crystals influence many of the ~~properties~~ physical properties of materials.

Crystal imperfections are broadly classified into four major classes as below.

- ① Point defects (Zero dimensional defects)
- a) Vacancies
 - b) Interstitials
 - c) Impurities
 - d) ~~electronic defects~~



- ② Line Defects (One dimensional defects)
- a) Edge dislocations
 - b) Screw dislocations

- ③ Planar or surface defects (Two dimensional defects)
- a) Grain boundaries
 - b) Tilt boundaries
 - c) Twin boundaries

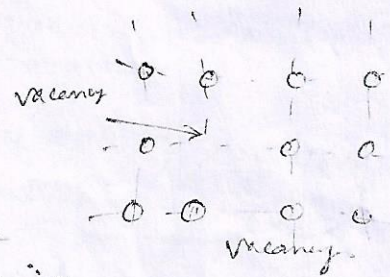
4) Volume Defects.

Point Defects: point defects are small along all three dimensions. Their effect is local. All the atoms in a solid possess vibrational energy and at all temperatures above absolute zero, there will be a finite no. of atoms which have sufficient energy to break the bonds, which holds them in ^{their} equilibrium position. Once the atoms are free from their lattice points, they give rise to point defects. Also due to the presence of impurity atoms point defects are likely to occur.

① Vacancies :- A vacancy or vacance site means an unoccupied atom position with in a crystal lattice, or are simply empty atoms sites.

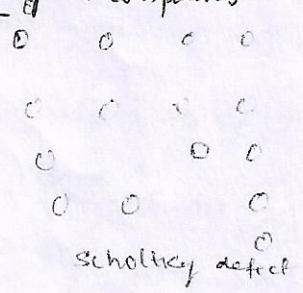
Vacancies may occur as a result of imperfect packing during solidification or they may arise due to thermal vibrations of atoms at elevated temp, because due to increase in thermal energy, the individual atoms will jump out of their position of lowest energy.

The atoms surrounding a vacancy tend to be close together, there by distorting lattice planes.



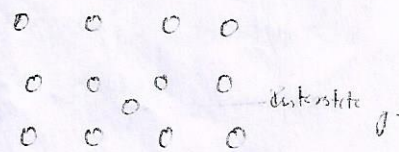
Schottky defect: these are closely related to vacancies. pair of vacancy in compounds

It is formed when an atom is removed from its lattice point and is replaced at any position on the surface of the crystal, pair of $+ve$ & $-ve$ ions misplaced



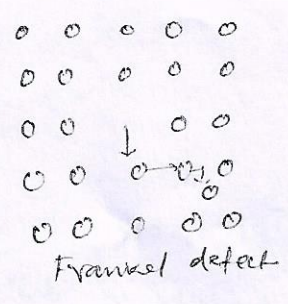
② Interstitials: If an atom occupies a definite position in the lattice, ~~not~~ between the atoms of the ideal crystal, then these are called interstitial defects. The interstitial may be either a normal atom of the crystal or any foreign atom.

These are normally occur in crystals in which, the atomic packing factor is low.



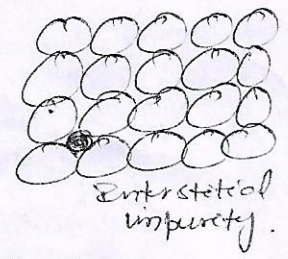
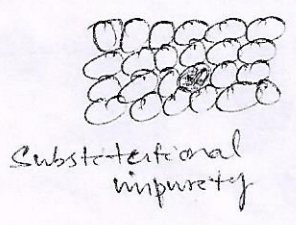
Interstitially produces atomic distortion because interstitial atom tends to push the surrounding atoms farther apart, unless the interstitial atom is smaller than the rest of the atoms in the crystal.

Frankel defect:- Sometimes an atom may leave its regular site and may occupy nearby interstitial site, by sequence of jumps, giving rise to two defects simultaneously i.e. one vacancy and one interstitial. These two defects together is called Frankel defect:



② Impurities: Impurities may be small particles (such as slag inclusions in metals) embedded in the structure, or foreign (metal) atoms in the lattice.

Impurity atoms are introduced into the crystal structure as
 1) Substitutional or
 2) Interstitial atoms
Substitutional impurities: Foreign atoms may occupy lattice sites from which the regular atoms are missing.



Interstitial impurities:- Foreign atoms may occupy positions between the atoms of the ideal crystal.

Impurity atoms are generally have ~~different~~ atomic radii and electronic structures different to that of host atoms and hence they considerably distort the lattice.

These defects occur in metallic, covalent and ionic solids and play a very important role in many solid state processes such as diffusion, phase transformation etc.

④ Electronic defects: These defects occur due to change in charge distribution in solids. These are free to move in the crystal under the influence of an electrical field and changes the electronic conductivity of certain solids.

Effect of point defects.

- ① They increase the hardness and tensile strength due to distortion of the lattice.
- ② They increase the electrical conductivity
- ③ Vacancies increase the diffusion and phase transformation.

Line Defects or (Dislocations):-

A dislocation may be defined as a disturbed region between two perfect parts of a crystal. It is a line defect in a crystal structure whereby a part plane of atoms is displaced from its symmetrically stable position in the array.

The dislocation is responsible for the phenomenon of slip, by which most metals deform plastically. It is the boundary between the slipped region and the unslipped region of a crystal.

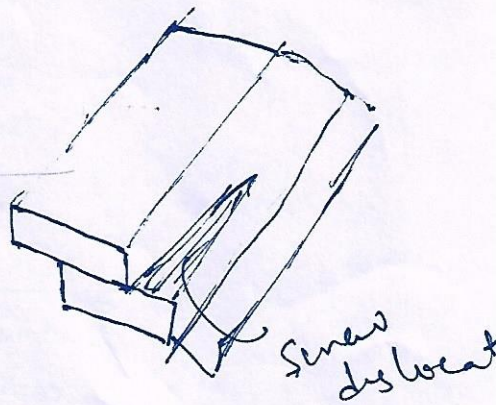
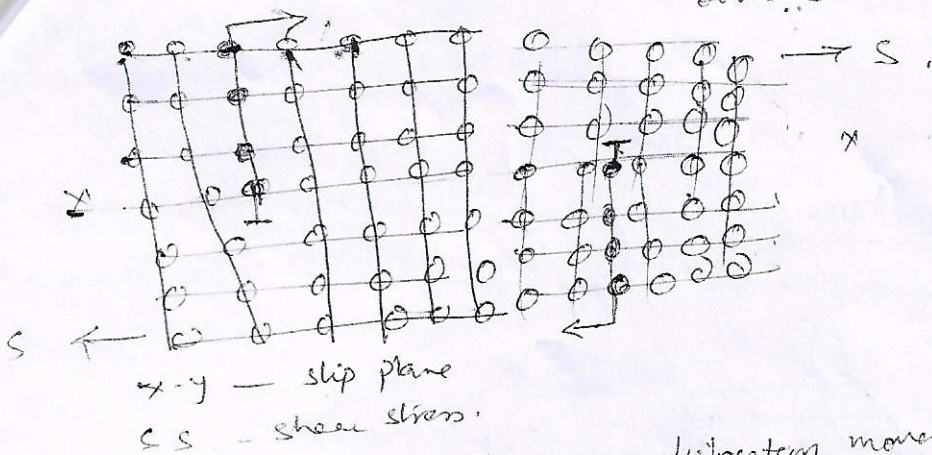
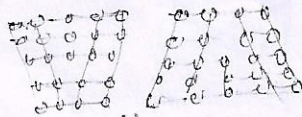
Most of the mechanical properties like slip, strain hardening, the yield point, creep, fatigue etc are affected by dislocations.

Types of dislocations } edge dislocations
} screw dislocations

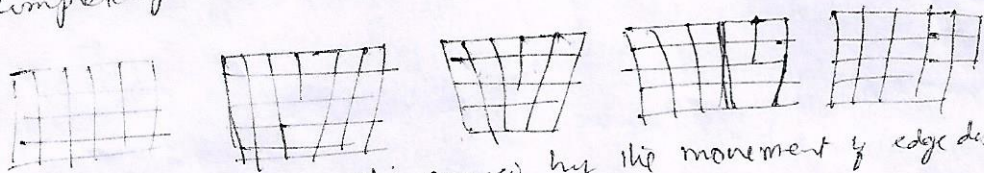
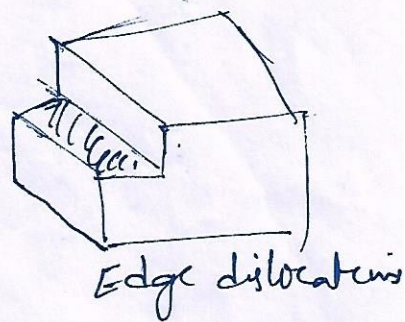
edge dislocation - These dislocations are the defects ^{which arise} due to the insertion of an extra plane of atoms either above or below the slip plane. If this extra plane of atoms is above the slip plane, the defect is called positive dislocation ~~and~~ (denoted by the symbol, \perp) and if

24/09/21
 24, 09, 21, 35, 36, 37, 38
 41, 54

its extra plane is below the slip plane, it is called negative dislocation (T).



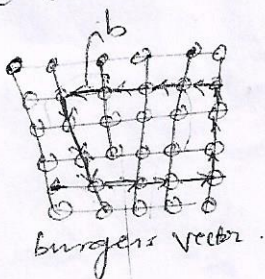
Under a shear stress \Rightarrow a +ve dislocation moves to the right and -ve dislocation moves to the left.
 Gliding of dislocation along slip planes out of the crystal completely produces slip.



slip caused by the movement of edge dislocation.

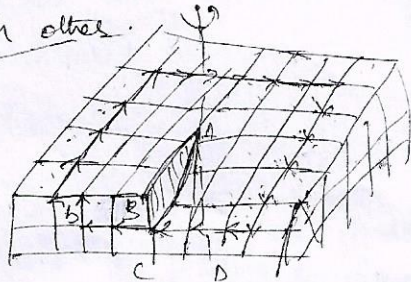
The dislocation lines can also be described by Burgers vector (b). Burgers vector indicates the amount and direction of the shift of the lattice on the slip plane.

Burgers vector of a dislocation line can be found out by using Burgers loop or circuit. In a perfect crystal, Burgers loop is a closed circuit whereas in a plane containing dislocation, the circuit fails to close. The vector necessary to close the circuit is called Burgers vector.



In edge dislocation, the Burgers vector lies at an angle to the line of dislocation.

Screw Dislocation. In screw dislocations, the atoms are displaced in two separate planes per to each other.

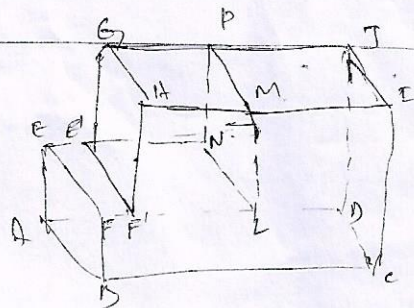
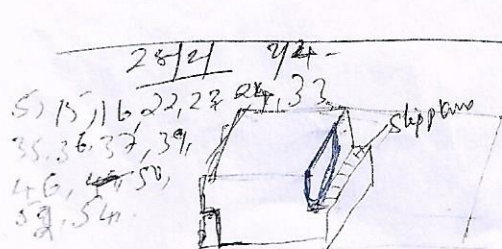


The upper portion of the crystal has been sheared by an atomic distance (as shown by the shaded area) to the right relative to the lower portion. No slip is taken to the right of AD, and AD is the dislocation line.

Screw dislocation is parallel to the burger's vector.

Screw dislocation may be thought of as having been produced by cutting a crystal along a straight line and then shearing the atoms by a burger's vector parallel to the dislocation line.

The name screw dislocation is given because it transforms successive atomic planes into the surface of a helix around the dislocation line. This dislocation has ~~high~~ neither tensile nor compressive stresses but has shear stresses.

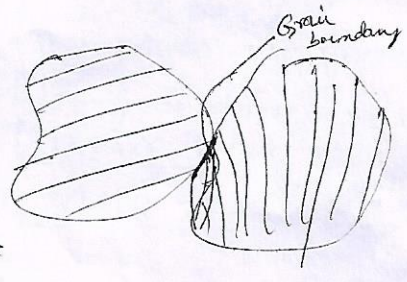


Line Defects: These defects arise due to change in stacking of atomic planes. during solidification or mech. & thermal treatment.

the change may be due to \rightarrow Orientation of the planes
 \rightarrow stacking sequence of the planes.

(ii) Grain boundaries: These are the defects which separate grains of diff. orientation from each other in a polycrystalline material.

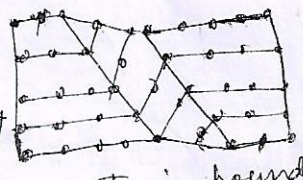
Two randomly oriented grains have a region of transition at the grain boundary where the atomic packing is imperfect.



These defects are ~~observed~~ called high angle boundaries

Twin Boundaries: - The atomic arrangement on one side of a twin boundary is a mirror image of the arrangement on the other side.

Twin boundaries occur in pairs, such that the orientation change introduced in one boundary is restored by the other.



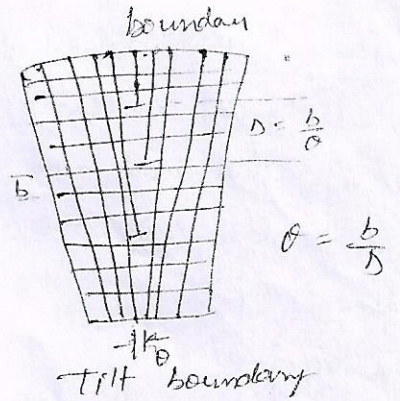
Twin boundary.

The region between the pair of boundaries is called the twinned region.

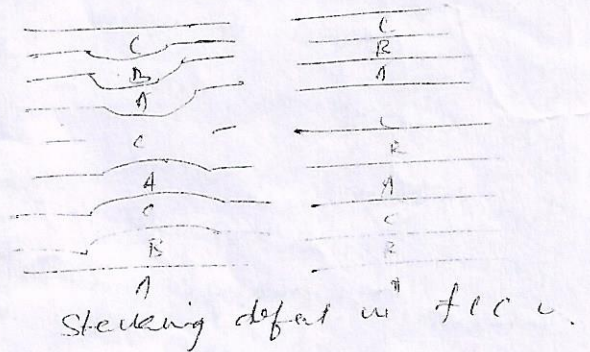
Tilt boundaries, these are called low-angle boundaries as the orientation difference between two neighbouring crystals is less than 10° .

These are generally described by suitable arrays of edge dislocations.

A tilt boundary is composed of edge dislocation lying one above the other in boundary.



Stacking Defects - these defects arise from the stacking of one atomic plane out of the sequence on another while the lattice on either side of the fault is perfect.



Volume defects - such as cracks may arise when there is only small electrostatic dissimilarity between the stacking sequence of planes in metals.

eg: group of atoms missing - void etc are volume defects

$30 \times 15 = 33, 32, 31$
 $29, 06, 206, 41, 281$
 $20, 42, 47, 55, 16, 19,$
 $44, 9, 53, 8, 17, 18, 27,$
 s) 304, 303, 2, 37, 51, 3.

$312, 305, 352, 1$
 $327, 304$

Dislocations - effect Mech. properties

- Dislocation is a boundary between a slipped & un-slipped regions of a slip plane of a crystalline solid

- The slip plane is a specific crystallographic plane of a crystal having much higher atomic density than the rest of the plane

Slip plane is a closed packing plane
slip plane is a largest-atomic density plane

Fracture

Failure of materials

Failure — An event that does not accomplish its intended purpose.

- Loss of ability to function.

Failure — Many ways — ex: excessive deformation, fracture, corrosion, burning, degradation of properties etc.

Fracture — result of failure by mechanical means.

Fracture — Separation of a solid body into two or more parts under the action of stress.

Fracture occurs in different ways, depending on the state of the stress, the rate of application of stress and the temp.

Simple fracture (fracture due to application of uni-axial stress) is focused in this chapter.

Fracture Components

- 1) Crack initiation
- 2) Crack propagation.

Fractures can be basic classification

- 1) Ductile fracture
- 2) Brittle "

Fractures are classified w.r.t. several characteristics as below.

Characteristic	1	2
1. strain to fracture	Ductile	Brittle
2. Crystallographic mode	Shear	cleavage
3. Appearance	Dull, fibrous & gray	bright & granular.
4. Crack propagation	Along grain boundaries (Intergranular)	Through grain boundaries (Transgranular)

Shear fracture - promoted by shear stresses, occurs as a result of extensive slip on active slip plane

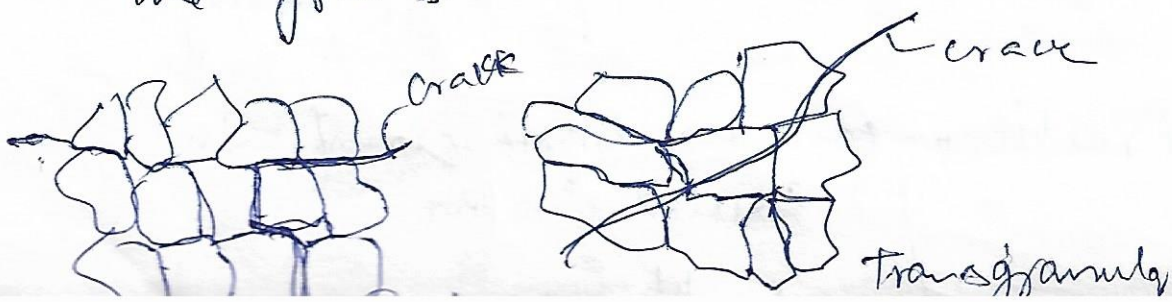
- surface appears gray & fibrous

Cleavage fracture - by tensile stresses acting normal to cleavage plane.

- surface appears bright & granular.

Intergranular fracture - Crack propagation along the grain boundaries.

Transgranular - Crack propagation through the grains.



Ductile Fracture - Considerable amount of plastic deformation before fracture (i.e. before & during crack propagation)

Brittle fracture: minor or no deformation during the crack propagation. (To be avoided always).

Deformation of a material depends on:

- strain rate
- Rate of loading
- Temp.
- crystal structure

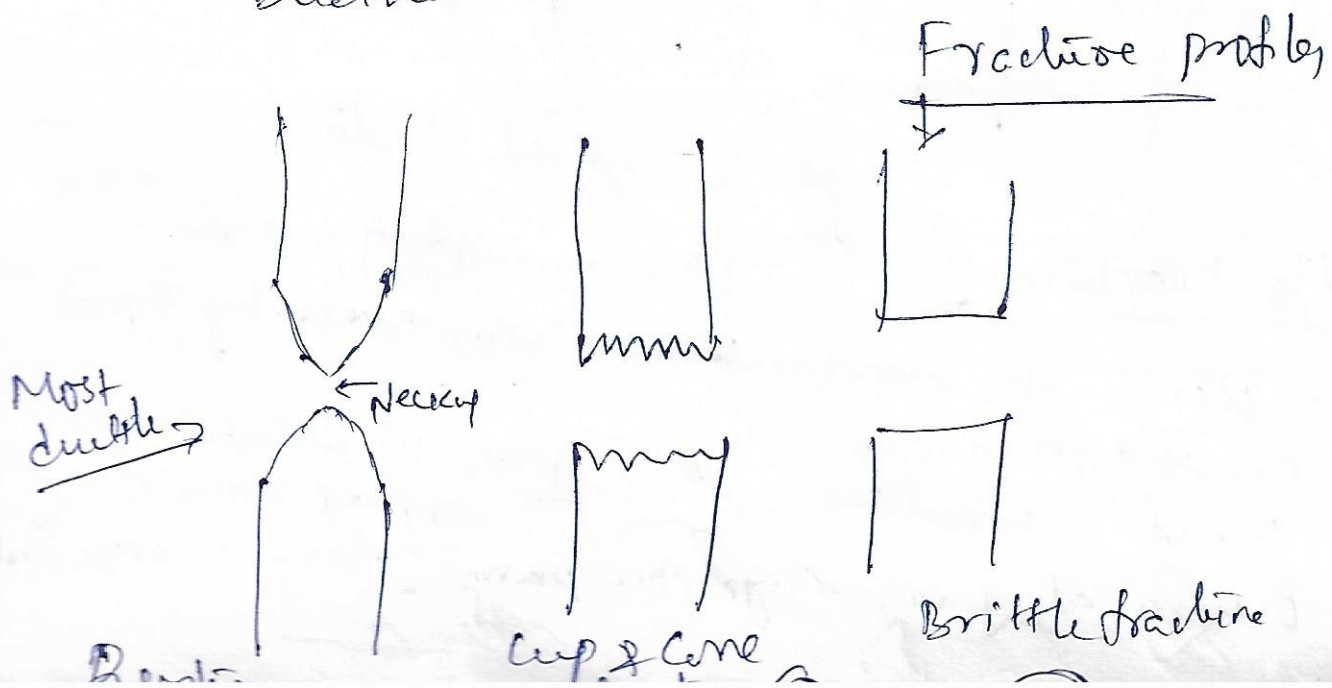
Under the action of tensile stress, most ~~metals~~ materials are ductile.

Ceramics - brittle

Polymers - ~~both~~ Both type

Brittle fracture - BCC or HCP.

Ductile " - FCC.

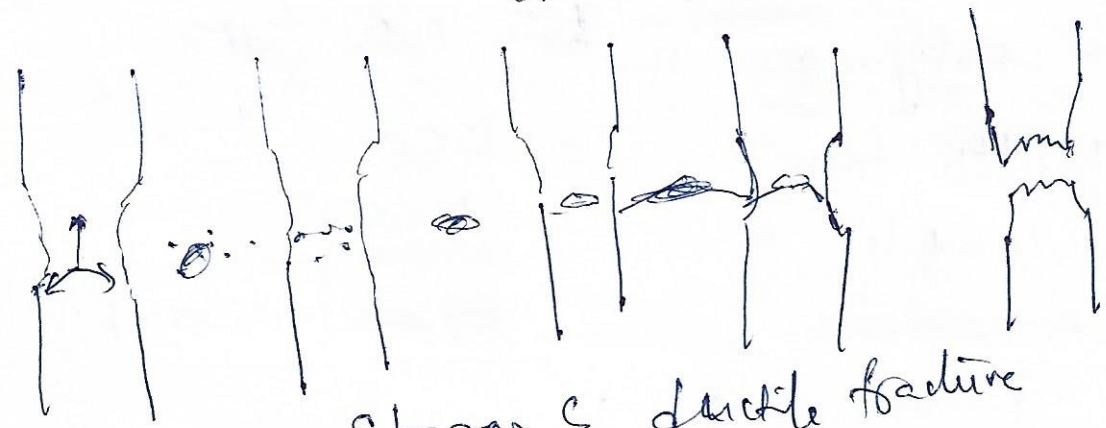


Rupture - 100% necking
 cup & cone fracture - ~~no~~ moderate necking,
 formation of voids, cracks and finally
 shears.

Brittle - NO necking; transgranular
 ex: Ceramics, glasses.

Ductile fracture - Appreciable plastic deformation,
 slow tearing of the metal with the
 expenditure of considerable energy.

Ductile Fracture stages - a) Necking
 b) formation of cavities
 c) growth of cavities to form cracks
 d) final failure with rapid
 crack propagation.



Stages of ductile fracture

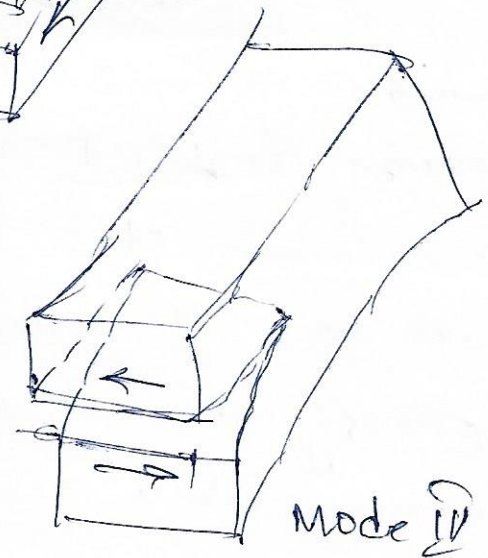
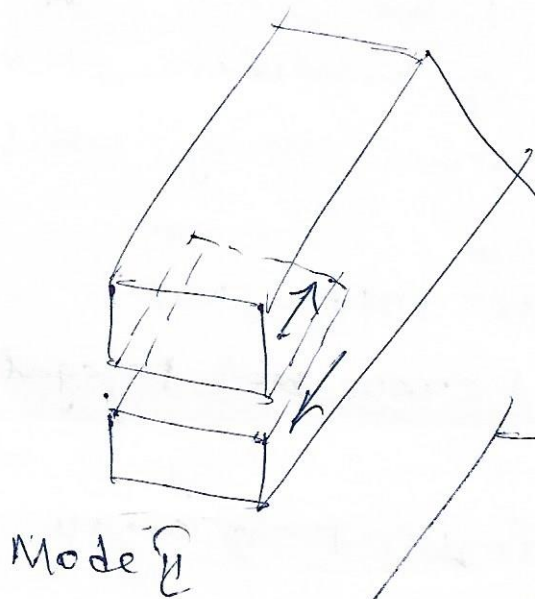
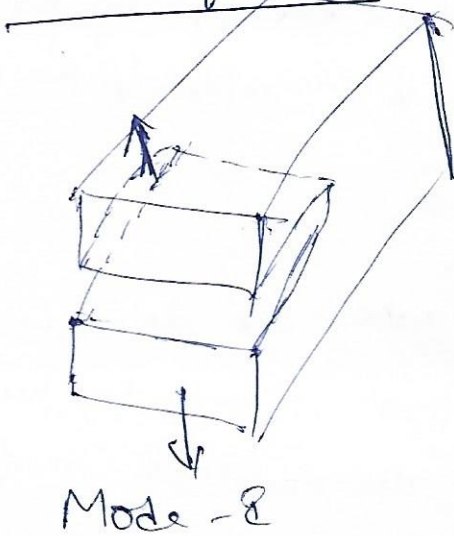
Brittle Fracture - With little or ^{plastic} wide deformation
 - occurs at unpredictable stress levels, by rapid

- crack propagation
- Direction crack propagation \perp to the direction of applied stress.
- occurs along crystallographic planes, called cleavage fracture.

Brittle fracture stages: - ②

- 1) Plastic deformation that causes dislocation ~~at~~ pile ups at obstacles
- 2) Micro crack nucleation due to high shear stresses
- 3) Crack propagation

Modes of fracture



Mode I (Opening Tensile mode)

- Crack surfaces are displaced normal to themselves.

Mode II (Sliding mode): -

- Crack surfaces are sheared relative to each other, in a direction normal to the edge of the crack.

Mode III (Tearing mode)

- Shearing action is parallel to the edge of the crack.

Griffith Theory

Brittle material contains no. of micro cracks which causes stress rise in localized regions at a nominal stress which is well below the theoretical value.

When one of the cracks spreads into a brittle fracture, it produces an increase in the surface energy of the sides of the crack. Source of the increased surface energy is the elastic strain energy, which will be released as crack spreads.

Griffith proposed that

A crack will propagate when the decrease in elastic strain energy is at least equal to the energy required to create the new crack surface.

Elastic energy stored under tensile stress will be released as crack propagates. Part of this energy is expended in forming the surface of the crack, while remaining is transformed into kinetic energy.

Strain energy released in a thin plate of unit thickness is

$$U_e = \frac{\pi \sigma^2 c^2}{E}$$

where E = Young's modulus

σ = Applied stress

c = $\frac{1}{2} \times$ crack length

Surface energy gained by the system due to new surface formed as a crack of length $2c$ is

$$U_s = 4\gamma c$$

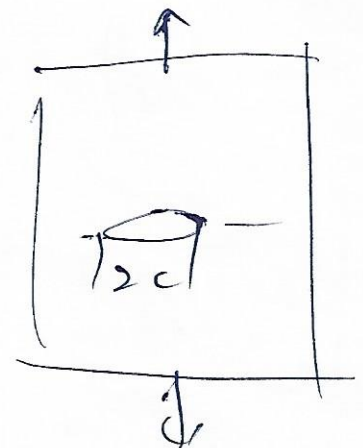
where γ = surface energy of each face

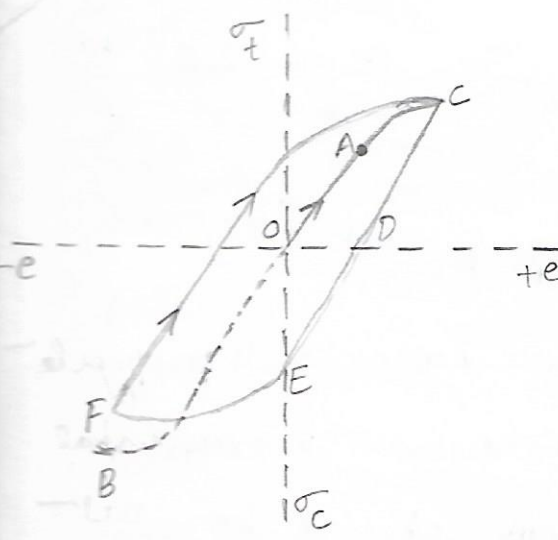
According to Griffith, such a crack will propagate and produce brittle fracture when an incremental increase in its length does not change the net energy of the system.

$$\therefore \frac{\partial U_e}{\partial c} = \frac{\partial U_s}{\partial c} \Rightarrow \frac{\partial \left(\frac{\pi \sigma^2 c^2}{E} \right)}{\partial c} = \frac{\partial (4\gamma c)}{\partial c}$$

$$\Rightarrow \frac{2\pi\sigma^2 c}{E} = 4\gamma \Rightarrow \left[\sigma = \sqrt{\frac{2E\gamma}{c\pi}} \right]$$

σ = stress required to propagate a crack in this plane under plane stress.

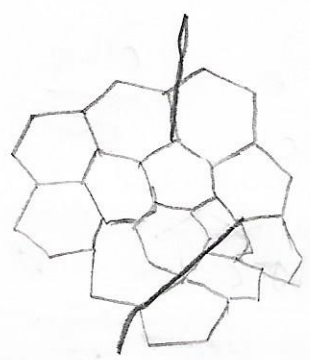




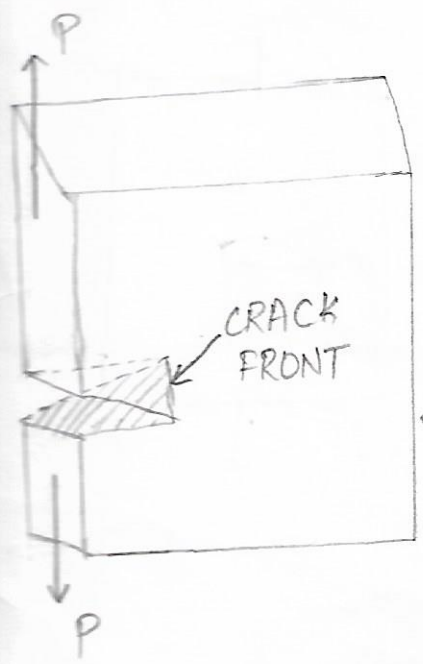
Bauschinger effect



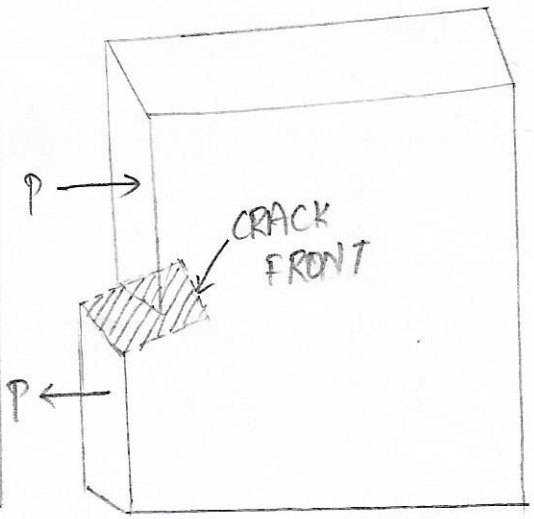
(a) Transgranular Fracture at ordinary temperature



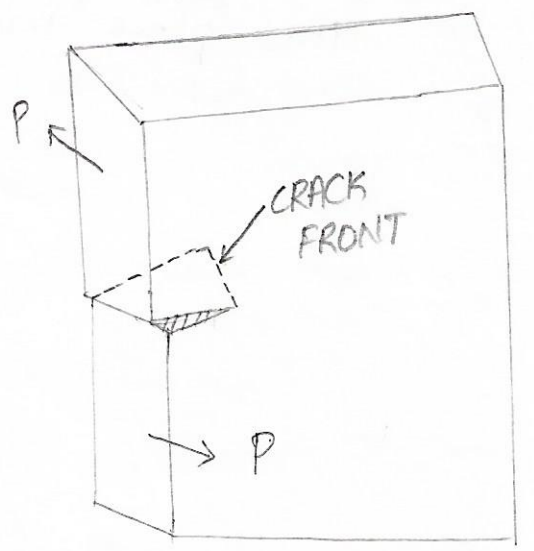
(b) Intergranular Fracture at high temperature



Mode (1) Opening or tensile mode



Mode (2) Sliding mode



Mode (3) Tearing mode