

FEDERAL UNIVERSITY OYE-EKITI FACULTY OF ENGINNERING & TECHNOLOGY

DEPARTMENT OF MATERIALS AND METALLURGICAL ENGINEERING

MME-201 (MATERIALS SCIENCE)

SUMMARISED LESSON NOTE

Course Outline

Structure of Matter; Crystal imperfections, Simple Phase Diagrams of Alloys;

Physical Properties of Materials (i.e., wood, cement, plastics and alloys); Mechanical Properties of Engineering Materials: Engineering and True Stress-Strain curves, Ultimate Strength, Ductility, Impact Strength, Hardness, Creep and Fatigue Failure.

Electrical Properties: Conductivity, Semi-Conductivity and Superconductivity; Optical and Magnetic Properties of Materials; Stability of Materials in the Service Environment: Corrosive Media, Sub-zero and Elevated Temperature Irradiation.

Basic Criteria for the Selection of Materials for Engineering Applications. Engineering Properties of Wood, Concrete, Ceramic, Polymers, Ferrous and Non-ferrous Metals and Alloys. Cryogenic, Corrosive Media and Nuclear Application.

CHAPTER ONE

1.0 INTRODUCTION TO MATERIALS SCIENCE AND ENGINEERING

Materials have always been an integral part of human culture and civilization. For example, stone, bronze, and iron ages of the past. Likewise, today's advanced technologies involve sophisticated materials, since all of them utilize devices, products, and systems that must consist of materials. The engineers expertise is in adapting materials and energy for society's needs. The theme of this course is that the properties of materials depend upon their internal structure. In turn, the properties influence the performance of a material, both during manufacture and in ultimate service. As responsible engineers, we are interested in improving the performance of the product we are designing or manufacturing. Electrical engineers want integrated circuits to perform properly, switches in computer to react instantly, and insulators to withstand high voltages even under the most adverse conditions. Civil, structural, and architectural engineers wish to construct strong, reliable structures that are aesthetic and resistant to corrosion. Petroleum and chemical engineers require drill bits or piping that survives in abrasive or corrosive conditions. Automotive engineers desire light weight yet strong and durable materials. Aerospace engineers demand light-weight materials that perform well both at high temperatures and in the cold vacuum of outer space. Mining engineers are interested in efficient excavating tools, explosives and drill bits. However, Metallurgical and Materials wish to produce these materials and shape them in a more economical way, yet, with improved properties. As a result of our responsibilities to the society, it becomes very necessary to be aware of the types of materials available, to understand their general behaviour and capabilities, and to recognize the effects of the environment and service conditions on the material's performance.

1.1 CLASSES OF MATERIALS

It is convenient to group materials into four main classes; they are Metals, Ceramics, Polymers, and Composites. However, Semiconductors may be considered another class of materials.

Metals: They are characterized by their high thermal and high electrical conductivity. They are opaque and usually may be polished to a high luster. Commonly, but not always, they are relatively heavy and deformable. Furthermore, they possess relatively high strength, high stiffness, and ductility and shock resistance. They are particularly useful for structural and load-bearing applications. Although pure metals are occasionally used, combinations of metals called alloys are normally designed to provide improvement in a particular desirable property or permit better combinations of properties. Metals and alloys include, steel, aluminum, zinc, magnesium, cast iron, titanium, copper, nickel, bronze, brass, and many others.

Ceramics: These are compounds that contain metallic and non-metallic elements. Such materials include bricks, glass, tableware, insulators, and abrasives. Each of these materials is relatively hard and brittle. Indeed, hardness and brittleness are general attributes of ceramics, along with the fact that they tend to be more resistant than either metals or polymers to high temperatures and to severe environments. The basis for these characteristics is found in the electronic nature of the constituent atoms. Consistent with their natural tendencies, the metallic elements release their outermost electrons and give them to the non-metallic atoms, which retain them. The result is that these electrons are immobilized, so that the typical ceramic materials are a good insulator, both electrically and thermally. Equally important, the positive metallic ions (atoms that have lost electrons) and the negative ions, non-metallic ions (atoms that have gained electrons) develop strong attractions for each other. Each cation (positive) surrounds itself with anions (negative). Considerable energy is usually required to separate them. Consequently, it is not surprising that ceramic materials tend to be hard (mechanically resistant), refractive (thermally resistant) and inert (chemically resistant). Notwithstanding the good strength and

hardness of ceramics, their ductility, formability and shock resistance are poor. As a result, ceramics are less often used for structural or load-bearing applications than are metals. Finally, many ceramics possess a number of unusual and desirable optical, electrical and thermal properties.

Polymers: These include rubber, thermoplastics, thermosetting materials and many types of adhesives. They are produced by creating large molecular structures from organic molecules, obtained from petroleum or agricultural products, in a process known as polymerization. Polymers have low electrical and thermal conductivity, low strength, and are not suitable for use at high temperatures. Some polymers (thermoplastics) have excellent ductility, formability, and shock resistance while others (thermosets) have the opposite properties. Polymers are light weight and frequently have excellent resistance to corrosion. They are poor reflectors of light, tending to be transparent or translucent (at least in thin sections). They are used as insulators.

Composites: are formed from two or more materials, producing properties that cannot be obtained by any single material. Concrete, plywood, and fiberglass are typical, although crude, examples of composites materials. With composite, we can produce lightweight, strong, ductile, high-temperature resistant materials that are otherwise unobtainable, or produce hard, yet, shock-resistant cutting tools that would otherwise shatter. Metal-matrix composites and ceramic-matrix composites are good examples of composite materials

1.2 STRUCTURE-PROPERTY-PROCESSING RELATIONSHIP

The properties of engineering materials are dependent to a large extent on their structure. However, the structure is determined by the atoms that made it up and the arrangement of these atoms. Every material, that is, matter, is made up of atom and the atoms have different numbers and arrangements of electrons around the nucleus. These electronic arrangements dictate the type of bonding of the material.

For instance, ceramics have different type of bond from polymers and the later are different from metals. Most of the properties of these materials are dictated fundamentally by the type of bonding in them. The properties of materials can be considered in two broad categories viz: mechanical and physical. The mechanical properties describe how the material responds to an applied force or stress. Most common mechanical properties are the strength, ductility, stiffness, impact, fatigue, creep and wear which are determined by their crystal structure. The mechanical properties determine how well the materials perform in service and the ease with which the materials can be formed into a useful shape. Often, small changes in the structures have a profound effect on the mechanical properties of the material. Materials such as metal, ceramics and some polymer possessed a regular atomic arrangement and are called CRYSTALS, while some like lack the orderly arrangement of atoms which are called AMORPHOUS or NON-CRYSTALLINE. The physical properties depend both on the structure and processing of the material. Most common physical properties include electrical, magnetic, optical, thermal elastic and chemical behaviour. These properties are generally influenced by the presence of defects in the atomic arrangement as well as the processing techniques the materials have been used to manufacture them. The structures influence the final behaviour of the product. In most materials, more than one phase may be present, with each phase having its unique crystal structure, and properties. Control of the type, size, distribution and amount of these phases within the main body of the material provides an additional way to control properties.

Processing Techniques: Materials processing produces the desired shape of a component from the initial material. For instance, metals, can be processed by pouring liquid metal into mould (casting), joining of individual pieces of metal (welding, brazing, bending, adhesive bonding), forming the solid metal into useful shape at high pressures (forging, drawing, extrusion, rolling, bending), compacting tiny metal (powder metallurgy), or removing excess materials (machining). Often a material is heated at some temperature below its melting point to effect a desired change in structure. The type of processing employed at least depends on the properties and thus the structure of the material.

CHAPTER TWO

2.0 STRUCTURE OF MATTER

In this course "**Materials Science**", our major concern is the application of the structure of matter to explain materials behaviour in service. Accordingly, the purpose of this chapter is to acquaint the students with the simple, basic concepts of the structure of matters.

The structure of a material may be divided into four levels - atomic structure, atomic arrangement, micro-structure, and macro-structure (Crystal Structure). Although, our main concern is to understand and control the micro-structure and macro-structure of various materials, we must first understand the atomic and crystal structures.

2.1 ATOMIC STRUCTURE

Generally, atom is composed of a nucleus surrounded by electrons. The nucleus contains neutrons and positively charged protons.

Electrons are held to the nucleus by an electro-static force of attraction. The electrical charge carried by each electron and proton is 1.60×10^{-19} coulombs. Because the numbers of electrons and protons in the atom are equal, the atom as a whole is electrically neutral.

The atomic number of an element is equal to the number of electrons or protons in each atom. The mass of each proton and neutron is about 1.67×10^{-24} g, but the mass of each electron is only 9.11×10^{-28} . The atomic mass M, which is equal to the average number of protons and neutrons in the atom, is the mass of the Avogadro number N_A of atoms.

 $N_A = 6.02 \times 10^{-23} \text{ mol}^{-1}$ is the number of molecules in a g/mole. Atoms of the same element that contain different number of neutrons in the molecules are called <u>Isotopes</u> and thus have a different atomic mass.

Il protons 12 Neufrons $Ma = 1s^2 2s^2 2p6 3s'$ 00 C

Atomic Structure of Sodium

** Students are advised to read up the electronic structure of atoms, electronegativity and the periodic table in standard college chemistry texts.

2.2 ATOMIC BONDING

Some of the physical properties e.g. melting and boiling points and to some extent the mechanical properties of materials depend upon the strength and nature of the bond between the atoms. Five mechanisms by which atoms are bonded together are recognized. These are: Metallic Bonding, Covalent Bonding, Ionic Bonding, Dative Bonding and Van-Der-Waals Bonding.

a) The Metallic Bonding: The metallic elements which have a low valence, give up their valence electrons to form a "cloud" of electrons surrounding the atoms. These valence electrons, which are no longer associated with any particular atom are delocalized, that is, move freely within the electron cloud and become associated with several atoms cores. The positively charged atoms cores are held together by mutual attraction to the electron, thus producing the strong metallic bond. The bonds are however, non-directional as electrons holding the atoms together are not fixed in one position. This picture of a metal is called the Free Electron Theory and gives an explanation of the electrical conductivity of metals. Furthermore, when a metal is bent and the atoms attempt to change their relationship to one another, the orientation of the bond merely

shifts, rather than the bond breaking. This permits metals to have good ductility and to be deformed into useful shapes.



Metallic Bond

(b) Covalent Bond: In covalent bonding, the stable arrangement of eight electrons in an outer shell is achieved by a process of electron sharing rather than electron transfer. Each instances of sharing electrons between one or more atoms represents one covalent bond, and the bonds have a fixed directional relationship with one another. Covalent bonds are very strong, though materials, bonded in this manner have poor ductility, and poor electrical conductivity. When a silicon rod is bent, the bonds must break if the silicon atoms are to permanently change their relationship, to one another. Furthermore, for an electron to move and carry a current, the covalent bond must be broken, requiring high temperature or voltages. Covalently bonded materials are brittle and behave as electrical insulators. As an example, silicon molecule or aggregate is formed by five silicon atoms that are covalently bonded together as shown below:

 $CL = CL_{a}$ $tO = D_2, C + H_4 = CH_4$ $H + O + H = H_2O, N + H_3 = NH_3$ Ø to Silicon aton Silicon Moleantes

Many ceramic and polymer materials are fully or partly bonded by covalent bond e.g bricks, glass, C_{H4} , diamond etc.

c) The Ionic or Electrovalent Bond

When more than one type of atom is present in a material, one atom may donate its valence electron to a different atom, filling the outer energy shell of the second atom, both atoms having a stable shell of electrons. The atoms have now acquired an electrical charge and behave as ions. The electron contributing atom is left with a net positive charge and is a <u>Cation</u>, while the electron accepting atom is left with a net negative charge and is an <u>Anion</u>. The oppositively charged ions are then attracted to one another to produce **Ionic or Electrovalent Bond**. The bond is very strong which is evidenced by the high melting temperatures of ionic solids (NaCl-801°C, NaF-988°C, MgO-2640°C, CaO-2570°C and Al₂O₃-2020°C). For example, sodium and chlorine form monovalent ions by reactions which may be written as:





Attraction between Na⁺_and Cl⁻ produces NaCl with many ions, produce NaCl crystal. When a force is applied to an ionic bond, the electrical balance between the ions is upset. This partly accounts for the reason why ionically bonded materials behave in a brittle matter.

Electrical conductivity is poor, especially in the solid state, as the electrical charge is transferred by the movement of entire ions which do not move as easily as electrons.

d) The Co-ordinate or Dative Bond

The co-ordinate bond is a variation of the covalent bonding which both of the shared electrons are provided by one of the atoms participating in the bonding, e.g. bonding of oxygen to sulphur in the shulphate ions. The sulphur atoms provide all the electrons required for covalent linkages with three oxygen atoms, while the other two electrons are obtained from an ionic donor. This two types of bonds are obtained within one molecule.



Coordinate Bond

e) Van-Der Waals or Intermiolecular Forces

In addition to the primary types of interatomic bonding discussed above, there also exist weaker bonds, owing to the polarization of atoms or molecules. i.e, some portions of the molecule or atom tend to be positively charged while other portions are negatively charged. Based on the weak electrostatic attraction, this type of bonding is called Van-der-waals or hydrogen bonding or bridge.

Van-der-waals bonding is a secondary bond, but the atoms within the molecule or group of atoms are joined by strong covalent or ionic bonds. Heating of water to the boiling point breaks the van-der-Waals bonds and changes water to steam, but much higher temperature are required to break the covalent bonds joining oxygen and hydrogen atoms together. Van-der-waals bonds accounts for the susceptibility of PVC to significant deformation without breaking, even though each PVC molecule is a brittle substance by virtue of its covalent bond.



Polarization of Water Molecule

2.3 BINDING ENERGY AND INTERATOMIC SPACING

The inter-atomic spacing is the equilibrium distance between the atoms caused by a balance between repulsive and attractive forces. For instance, in the metallic bond, the attraction between the electrons and the atom core is balanced by the repulsion between the atom cores. The equilibrium separation occurs when the total energy of the pair of atoms is at a minimum. The inter-atomic spacing in a solid metal is equal to the atomic diameter, or twice the atomic radius r; except for the ionically bonded materials in which the inter-atomic spacing is the sum of the two different ionic radii.

The minimum energy, as shown in the figure below, is the **<u>Binding Energy</u>**, or the energy required to create or break the bond.

Binding Energy and Interatomic Spacing in Equilibrium Position.

When a crystal is subjected to an external load, the distance between the atoms become greater and the atoms are displaced from their equilibrium position in the crystal. This destroys the equilibrium between the forces of repulsion and attraction characteristics of the equilibrium state of the atom in the lattice and result in the appearance of internal forces tending to return the atoms to their initial equilibrium positions. The value of those forces per unit cross-section area of the crystals is term **STRESS**. To now examine the stress, we shall uphold the fact that, the energy of interaction of particles 1 and 2 in a solid is a function of the distance S between them. This can be described by the curve U(s) schematically shown in the figure below

Variation of (a) Interaction Energy and (b) Interaction Force with the displacement of a particle from Equilibrium Position by a distance x.

When a particle 2 is displaced from its equilibrium position to a distance X, that is when the distance between the particles is increased to S = So + X, the particle's energy grows and becomes U(S). The change in energy (U(x) = U(S) - U(So), can be found if we expand U(S) into Taylor series in power of X.

Leaving only the quadratic term of the series and taking into account the fact that 0^1 is zero i.e. , we obtain:

Where β is the rigidity of the bond.

This expression is an approximation (Harmonic approximation). The force which appears between the particles 1 and 2 when the distance between them is changed by x is equal to:

It follows from relation (*) above that the force is linearly dependent on x and is directed towards the position of equilibrium, as indicated by the minus sign. It is to be noted that such a force caused the body to oscillate harmonically.

Now, let us imagine that a tensile load F is applied to a rod with a cross- sectional area A and a length L. This load changes the distance between the neighbouring atomic planes 1 and 2 by the amount x, causing thereby an extension of the rod by ΔL

Uniaxial Extension of a Rod by an External Force F

it will be counterbalanced by the internal forces F_{int} equal numerically to,

where: N = Number of particle in the atomic layer of Area A.

The stress δ which appear in the extended rod will be,

Multiplying and dividing the right-hand side of (+) by the distance between the atomic planes, so, we obtain:

E is termed the elasticity modulus or Young's modulus, and E = X/So is the relative change in the lattice parameter in the direction of the external force F.

Also $E = \Delta L/L$ i.e., Relative Elongation of the sample under the action of the external tensile load.

Equation (++) is also known as Hooke's Law.

Electrostatically, the potential energy due to attraction is $U_{atrr} =$, and in close range, the potential energy due to repulsion is $U_{repul} =$

Consequently, the total potential of the system is U_{Total} =

If at equilibrium, the resultant force on the system is zero i.e., F = 0, , then. it can shown that $U_{Total} =$ or that $U_{Total} =$

CHAPTER THREE

3.0 CRYSTAL STRUCTURE, CRYSTAL SYSTEM AND CRYSTAL ANALYSIS

3.1 CRYSTAL STRUCTURE

The most obvious feature distinguishing a solid from a liquid or gas is its characteristics shape or rigidity. This distinction is due to the fact that in a solid, the structural units are fixed in a characteristic ordered arrangement by large intermolecular forces. We describe this situation by saying that solids have both short-range and long-range order i.e. a minute sample of a crystalline solid containing only a few atoms, ions or molecules which is a representative of the entire solid. Crystalline solids (other than cubic crystals) have anisotropic properties because the ordering of the structural units is different in different directions e.g. Silver-Iodide, in which the coefficient of thermal expansion is positive along one of the crystal directions and negative along another.

Long-range order is common in metals and polymers. It is a special arrangement of atoms extending throughout the entire material.

Short-range order is common in some ceramics and water. It is a special arrangement of atoms extending only to the atoms nearest neighbours, e.g. H - 1045° - H covalent bond of H₂0 molecule.

No order arrangement is found in gases, i.e. atoms have no order, just random filling of space.

(a) Space Lattices or Lattice Points/Unit Cells:

Atoms in crystals form regular repetitive grid-like pattern or lattice. It is a network of points such that every point has identical surrounding. The points of a lattice may be occupied by a single atom (as in most metals) or by a group of atoms. Each such group is identical in composition and orientation to every other group in the crystal Lattice is therefore a collection of points, called lattice points or space lattices which are arranged in a periodic pattern so that the surroundings of each point in the lattice are identical. Lattice differs from materials to materials in both shape and size, depending on the size of the atoms and the type of bonding between atoms. The crystal structure of materials therefore refers to the size, shape and atomic arrangements within the lattice.



A Point Lattice, indicating the Unit Cell

To specify the arrangement of atoms in a crystal structure, it is customary to give their coordinates with respect to a set of coordinate axes chosen with an origin at one of the lattice points.

Each space lattice has some convenient set of axes that is conventionally used with it. These axes are not necessarily orthogonal but in case where there is sufficient symmetry, they are chosen so that two or all the three are mutually perpendicular. Similarly, the chosen units of length along the axes are not necessarily equal and again with sufficient symmetry, the units along two or three axes are equal.



The figure above shows a space lattice by the intersections of lines. The three axes are OX, OY and OZ and the units of lengths along them are distance between the space lattice points i.e. a, b, c. and the angles between the axes are α , β , and γ .

The space lattice is therefore completely determined by a, b, c while α , β , and γ called lattice parameters. The network of planes through the points of a space lattice divides the regions into prisms called **Unit Cells**, i.e. unit cell is a sub-division of the lattice that still retains the overall characteristics of the entire lattice. If the unit cell is the smallest possible, then it is a primitive cell.

3.2 CRYSTAL SYSTEMS

Individual crystal can often be recognized by their characteristics external shape. Thus, crystals of sodium chloride grown from aqueous solution are invariably cubic with well-defined faces and with characteristics angles between these faces (90° each).

The very large number of crystal systems may be classified according to the length of the crystal axes and the angles between them. There are seven such sets known as seven crystals systems. Within each system, there exist one or more types of space lattice distinguished by differing degrees of symmetry within the unit cell. There are 14 of such unit cells or Bravais Lattices grouped into these seven crystal structures. By references to three principal axes, each crystal system may now be defined as follows:



The Seven Crystal Systems

	2001	051 -01		
	10/00/11/1	111	AL ANGLE	EXAMPLE
			$= \chi = 90^{\circ}$	SC, FCC & BCC
	100	10	$\gamma = \gamma = 90^{\circ}$	ST, BCT
26			$\gamma = \gamma = 90^{\circ}$	SC, BCO & FCO
4	Monoclinic	a = b = c	$\alpha = \beta = 90^{\circ} = \gamma$	SM, Base CM
5	Triclinic	a = b = c	$\alpha = \beta = \gamma = 90^{\circ}$	Triclinic
6	Hexagonal	a = b = c	$\alpha = \beta = 90^{\circ} \text{ y} = 120^{\circ}$	НСР
7	Rhombohedral	a = b = c	$\alpha = \beta = \gamma = 90^{\circ}$	Rhombohedral

(c) Miller Indices

Sometimes, it is necessary to refer to a specific planes and direction within a crystal lattice. The notation used is the Miller indexing system of h, k, l

(1) <u>Coordinate of Points</u>: Atom positions in the lattice or unit cell can be located by constructing the right handed coordinate system. Distance is measured in terms of the no of lattice parameters as we must move in each of x, y, z coordinates to get from the origin to the point in question

- (2) <u>Directions in the Unit Cell:</u> Certain directions in the unit cell are of particular importance. For example, metals deform in directions along which atoms are in close contact. Properties of a material may depend on the direction in the crystal along which the property is measured. To describe these directions, Miller indices are used and the procedure for finding the indices .are as follows; using the right hand co-ordinate system.
 - (i) Determine the co-ordinate of two points that lie in the direction.
 - (ii) Subtract the coordinate of the "tail" points from that of the "head" point, to obtain the number of lattice parameter travelled in the direction of each axis of the coordinate system.
 - (iii) Clear fractions and/or reduce the results obtained to lowest integers.
 - (iv) Enclose the numbers in square brackets. If negative sign is produced, represent it with a bar on the numbers



Direction A

- (i) Two points are 1,0,0 and 0,0,0
- (ii) 1,0,0 0,0,0 = 1,0,0
- (iii) No fractions to clear
- (iv) [100]

Direction B

- (i) Two points are 0,0,1 and $\frac{1}{2},1,0$
- (ii) 0,0,1, -1/2,1,0 = -1/2, -1,1
- (iii) 2(-1/2,-1,1)=--1,-2,2
- (iv) [1,2,2]

Points to note

- a) A direction and its negative are not identical e.g. [100] is not equal to [100] they represent same line but opposite directions.
- b) A direction and its multiple are identical e.g. [100] is the same as [200]
- c) Certain groups of directions are equivalent, they have their particular indices primarily because of the way we construct the coordinates. E.g [100] and [010] as shown below.

Such groups of equivalent directions are referred to as **"Directions of a form"** and are indicated by carets <>, e.g. in cubic system,

< 111> = [111], [111], [111], [111], [111], [111], [111], [111], [111], (111], [111], [111], (111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [111], [11], [11], [11], [11], [11], [11], [11], [11], [11], [1

the The intercept of plane w.r. k. Z x-9215 15 x= 20, 4 = 00, 600 001

3. <u>Planes in the Unit Cell:</u>

Certain planes of atoms in a crystal are also significant e.g. metals deform along planes of atoms that are most tightly packed together. To identify these important planes, Miller indices are used as described in the following procedure:

- (i) Identify the points at which the plane intercepts the X, Y, and Z coordinates in terms of the number of lattice parameter. If the plane passes through the origin, the origin of the coordinate system must be moved.
- (ii) Take reciprocal of these intercepts.
- (iii) Clear fractions but do not reduce to lowest integers.
- (iv) Enclose the result in parentheses, () with bar over negative numbers



Plane A

Plane B

- X = 1, Y = 1, Z = 1(i) (i)
- (ii) 1/X = 1, 1/Y = 1, 1/Z = 1
- (iii) No fraction to clear
- (iv) (111)

- X = 1, Y = 1, Z = 1
- 1/X = 0, 1/Y = 2, 1/Z = 0(ii)
- (iii) No fraction to clear
- (iv) (020)



- (i) The origin must be moved since the plane passes through 0,0,0. Let us move the origin one lattice parameter in the y-direction; then, $X = \infty$; Y = -1, $Z = \infty$
- 1/X = 0, 1/Y = -1, 1/Z = 0(ii)
- No fraction to clear (iii)
- (iv) $(0\ 1\ 0)$

The following points about Miller Indices for planes should be noted.

- a) Planes and their negatives are identical
- b) A planes and its multiples are not identical
- c) In each unit cell, Planes of a form represent groups of equivalent planes that have their particular indices because of the orientation of the coordinates. These groups of equivalent planes are signified by braces e.g., $\{110\} = (110), (101),$ (011)

d) In cubic systems, a direction that has the same indices as a plane is perpendicular

to that plane.



(d) <u>Miller Indices of Plane for Hexagonal Unit Cells:</u>

The three miller indices (h, k, l) can describe all possible planes through any crystal. In hexagonal system, however, it is commonly useful to establish four axes, three of them coplanar (as shown in the figure below). This leads to four intercepts and (h, k, l) indices. The h, k, i, l indices is usually referred to as Miller-Bravais Indices for hexagonal unit cells. The fourth index "i" is an additional index that mathematically is related to the sum of the first two:

h+k = -i therefore, i = -(h+k)

These optional (h, k, i, l) indices are generally favoured because they reveal hexagonal symmetry more clearly. Although partially redundant, i.e., they are used almost exclusively in preference to the equivalent (h, k, l) indices in scientific papers.



Plane A

Plane B

$\mathbf{a}_1 = \mathbf{a}_2 = \mathbf{a}_3 = \infty, \mathbf{c} = 1$	$a_1 = a_2 = 1; a_3 = -1/2, c = 1$	
$1/a_1 = 1/a_2 = 1/a_3 = 0, \ 1/c = 1$	$1/a_1 = 1/a_2 = 1$, $1/a_3 = -2$, $1/c = 1$	
No fraction to clear	No fraction to clear	
(0001)	(1121)	
Direction C	Direction D	
(i) Two points are 0,0,1 and 1,0,0	(i) Two points are 0,1,0 and 1,0,0	
(ii) 0,0,1 - 1,0,0 = -1,0,1	(ii) 0,1,0 - 1,0,0 = -1,1,0	
(iii) No fractions to clear or integers to reduce	(iii) No fraction to clear or integers to reduce	
(iv) (101) [101]	(iv) (110) [110]	

3.3 CRYSTALS ANALYSIS

Most common crystals structures in which most metals crystallize are fcc and bcc of the cubic system and the hexagonal packed structure of the hexagonal lattice.

In analyzing the crystals, the following characteristics are necessary:

(i) <u>Number of Atoms per Unit Cell</u>: A specific number of lattice points define each of the unit cells e.g. corners, body-centered and face-centered positions of the cells are easily identified. In counting the number of lattice points, it must be recognized that lattice

points may be shared by more than one unit cell. Thus, in determining the number of atoms per unit cell, the general formula is: $N = N_c/8 + N_f/2 + N_b$

Where N_c – Number of lattice points at the corners

N_f-Number of lattice points at the faces

N_b-Number of lattice points within the crystal body

For example, fcc has eight lattice points at the corners, six lattice points at the faces and none with the body

Therefore, $N = N_c/8 + N_f/2 + N_b = 8/8 + 6/2 + 0 = 1 + 3 + 0 = 4$ <u>atoms/cell</u>

However, for HCP, the formula $N = N_c/6 + N_f/2 + N_b$

For example, HCP has twelve lattice points at the two hexagonal corners which are shared by six unit cells, two lattice points at the faces shared by two unit cells and three with the body. Therefore $N = N_c/6 + N_f/2 + N_b = 12/6 + 2/2 + 3 = 6$ atoms/unit cell

(ii) <u>Atomic Radius and Lattice Parameter:</u> In simple structures, there is relationship between the apparent size of the atom and the size of the unit cell. We must locate the direction in the unit cell along which atoms are in continuous contact. These are the close-packed directions. The desired relationship can be determined by simple geometry of the length of the direction relative to the lattice parameter, and then adding the number of atomic radii along this direction.



BCC

$$m^{2} = a_{0}^{2} + a_{0}^{2} = 2a_{0}^{2}$$

$$m = \sqrt{2}a_{0} = a$$

$$m = \sqrt{2}a_{0} = a$$

$$(4,r)^{2} = a_{1}^{2} + (\sqrt{2}a_{0})^{2} = a_{0}^{2} + 2a_{0}^{2}$$

$$(4,r)^{2} = 3a_{0}^{2} + a = \sqrt{2}a_{0}$$

$$(4,r)^{2} = 3a_{0}^{2} + a = \sqrt{2}a_{0}^{2}$$

$$(5,r)^{2} + a = \sqrt{2}a_{0}^{2} + a = \sqrt{2}a_{0}^{2}$$

$$(5,r)^{2} + a = \sqrt{2}a_{0}^{2} + a = \sqrt{2}a_{0}^{2}$$

$$(5,r)^{2} + a = \sqrt{2}a_{0}^{2} + a = \sqrt{2}a_{0}^{$$

(iii) <u>Coordination Number (CN):</u> The number of atoms touching a particular atom or the number of nearest neighbours is termed coordination number. It is the number indicating how tightly and efficiently atoms are packed together. E.g., Simple Cubic has CN of 6, BCC has CN of 8 and FCC has CN of 12.

(iv) <u>Packing Factor (P.F)</u>: This is the fraction of space occupied by atoms, assuming the atoms are hard spheres. The general expression for the packing factor is:

 $P.F = \frac{No. of atoms/Cell x Volume of each atom}{Volume of Unit Cell}$ For example, for fcc cell, N = 4atoms; $V_{atom} = 4\pi r^3 / 3$

(v) <u>**Density:**</u> The theoretical density of a metal can also be calculated using the properties of the crystal structure. The general formula is:

Density
$$\rho = (\underline{\text{Atoms/Cell}}) \times \underline{\text{Atomic mass of each atom}}$$

Volume of Unit Cell x Avogadro's No.

For instance, for BCC-Iron having a lattice parameter of 2.866A, atoms/cell = 2, atomic mass = 55.85 g/mole, Volume of unit cell = $a_0^3 = (2.866 \times 10^{-8}) \text{ cm}^3 = 23.55 \times 10^{-24} \text{ cm}^{3/\text{cc}}$

Avogadro number = 6.02×10^{23} atoms/g.mole.

Density
$$\rho = 2 \times 55.85$$
 Atomic mass of each atom
23.55 $10^{-29} \times 6.02 \times 10^{23}$ = 7.879/cm³

- (vi) <u>HCP:</u> The Hexagonal Closed-Packed structure is a special form of the hexagonal lattice. The HCP cell has two lattice points per cell or two atoms/unit cell one at a corner which may be taken as the origin of coordinate and the other with coordinates 2/3, 1/3, $\frac{1}{2}$, (a_1, a_2, a_3) relative to it.
- (vii) <u>Anisotropic Behaviour:</u> Due to difference in atomic arrangement in the planes and directions within a crystal, the properties also vary within direction. A material is **anisotropic** if its properties depend on the crystallographic direction along which it is measured. However, if the properties are identical in all directions the crystal is **isotropic**.

For example, Aluminium crystal is anisotropic because its elastic modulus along [100] and [111] are 9.2 and 11.0 respectively, whereas the random value is 10.

(viii) <u>Interplanar Spacing</u>: The distance between two adjacent parallel planes of atoms with the same Miller indices is called inter-planar spacing, d_{hkl}. For cubic materials, this is given by the general equation:

$$d_{h,k,l} = \frac{ao}{\sqrt{h^2 + k^2 + l^2}}$$

Where: $a_0 = lattice parameter$

 $d_{h,k,l}$ = miller indices of the adjacent planes being considered.

X-ray having a known wavelength is made to strike the powdered specimen. The X-ray beam is then diffracted at a specific angle from the incident beam according to the Bragg' Law.

$$n\lambda = 2 d_{hkl} \operatorname{Sin} \theta$$

Where: n - Order of the diffraction, and are integers, λ - Wavelength of the diffraction,

 θ - Diffraction of angle, d_{hkl} - Interplanar Spacing

If the wavelength is fixed, then the atoms on any particular plane cause the x-ray to be diffracted at a particular angle. The diffracted X-ray beam intersects and exposed a film surrounding the specimen. By analyzing the film and calculating the 2θ angle, the inter-planar spacing can be determined. It should be noted that the statement of the Bragg's law is that, the diffraction angle θ depends upon the wavelength λ of the X-rays and the d_{hkl} between the planes.

Examples: Suppose Chromium radiation of wave length 2.291A produced a diffracted line on a film at $2\theta = 58.2^{\circ}$. What is the inter-planar spacing of the crystallographic plane that produced the diffracted line, take n = 1.

Solution:

$$n\lambda = 2 d_{hkl} \operatorname{Sin} \theta$$

Therefore, $d_{hkl} = n\lambda/2 \sin\theta$

$$d_{hkl} = 1 \ge 2.291/2 \operatorname{Sin} 29.1 = 2.355 \mathrm{A}$$

therefore $d_{hkl} = 2.355 \times 10^{-8}$ cm



CHAPTER FOUR

4.0 SOLIDIFICATION, CRYSTALLINE IMPERFECTIONS AND DIFFUSION IN SOLIDS

4.1 SOLIDIFICATION OF METALS

The solidification of metals and alloys is an important industrial process since most metals are melted and then cast into a semi-finished of finished shape.

In general, the solidification of a metal or alloy can be divided into the following steps:

(i) The formation of stable nuclei in the melt (Nucleation).

(ii) The growth of nuclei into crystals and the formation of a grain structure

The shape that each grain acquires after solidification of the metal depends on many factors, of which thermal gradients are important. The two main mechanisms, by which nucleation of solid particles in liquid metal occurs are **homogenous nucleation and heterogeneous nucleation**.

(i) <u>Homogenous Nucleation</u>: In a liquid melt, nucleation occurs when the metal itself provides the atoms to form nuclei. When a pure liquid metal is cooled below its equilibrium freezing temperature to a sufficient degree, numerous homogenous nuclei are created by a slowmoving atoms bonding together.

Homogenous Nucleation usually requires a considerable amount of under-cooling which may be as much as several hundred degree Celsius for some metal e.g. Pb - 327°C, Al - 660°C, Fe - 1535°C, Cu - 1083°C, and Ag - 962°C. For a nucleus to be stable so that it can grow into a crystal, it must reach a **Critical Size**. A cluster of atoms bonded together which is less than the critical size is called a **Nucleus**. Because of their instability, embryos are continuously being formed and re-dissolved in the molten metal due to the agitation of the atoms.

Two kinds of energy changes usually accompany homogeneous nucleation are the **Volume or Bulk Free E3nergy**; released by the liquid to solid transformation, and the **Surface Energy** required to form the new solid surfaces of the solidified particles.

Also, the driving energy for the liquid-to-solid transformation for pure metal is the difference in the volume (bulk) free energy G_v of the liquid and that of the solid. If G_v is the change in free energy between the liquid and solid per unit volume of metal, then the free-energy change for a spherical nucleus of radius **r** is $3/4\pi r^3 \Delta G_v$, since the volume of a sphere is $\sqrt[3]{4\pi}r^3$. In equation form, the total free-energy change for the formation of a spherical embryo or nucleus of radius **r** formed in freezing pure metal:

$$\Delta G_{\rm T} = 3/4\pi r^3 \Delta G_{\rm v} + 4\pi r^2 \Sigma$$

Where $\Delta G_T =$ Total Free Energy Change

r = Radius of Embryo or Nucleus ΔG_v = Volume of Free Energy

X = Specific Surface Free Enegy

Similarly, the Critical-sized nucleus is related to the amount of undercooling by the relation:

$$r^* = 2 \Delta T_m / \Delta H_f \Delta T$$

Where: $r^* = Critical radius of nucleus$ $\mathfrak{X} = Specific Surface Free Enegy$ $\Delta H_f = Latent heat of fusion$ $T_m = Melting point of the material$

 ΔT = Amount of under-cooling at which nucleus is formed

(ii) <u>Heterogenous Nucleation</u>: This is nucleation that occurs in a liquid on the surface of its container, insoluble impurities, or other structural material which lowers the critical free energy required to form a stable nucleus. Since large amounts of under-cooling do not occur during industrial casting operations and usually range between 0.1 - 10°C, the nucleation must be heterogeneous and not homogenous. For heterogeneous nucleation to take place, the solid nucleating agent (impurity solid or container) must be wetted by the liquid metal. Also, the liquid should solidify easily on the nucleating agent.

Heterogeneous nucleation usually takes place on the nucleating agent because the surface energy to form a stable nucleus is lower on this material than if the nucleus is formed in the pure liquid itself (homogeneous nucleation). Since the surface energy is lower for heterogeneous nucleation, the total free-energy change for the formation of a stable nucleus will be lower and the critical size of the nucleus will be smaller. Thus a much smaller amount of under-cooling is required to form a stable nucleus produced by heterogeneous nucleation. After stable nuclei have been formed in a solidifying metal, these nuclei grow into crystals.

4.2 <u>CRYSTALLINE IMPERFECTIONS</u>

In reality, crystals are never perfect and contain various types of imperfections and defects which affect many of their physical and mechanical properties, which in turn affect many important engineering properties of materials such as the cold formability of alloys, the electronic conductivity of semiconductors, the rate of migration of atoms in alloys, and the corrosion of metals.

Defects are classified based on their size and geometry. There are three basic types of lattice imperfections - Point defects (defects of the order of atomic size), Line defects or Dislocation (defects that extend along a line in the crystal structure, that is, one dimensional), and plane or Surface defects

(which are two dimensional). Nevertheless, these lattice imperfections can be favourably altered. These defects are sometimes intentionally introduced into the crystal lattice to produce a desired set of mechanical and physical properties. For instance, the control of these defects through alloying, heat treatment or processing techniques leads to improved engineering materials.

(a) **Point Defects:** Points defects are localized disruption of lattice, involving one or possibly several atoms. When an atom is missing from a normal lattice point, a vacancy is produced.

(i) Vacancies are introduced into the crystal structure during solidification. Rapid cooling from higher temperature to lower ones usually entraps the vacancies, by plastic deformation, or as a consequence of radiation damage. Apart from normal vacancies, four other types of point defect can be identified in crystal viz: Interstitial, Substitutional, Frenkel and Schottky defects.



(i) Interstitial Defect: This is formed when an extra atom is inserted into the lattice structure at a site which is not a normal lattice point. It may be self-interstitial or by impurity/solute atom.

(ii) Substitutional Defect: This occurs in the crystal when an atom is replaced by a different type of atom. The substitutional atom remains at the normal lattice point. A metal containing substitutional solute atoms is called solid solution

(iii) Frenkel Defect: In ionic crystals, point defects are more complex due to the necessity to maintain electrical neutrality. if a positive cation moves into an interstitial site in an ionic crystal lattice, a cation vacancy is created in the normal ion site. This vacancy-interstitial pair is called a Frenkel imperfection.

(iv) Schottky Defect:_When two oppositely charged ions are missing from an ionic crystal lattice, a cation-anion divacancy is created which is known as a Schottky imperfection.



<u>Note:</u> Both interstitial and substitutional defects are present in materials as impurities and may also be intentionally introduces as alloying elements. The number of these defects is usually independent of temperature.

Point defects disturb the perfect arrangement of the surrounding atoms. For example, when a vacancy or a small substitutional atom is present, the surrounding atoms collapse towards the point defect stretching the bonds between the surrounding atoms, and producing a tensile stress field. A line defect moving through the general vicinity of the point defect encounters a lattice in which the atoms are not at their equilibrium positions. This disruption requires that a higher stress be applied to force the line defect past the point defect, therefore increasing the strength of the metal.

Example: Iron has a measured density of 7.87g/cm³. The lattice parameter of BCC iron is 2.866°A. calculate the percentage (%) of the vacancies in the pure iron.

Solution:

calculate the percentage (%) of the vacancies in the pure iron. ate the percentage (%) of the vacancies in the pure iron. on: $PF = Packing fatter = atoms/cell \times Atomic mass of Fe$ Volume of cell × Auogadro Another= atom/cell × 55-85(2.866 × 10⁸)³ × 6.02×10²³ = 7.87(2.866 × 10⁸)³ × 6.02×10²³ × (2.866×10⁸)³Atoms/cell = 7.87 × 6.02×10²³ × (2.866×10⁸)³55.85Solution: In normal or perfect BCC, there are two atoms [cell. Thus, the difference must be due to presence of vacancies Therefore, To Vacancies = 2-1.998 × 100 % 0.1 %

(b) Line Defects or Dislocations

Line imperfections or dislocations in crystalline solids are defects that cause lattice distortion centered on (around) a line. Dislocations are created during the solidification of crystalline solids. They are also formed by the permanent or plastic deformation of crystalline solids and by vacancy condensation and/or by atomic mismatch in solid solutions. The two main types of dislocation are the **Edge and Screw Dislocations**. A combination of the two gives **Mixed Dislocations**, which have edge and screw components.

(i) **Edge Dislocation:** - An edge dislocation is created in a crystal by the insertion of an extra half plane of atoms. The symbol 1 is used to indicate a positive edge dislocation, while the symbol 1 indicates a negative edge dislocation. The displacement distance of the atoms around the dislocation is called the
Slip or Burgers vector b, and is perpendicular to the edge- dislocation line. Dislocations are nonequilibrium defects and store energy in the distorted region of the crystal lattice around the dislocation. The edge dislocation has a region of compressive strain where the extra half plane of atoms is, and a region of tensile strain below the extra half plane of atoms.

The process by which a dislocation moves and causes a metal to deform is called a **Slip**. The direction in which the dislocation line moves is called the **Slip direction** and it is the direction of the Burger's Vector for the edge dislocation. During the slip, the edge dislocation sweeps out the plane formed by the Burger's Vector and the dislocation itself. This plane is called the **Slip Plane.** The combination of slip direction and slip plane is the **Slip System**.



Shear that creates an Edge Dislocation

Suppose gliding took place in the crystal K in the plane ABCD in the direction of the vector b involving the area AHED. The atomic planes on both sides from the slip plane AHED are displaced in relation to one another by the distance b in the slip direction. The boundary HE separating the area AHED, (where slipping took place) from the area HBCE, (where slipping has not yet taken place), constitutes an edge dislocation, and vector b is termed the Burger's vector. It describes how far slipping has proceeded in the area AHED.



Arrangement of Atoms in a Plane perpendicular to the Dislocation Line.

A dislocation whose burgers vector is equal to the lattice parameter is, called UNIT DISLOCATION. When a unit dislocation passes through a cross section of the crystal, one part of it shifts in relation to the other by a distance b. The motion of a positive dislocation to the left causes the same shift of the parts of the lattice as a motion of a negative dislocation to the right.



Screw Dislocation Plane

Screw Dislocation

Screw dislocation is produced by skewing a crystal so that one atomic plane produces a spiral ramp about a dislocation line or axis. The slip or Burger's vector of the screw dislocation is parallel to the dislocation line. Generally, screw dislocation may be formed in a perfect crystal by applying upward and downward shears stresses to regions of a perfect crystal by applying upward and downward shears stresses to regions of a perfect crystal which have been separated by a cutting plane. These shear stresses introduce a region of distorted crystal lattice in the form of a spiral ramp of distorted atoms called Screw dislocation. The region of distorted crystal is not well defined and is at least several atoms in diameter. Nevertheless, a region of shear strain is created around the screw dislocation in which energy is stored.

Calculations show the tangential stress needed to move the dislocation to be equal to:

Where G is the shear modulus; V is poisson ratio, b is inter-atomic spacing or distance and d is the distance between adjacent slip planes.

(iii) <u>Significance of Dislocation</u>

Due to the existence of dislocations in materials, it is possible for slip to occur in some ceramics and polymers. The slip process is particularly helpful in understanding the mechanical behaviour of metals.

- (1) The slip explains why the strength of metals is much lower_than the value predicted from the metallic bond.
- (2) Slip provides ductility in metals, in other words, the presence of dislocations in metals enables us to shape metals by various metal working processes such as forging and rolling, into useful shapes.
- (3) By interfering with the movement of dislocations, the mechanical properties of a metal or alloy can be controlled.

iv. Schmid's Law

In order to understand the differences in behaviour of metals that have different crystal structures, let us examine the slip process. Suppose we apply a unidirectional force F to a cylinder of metal which is one single crystal.



Let A_0 be the area normal to the axial force F and A_1 the area of the slip plane or shear area on which the resolved shear force F_r is acting. We can orient the slip plane and slip direction by defining the angles θ and λ . θ is the angle between the uniaxial force F and the normal to the slip plane area A_1 , and

 λ is the angle between the axial force and the slip direction.

In order for dislocations to move in the slip system, sufficiently resolved shear stress acting in the slip direction must be produced by the applied axial force.

The resolved shear stress is

The resolved shear force Fr is related to the axial force F by, $Fr = F \cos \lambda$.

Similarly, the area of the slip plane (shear area) A1 = A0/Cos

By dividing the shear force F cos λ by the shear area Ao/cos θ , we obtain.

By dividing the shear force $F \cos \lambda$ by the shear area $Ao/\cos \theta$, we obtain. $T_r = \frac{F \cos \lambda}{Ao/\cos \theta} = \frac{F}{Ao} \cos \lambda \cos \theta = 6 \cos \lambda \cos \theta$ $T_{0} = 8 \cos \lambda \cos \theta, \text{ is called schmid's Law}$

Example 1:

Calculate the resolved shear stress on the (111) (OT1) slip system of a unit cell in an FCC nickel single crystal if a stress of 13.7 MPa is applied in the {001} direction of a unit cell.

Solution

By geometry the angle λ between the applied stress and the slip direction is 45⁰, as shown in the figure



In the cubic system, the direction indices of the normal to a crystal plane are the same as the Miller indices of the crystal plane. Therefore, the normal to the (111) plane which is the slip plane is the [111] direction.

From the figure, $\cos \theta =$

By dividing the shear force
$$F \cos \lambda$$
 by the shear erea Ao/cos θ , we obtain

$$T_r = \frac{F \cos \lambda}{A_0 / \cos \theta} = \frac{F}{A_0} \cos \lambda \cos \theta = 6 \cos \lambda \cos \theta$$

$$T_0 = 8 \cos \lambda \cos \theta, \text{ is called schmid's Law}$$

Example 2:



Suppose we have a BCC structure with a lattice parameter of 4.0 A^o that contains the dislocation shown in the diagram above. Determine the direction and length of the Burger's vector b.

Solution:

The clockwise loop around the dislocation is closed by the vector b. because b is perpendicular to the (222) planes, the miller indices of direction b must be [222] 0r [111]. The length of b is the distance between two adjacent (222) planes.

(c) <u>Surface Defects</u>

These are defects in crystals due to the atoms on the surface that do not have identical surroundings with those in the interior. They are defects at the boundaries that separate a material into regions, each region having the same crystal structure but different orientations.

1. <u>Grain Boundaries:</u> The microstructure of metals and many other solid materials consists of many grains. A grain is a portion of the material within which the arrangement of the atoms is identical, but the orientation of the atom arrangement or crystal structure is different for each adjoining grain.



The lattices in each grain are identical, but the lattices are oriented differently.

A grain boundary is the surface that separate the individual grains and is a narrow zone in which the atoms are not properly spaced.

2. <u>Small-angle Grain Boundaries:</u> A small angle grain boundary is an array of dislocations that produces small mis-orientations between the adjoining lattices. The small angle boundaries are not as effective in blocking slip because the surface energy is less than that at a regular grain boundary. Small angle boundaries formed by edge dislocation are called <u>tilt boundaries</u>, and those caused by screw dislocations are called, <u>twist boundaries</u>.

A twin boundary is a plane across which there is a special mirror mis-orientation of the lattice structure.



(a) Perfect Crystal



(b) Twin Boundary

Formation of a twin boundary

Twin boundary is a plane defect created when a crystal is sheared such that the sheared part becomes the mirror image of the unsheared part. It is produced when a shear force acting along the twin boundary causes the atoms to shift out of position. The mirror image is the twin boundary. Twinning occurs during deformation or heat treatment of certain metals. The twin boundaries interfere with the slip process and increase the strength of the metal. The movement of twin boundaries can also cause a metal to deform.

(C) DIFFUSION IN SOLIDS

Diffusion can be defined as the mechanism by which matter is transported through matter. Atoms in gases, liquids and solids are in constant motion and migrate over a period of time. In solids, atomic movements are restricted due to bonding to equilibrium positions. However, **thermal vibrations** occurring in solids do allow some atoms to move. Diffusion of atoms in metals and alloys is particularly important since most solid state reactions involve atomic movements.

There are two main mechanisms of diffusion of atoms in crystalline lattice: (1) the vacancy or substitutional mechanism and (2) the interstitial mechanism.

 <u>Vacancy or Substitutional Mechanism:-</u> Subject to availability of vacancies in the lattice, atoms can move in the crystal lattice from one atomic site to another if there is sufficient activation energy, usually provided by the thermal vibration of the atoms.



Activation Energy required to move an Atom into a Vacant Site.

2. <u>Interstitial Mechanism:-</u> The interstitial diffusion of atoms in crystals lattices takes place when atoms move from one interstitial site to another neighbouring interstitial site without permanently displacing any of the atoms in the matrix crystal lattice. For this process to occur, the size of the diffusing atoms must be relatively small compared to the matrix atoms.

Generally, diffusion under steady-state conditions (i.e., when concentration of the solute atoms does not change with time) is considered a no chemical interaction process. Hence, the flux or flow of atoms in this type or system can be represented by the equation:

$$J = -D dc/dx$$

Where: J = flux or net flow of atoms

D = proportionality constant called the diffusivity (atomic conductivity) or diffusion coefficient.

dc/dx = Concentration gradient.

A negative sign is used because the diffusion is from a higher to a lower concentration; i.e. a negative diffusion gradient. This is Fick's first Law of Diffusion.

Variables (factors) which affect diffusivity values include (a) type of diffusion mechanism. (b) temperature at which the diffusion takes place (c) type of crystal structure of the solvent lattice (d) type of crystal imperfections present. (e) concentration of diffusing species.

However, steady state diffusion is not commonly encountered with engineering materials. In most cases, non-steady state diffusion in which concentration of solute atoms at any point in the material changes with time takes place. For cases of non-steady state diffusion in which the diffusivity is independent of time, Fick's second Law of Diffusion apples, which is

The derivation and solving of this differential equation is beyond the scope of this course.

Nevertheless, the particular solution to this equation in which a gas A is diffusing into B solid is of great importance for some engineering diffusion processes, and could be applied to solve some practical industrial diffusion problems.

Let us consider the case of a gas A diffusing into a solid B. As the time of diffusion increases, the concentration of solute atoms at any point in the X direction will also increase, for times T_1 and T_2 . If the diffusivity of gas A in solid B is independent of position, then the solution to Fick's Second Law is:

$$\frac{C_{s}-C_{x}}{C_{s}-C_{o}} = \operatorname{erf}\left(\frac{x}{V_{DE}}\right)$$

Where Cs = surface concentration of element in gas diffusion into the surface

Co = initial uniform concentration of element in solid

Cx = concentration of element at distance x from surface at time t.

- X = distance from surface
- D = diffusivity of diffusing solute element.

Diffusion of a gas into a solid.

Example:

Consider the gas carburizing of a gear of 1020 steel at 927°C (1700°F). Calculate the time in minutes necessary to increase the carbon content to 0.40% at 0.50mm below the surface. Assume that the carbon content at the surface is 0.90% and that the steel has a norminal carbon content of 0.20%. $D_{927oC} = 1.28 \text{ x}$ 10°11 m²/s.

Solution

$$\frac{C_8 - C_8}{C_8 - C_6} = e_7 f \frac{\pi}{2 \Delta t}$$

$$C_8 = 0.90^{\circ} l_7, \quad x = 0.5 \text{ hm} = 5 \times 10^{-4} \text{ M}$$

$$C_0 = 0.2^{\circ} l_9 \quad D_{929^{\circ}_6} = 1.28 \times 10^{-11} \text{ m}^2 \text{s}^{-1}$$

$$C_{01} = 0.4^{\circ} l_7, \quad t = ?$$
Be substitution, we have
$$\frac{0.9v - v.4v}{v(1.28 \times 10^{-11} \text{ ms}^{-1})t}$$

$$\frac{0.5}{v.7} = e_7 f \quad \frac{69.88}{vt} = 0.7143$$

$$Left \quad Z = \frac{69.88}{vt} \quad \therefore e_7 f = 0.7143$$

We need a number for Z whose error function (erf) is 0.7143 from the reference table we find this number by interpolation to be 0.755

CHAPTER FIVE

EQUILIBRIUM PHASE DIAGRAMS

The mechanical properties of material can be controlled by the addition of point defects, in particular, substitutional and interstitial atoms.

The point defects not only disturb the atomic arrangement in the lattice but also interfere with the slip or dislocation movement. In essence, the point defects cause the material to be solid solution strengthened. The introduction of point defects also changes the composition of the material and influences the solidification behaviour. This effect will be examined by introducing the phase equilibrium diagram.

4.1 <u>Cooling Curves:</u>

A cooling curve is a plot of the temperature of the metal or material observed at intervals against time. The material (metal) eventually solidifies at a constant temperature, known as its freezing point.





However, we rarely employ absolutely pure metals in engineering designs, especially structural materials. Most of our engineering materials are alloys of one form or the other. The cooling curve for alloys differ from that of pure metals, as freezing takes place over a range of temperature. The constituent elements in most industrial alloys are completely soluble in each other in the liquid state i.e. they mix perfectly and do not form two layers of liquid as do oil and water. Two metals which are completely soluble in each other in the liquid state may after solidification,

(a) remain completely soluble in each other to give a perfectly homogeneous solid, termed a <u>solid</u> <u>solution, (b)</u> be completely insoluble in each other, (e) be partially soluble in each other, and (d) combine to form an intermetallic compound.



Cooling Curve for Solid Solution (Alloys)

Such curve as shown above can be obtained for various compositions of the alloy concerned. If the 1st arrest points in each case is noted a collection of all the 1st arrest points will give the **Liquidus Line** in a Temperature-Composition Diagram. Similarly, a collection of the 2nd arrest points will give the **Solidus Line**.

Thermal Equilibrium Diagrams

A thermal equilibrium diagram is a temperature-composition graph which indicates the structural changes that take place during extremely low rates of heating and cooling of an alloy. The term 'equilibrium' denotes that the heating and cooling of the alloy is carried out so slowly that at all temperatures, all possible changes are allowed to go to completion. Such conditions are rarely met in practice; however, the diagrams form a useful basis for the study of alloys. If the structure is not in true equilibrium but is in a meta-stable state, i.e., almost stable, then the resulting diagram is called **Phase Diagram**. A phase diagram is a diagram showing the phases and the phase compositions at each combination of temperature and overall positions. A mass of material, whether solid, liquid, gaseous or a mixture of these states is called **a system**. A system consists of one or more phases, each of which is a definite, homogeneous physically distinct substance. A phase therefore can be defined as a material having the same composition, structure and properties everywhere under equilibrium conditions.

When a phase contains only two components, it is referred to as a **Binary Phase**, and the corresponding diagram is called a **Binary Equilibrium Phase Diagram**

Solid Solution Alloys

A solid binary alloy consists of a single phase with a particular crystal lattice structure in which both components (metals) are present. This is known as a solid solution. There are two types of solid solution depending on the position of the atoms of the alloying elements in the space lattice of the basis metal. There are substitutional and interstitial solid solutions.

(i) Substitutional Solid Solution:- It is formed when the atoms of the basis or solvent metal are replaced by atoms of the added or solute element. This replacement may occur in either (a) a random manner with no regular pattern of solute atoms or (b) an ordered arrangement where the solute atoms exist in a regular pattern.



Replacement Pattern: (a) Random Replacement

(b) Ordered Replacement

(ii) Interstitial Solid Solution: In this case, the solute atoms fit into the interstices between the atoms of the solvent metal. This requires that the solute atom must be very small compared to the solvent atom.

FACTORS AFFECTING SOLID SOLUBILITY

For an alloy system to exhibit complete solid solubility, the following conditions must be satisfied:

- 1. **Crystal Structure:** The metals must have the same crystal structure, otherwise, there must be some point at which there is a transition from one phase to a second phase with a different structure.
- Atomic Size:- The atoms of the metals must be of similar size with no more than 15% differences in atomic radii.
- 3. Electrochemical Properties:- The greater the difference between the electrochemical properties of the metals concerned, the greater is the tendency to form intermetallic compound rather than a wide range of primary solid solution.
- 4. **Relative Valency:** The atoms of the metals must have the same valence; otherwise, the valence electron difference may encourage compounds formation rather than solutions.
- 5. Electron Concentration: The atoms of the metals must have about the same electronegativity. If the electronegativity differs significantly, compounds again tend to form, e.g. 2Na and Cl₂ combine to form 2NaC1.

Example

Determine which of the following alloy systems might be expected to display unlimited solid solubility (i) Ag-Au: (ii) Ca-A1. Solution:

(1) Ag-Au – This is because both have valence of 1, have the same electronegativity value and are FCC

crystal structure metals.

Ag = 1.445Å, ÅAu = 1.442Å Ag = 0.2°lo ∠ 15°lo ∴ Ag and Au have Complete solid solubility crystal structure metals. (1) (ii) Ca-AL Yea=1.97Å, YAL=1.43Å Yea=1.97Å, YAL=1.43Å . AF = 37.8°lo > 15°lo Ca and AL have limited solid solubility

Features of a Phase Diagram



The diagram above shows an isomophous phase diagram of a binary alloy AB exhibiting solid solubility. In arriving at the diagram, information obtained from a set of cooling curves of alloys of known composition are used. For instance, the first set of arrest points are joined to give the liquidus curve while those of the second set are joined to give the solidus curve.

Liquidus Temperature: This is the temperature above which all alloys must be heated to produce a completely liquid alloy that can be cast into useful shape. The liquid begins to solidify when the temperature cools to the liquidus temperature.

Solidus Temperature: This is the temperature below which all alloys are completely solid.

Freezing Range of Alloy: This is the temperature difference between the liquidus and solidus temperatures. Within the freezing range, two phases co-exit, a liquid and a solid.

Other sets of equilibrium diagrams exist displaying varying degree of solid solubility. These are those with:

(a) Complete Insolubility in the Solid State.



E- Eutectic Temperature: The lowest temperature at which both of the two solid phases are in equilibrium with the liquid phase. The binary eutectic mixture may contain two or more phases and the phases grow into solid by a eutectic reaction:



to form various characteristics pattern or eutectic structures e.g. Bi – Cd, Sn – Zn and Pb - Sn alloys.

(b) Partial Solubility in the Solid State.



E - Eutectic Temperature

aEb - Liquidus Curve

acEdb - Solidus Lines: Lines denoting the maximum solubility limits of element B in A and of element A in B respectively..

Like eutectic reaction, cooling of a solid solution transforms into two solid phases at constant temperature and fixed composition. Such reaction is called a <u>Eutectoid Reaction</u>

 $t S_2$ 8.9 723 (1) etd 0 E Å B °lo B

This diagram describes another feature of a phase diagram in which a mixture of liquid and solid transforms into a new solid phase at a fixed temperature. This reaction is called **Peritectic Reaction** and its corresponding temperature – peritectic temperature. In the diagram above, the peritectic reaction occurs at point G and can be represented as:

$$L + \alpha = \beta$$

Like peritectic reaction, it is also possible that transformation occurs all in solid phases. In effect, two solid phases can combine to form a third on cooling and such process is called a **Peritectoid Reaction**.

$$S_1 + S_2 \leftrightarrow S_3$$

When in a three phase reaction, a liquid transforms into a solid and a second liquid phase on cooling, then a **Monotectic Reaction** is said to occur.

$$L \leftrightarrow \alpha + L_1$$
 e.g. Cu – Pb system.

(c) No Solid Solubility



This shows formation of inter metallic phase with two eutectic points. There are two types of intermediate phases that can occur.

- (a) Those which cover a range of composition and are somewhat to a solid solution e.g Cu/Zn system.
- (b) Those of fixed composition, usually corresponding to simple chemical formulae e.g. Fe₃C, Cu₃P, Cu₃Sn and Mg₂Sn.

It should be noted that intermediate phase do occur also when phases show partial solid solubility in one another.

PHASE RULE

Each phase present in an alloy has a composition expressed as % of each element in the phase. If there is only one phase in an alloy, then the composition of the phase equals the overall composition of the alloy. When two phases co-exist, such as liquid and solid, the composition of the phases is different from each other and from the original overall composition. This difference is explained by the Gibb's phase rule which is given as

$$\mathbf{F} + \mathbf{P} = \mathbf{C} + 2$$

Where:

P – Number of phases present

C – Number of components in the system

F – Number of degree of freedom

The components C are the smallest number of elements or compounds present in the system The degrees of freedom F are the number of variables such as temperature or phase composition that must be fixed to completely describe the system.

THE LEVER RULE

In the equilibrium diagram showing complete solid solubility, a two-phase region exists between the liquidus and solidus in which a liquid and a solid are in equilibrium.



Consider an alloy X whose liquid composition R is in equilibrium with solid composition S at temperature T.

The line joining R and S is called the **Tie Line** - the line is a horizontal line drawn in a two-phase region of a phase diagram to assist in determining the components of the phases. For alloy X at temperature T, i.e., at point P in a two-phase field, relative masses of the two phases in equilibrium are given by the relative distance PS and RP. This relationship may be expressed as:

Mass of liquid R x Distance RP = Mass of solid S x Distance PS

or

Mass of liquid R / Mass of solid S = PS / RP

This is known as the Inverse Lever Rule

Alternatively, the lever rule can be deduced as follows:



Let y = fraction of alloy X that is Solid

Therefore, 1 - y = fraction of alloy X that is Liquid

At P, by Mass Balance, we have:

$$(\% X \text{ in } L) (L-Y) + (\% X \text{ in } S)Y = \% X \text{ in the alloy}$$

Multiplying and rearranging, we have:

 $Y = \frac{\% X \text{ in alloy} - \% X \text{ in the liquid}}{\% X \text{ in the solid} - \% X \text{ in the liquid.}}$

In general, the lever rule can be written as:

Phase
$$\% = \frac{\text{Opposite arm of lever}}{\text{Total length of the Tie line}} \times \frac{100}{1}$$

Example

Determine the composition of each phase in a Cu - 40%Ni alloy at 1270° C given the liquidus and solidus composition as 37% and 50% respectively.

Solution

At 1270^{0} C, the tie line intersects the liquidus curve at 37% and the solidus curve at 50%.

Using the lever rule, we have:

% L =
$$\frac{50 - 40}{50 - 37}$$
 x $\frac{100}{1} = 77\%$

%
$$a = \frac{40 - 37}{50 - 37}$$
 x $\frac{100}{1} = 23\%$



CHAPTER SIX

6.0 ELECTRICAL PROPERTIES OF MATERIALS

The electrical properties of materials are of importance in many applications in engineering. The metal wires used to transmit current over long distances must have a high electrical conductivity so that little power is lost by heating of the wire. Ceramic are used as insulators to prevent arcing between conductors, semiconductors used to convert solar energy to electrical power must be as efficient as possible to make solar cells a practical alternative source of energy. Dielectric materials are used in capacitors to store electrical energy and in transducers to convert electrical signals to sound. Hence, it must be understood that the electrical behaviour of the various materials are diverse. Some need to be highly conductive electrically, e.g. connecting wires, whereas electrical insulation is required of others

e.g. the protective package encapsulation.



6.1 CONDUCTION

Electrical conduction is brought about from the motion of charge carriers due to response to an imposed electric field. These carriers are electrons which are negative charge. Others include anions and cations from ionic crystals and electron hole (missing hole) which are positive charge. The ease with which a material is capable of transmitting an electric current is expressed in terms of electrical conductivity or its reciprocal, resistivity. On the basis of its conductivity, a solid material may be classified as a metal, a semiconductor, or an insulator.

OHM'S LAW

One of the most important electrical characteristics of a solid material is the ease with which it transmits an electric current. Ohm's law relates the current I - or time rate of charge passage - to the applied voltage V as follows:

V = IR

Where V = Voltage in volts

I = Current in amps and

R = Resistance of the materials through which the current is passing

The units for V, I, and R are respectively, volts (J/C), amperes (C/s), and ohms (V/A).

The value of R is influenced by specimen configuration, and for many materials is independent of current. The resistivity ρ is independent of specimen geometry but related to R through the expression

 $\rho = RA/L$

Where: l = Distance between the two points at which the voltage is measured,

A = Cross-sectional area perpendicular to the direction of the current.

The unit of ρ is ohm-meter.

From the expression of Ohm's law and equation above

$$\rho = VA/IL$$

Electrical Conductivity

Electrical conductivity is used to specify the electrical character of a material. It is simply the reciprocal of the resistivity, or $\sigma = 1/\rho$

and is indicative of the ease with which a material is capable of conducting an electric current. The units for σ are reciprocal ohm-meters [(Ω -m⁻¹) or mho/m].

Also,

 $\sigma = nq\mu$

Where: $n = number of carriers (m^{-3})$

Q = charge on each carrier (C) and

 μ = mobility of each carriers (m²/V-s)

The mobility $\mu = \nu/E$

Where: v = drift velocity (m/s) and

E = Electrical field strength (the difference between two points divided by

.the distance separating them)

Ohm's law may be expressed as:

 $J = \sigma \epsilon$

Where: J = Current Density (Current per unit of specimen area I/A)

 ε = Electric Field Intensity, or Voltage Difference between two points divided by the

distance separating them; that is,

 $\epsilon = V/L$

Electrical Resistivity of Conductors

When an electric field is applied to metals for instance, there will be acceleration of free electrons which lead to electric current. However, the flow of these free electrons is impeded by defects in the metal crystal. The defects include dislocations, vacancies, impurities, atomic vibrations and interstitials. As the resistance to the electric current flow from these defects increases, the mobility of electron decreases.

The total resistivity of metal is given as: $\rho = \rho_T + \rho_D$

Where: ρ_T = resistivity due to thermal component and

 ρ_D = resistivity due to defects

 ρ_T varies linearly with temperature T. therefore $\rho_T = \rho_r (1 + \infty \Delta T)$

Factors affecting the Conductivity of Metals

The conductivity of a pure, defect free metal is determined by the electronic structure of atoms. But the conductivity can be affected by affecting the mobility of the carriers. Since mobility is proportional to the drift velocity V, then the mobility is low if the electrons collide with imperfections in the lattice. Therefore, we can significantly affect the conductivity by influencing the mobility of the carriers. In all, the factors affecting mobility and consequently the conductivity can be summarized as follows:

1. Temperature Effect: When the temperature of a metal increases, thermal energy cause the atoms to vibrate. At any instant, the atom may not be in its equilibrium position and therefore interacts with and scatters electrons. Because the mobility of electron is reduced, the resistivity increases. The change in resistivity with temperature can be estimated from the equation:

$$\boldsymbol{\rho} = \boldsymbol{\rho}_{\rm r}(1 + \infty \Delta T)$$

Where: $\rho_{r,i}$ is the resistivity at room temperature (25^oC)

 ΔT is the temperature difference

 ∞ is the temperature resistivity coefficient.

Example: Calculate the electrical conductivity of Copper at (a) 400°C and (b) -100°C

Solution:

The resistivity of copper at room temperature is $1.67 \times 10^{-6} \Omega$.cm and temperature resistivity coefficient is 0.0068Ω cm/°C.

At 400°C,

$$\rho = \rho_r (1 + \infty \Delta T) = (1.67 \times 10^{-6}) (1 + 0.0068 (400 - 25))$$

 $= 5.985 \text{ x } 10^{-6} \Omega.\text{cm}$

But
$$\sigma = 1/\rho = 1/5.985 \text{ x } 10^{-6} \Omega.\text{cm} = 1.67 \text{ x } 10^{5} (\Omega.\text{cm})^{-1}$$

At - 100⁰C

$$\rho = \rho_r (1 + a\Delta T) = (1.67 \text{ x } 10^{-6}) (1 + 0.0068 (-100 - 25))$$

= 0.307 x 10⁻⁶

Also
$$\sigma = 1/\rho = 1/0.307 \text{ x } 10^{-6} \Omega.\text{cm} = 32.5 \text{ x } 10^{5} (\Omega.\text{cm})^{-1}$$

2. Effect of Lattice Defects:

Lattice imperfections scatter electrons and thus reduce the mobility and conductivity of metals as illustrated in the diagram below.

Lattice importe illustrated in the diagram below. 00000 à Resis Imp

Effect of Processing and Strengthening: Strengthening mechanisms and metal processing techniques affect the electrical properties of a metal in different ways. Due to random distribution of the interstitial or substitutional atoms, solid solution strengthening is a poor way to obtain high strength in metals intended to have high conductivities. The alloying elements, e.g. nickel have large effect on the conductivity of copper-nickel alloys. The more the increase in the amount of zinc as alloying element in copper, the more the decrease in its conductivity



6.2 <u>SEMICONDUCTIVITY</u>

The electrical conductivity of the semiconducting materials is not as high as that of the metals; however, they have some unique electrical characteristics that render them especially useful. The electrical properties of these materials are extremely sensitive to the presence of even minute concentrations of impurities.

6.2.1 INTRINSIC SEMICONDUCTION

The energy gap E_g is small in some elements such as silicon (Si) and germanium (Ga). Hence, few electrons possess enough energy to be excited into the conduction band. These excited electrons leave behind unoccupied energy levels, holes, in the valence band. When a voltage is applied to the material, electrons in the conduction band accelerate towards terminal, while holes move towards the negative terminal. Current is therefore conducted by the movement of both the electrons and the holes which act as positive charge. The conductivity is determined by the number of electron-hole pairs.

The current flow can be expressed as: $\sigma = n_e q \mu_e + n_h q \mu_h$

Since $n_e = n_h = n$ Therefore: $\sigma = nq(\mu_e + \mu_h)$

At any temperature T, no. of e in the conduction band or h in the valence band is related to the band energy E_g according to the expression: $n_e = n_h = n = n_o \exp \{-E_g/2kT\}$ where $n_o = \text{constant}$

6.2.2 EXTRINSIC SEMICONDUCTION

This is produced when (dopant) atoms are introduced into semiconductor Most commercial semiconductors are extrinsic; that is, the electrical behaviour is determined by impurities, which, when present in even minute concentrations, introduce excess electrons or holes. For example, an impurity

concentration of one atom in 10^{12} is sufficient to render silicon extrinsic at room temperature. There are two major types of extrinsic semiconductors, they are:

n-Type Extrinsic Semiconduction: When an impurity atom such as antimony is added, which has a valence of five, to silicon or germanium, four of the electrons from the antimony atom will participate in the covalent bonding process, while the extra electron enters an energy level in a donor state just below the conduction band as shown below. Since the electron is not tightly bound to the atoms, only a small energy E_d is required for the electron to enter into the conduction band. No corresponding holes are created when the donor electrons enter the conduction band. Such semiconductor produced is refer to as n-Type Extrinsic Semiconduction.

to as n-Type Extrinsic Semiconduction. Conduction Band Valence banc

p-Type Extrinsic Semiconduction: When an impurity atom like gallium, which has a valence of three is added to a semiconductor, there are not enough electrons to complete the covalent bonding process. An electron hole is created in the valence band which can be filled by electrons from other location in the band. The holes act as acceptors of electrons. These holes have somewhat higher energy than normal energy and create an acceptor level of possible electron energies just above the valence band. An electron must gain energy of only E_a in order to create a hole in the valence band. The hole then moves and carries the charge. This is called p-Type Extrinsic Semiconduction.

000 Hole due to dopant otoms Conduction Band alence hand

SEMICONDUCTOR DEVICES AND THEIR APPLICATIONS

The unique electrical properties of semiconductors permit their use in devices to perform specific electronic functions. Diodes and transistors, which have replaced old-fashioned vacuum tubes, are two familiar examples. Advantages of semiconductor devices (sometimes termed solid-state devices) include small size, low power consumption, and no warm-up time. Vast numbers of extremely small circuits, each consisting of numerous electronic devices, may be incorporated onto a small silicon chip. The invention of semiconductor devices, which has given rise to miniaturized circuitry, is responsible for the advent and extremely rapid growth of a host of new industries in the past few years.

The p-n Rectifying Junction

A rectifier, or diode, is an electronic device that allows the current to flow in one direction only; for example, a rectifier transforms an alternating current into direct current. Before the advent of the p–n junction semiconductor rectifier, this operation was carried out using the vacuum tube diode. The p–n rectifying junction is constructed from a single piece of semiconductor that is doped so as to be n-type on one side and p-type on the other. If pieces of n-type and p-type materials are joined together, a poor rectifier results, since the presence of a surface between the two sections renders the device very inefficient. Also, single crystals of semiconducting materials must be used in all devices because electronic phenomena that are deleterious to operation occur at grain boundaries. Before the application of any potential across the p–n specimen, holes will be the dominant carriers on the p-side, and electrons will predominate in the n-region.



The Transistor

Transistors, which are extremely important semiconducting devices in today's microelectronic circuitry, are capable of two primary types of function. First, they can perform the same operation as their vacuum tube precursor, the triode; that is, they can amplify an electrical signal. In addition, they serve

as switching devices in computers for the processing and storage of information. The two major types are the junction (or bimodal) transistor and the metal-oxide-semiconductor field-effect transistor (abbreviated as MOSFET).

Pressure Transducers

The band structure and the energy gap are a function of the spacing between the atoms in the material. When pressure is applied to semiconductor, atoms are forced closer together, the energy gap decreases, and the number of electrons which can be excited into the conduction band increases, hence, conductivity increases. If we measure the conductivity, we can in turn calculate the pressure acting on the material which is the basis for the operation of pressure transducers.

Thermistors

The conductivity of semiconductor increases with temperature. By knowing the relationship between conductivity and temperature, we can use semiconductor to measure temperature. It is also used as fire alarm. When the thermistor heats, it passes a larger current through a circuit and activate the alarm.

6.3 <u>SUPERCONDUCTIVITY</u>

Superconductivity is a phenomenon whereby the resistivity of a material abruptly drop to zero as the material is cooled beyond a critical temperature T_c thereby leading to current flow in the material without resistance. It is basically an electrical phenomenon but there are magnetic implications relative to the super-conducting state. Superconducting materials are used primarily in magnets capable of generating high fields. As most high-purity metals are cooled down to temperatures nearing 0 K, the electrical resistivity decreases gradually till it becomes zero, and a current flows indefinitely. They are materials, however, for which the resistivity, at a very low temperature abruptly plunges from a finite value to one that is virtually zero and remains there upon further cooling. Materials that display this latter behaviour are called superconductors, and the temperature at which they attain superconductivity

is called the critical temperature. The critical temperature varies from superconductor to superconductor but lies between less than 1 K and approximately 20 K for metals and metal alloys. Recently, it has been demonstrated that some complex oxide ceramics have critical temperatures in excess of 100 K. the change from normal conduction to super-conduction, which occurs abruptly at a critical temperature Tc, is related to the magnetic characteristics of the electrons.
CHAPTER SEVEN

OPTICAL AND MAGNETIC PROPERTIES OF MATERIALS

7.1 OPTICAL PROPERTIES OF MATERIALS

When materials are exposed to electromagnetic radiation, it is sometimes important to be able to predict and alter their responses. This is possible when we are familiar with their optical properties and understand the mechanisms responsible for their optical behaviours. Optical Property therefore means a material's response to exposure to electromagnetic radiation and, in particular, to visible light.

7.1.1 ELECTROMAGNETIC RADIATION

Electromagnetic radiation is considered to be wave-like, consisting of electric and magnetic field components that are perpendicular to each other and also to the direction of propagation. Examples are: light, heat (or radiant energy), radar, radio waves, and x-rays. Each of them is characterized primarily by a specific range of wavelengths, and also according to the technique by which it is generated. The electromagnetic spectrum of radiation spans the wide range from γ -rays (emitted by radioactive materials) having wavelengths on the order of 10^{-12} m (10^{-3} nm), through x-rays, ultraviolet, visible, infrared, and finally radio waves with wavelengths as long as 10^{5} m.

Visible light lies within a very narrow region of the spectrum, with wavelengths ranging between about $0.4\mu m$ (4 x $10^{-7}m$) and $0.7\mu m$ (4 x $10^{-7}m$). The perceived colour is determined by wavelength. When light proceeds from one medium into another (e.g., from air into a solid substance), several things happen. Some of the light radiation may be transmitted through the medium, some will be absorbed, and some will be reflected at the interface between the two media. The intensity I_0 of the beam incident to the surface of the solid medium must equal the sum of the intensities of the transmitted, absorbed, and reflected beams, denoted as I_T , I_A and I_R and respectively,

$$\mathbf{I_0} = \mathbf{I_T} + \mathbf{I_A} + \mathbf{I_R}$$

Radiation intensity, expressed in watts per square meter, corresponds to the energy being transmitted per unit of time across a unit area that is perpendicular to the direction of propagation.

Light Interactions with Solids

The optical behaviour of a solid material is a function of its interactions with electromagnetic radiation having wavelengths within the visible region of the spectrum. Possible interactive phenomena include refraction, reflection, absorption, and transmission of incident light.

7.1.2 Optical Properties

Metals appear opaque as a result of the absorption and then re-emission of light radiation within a thin outer surface layer. Absorption occurs via the excitation of electrons from occupied energy states to unoccupied ones. Re-emission takes place by decay electron transitions in the reverse direction. The perceived colour of a metal is determined by the spectral composition of the reflected light.

- 1. **Refraction:** Light radiation experiences refraction in transparent materials; that is, its velocity is retarded and the light beam is bent at the interface. Index of refraction is the ratio of the velocity of light in a vacuum to that in the particular medium. The phenomenon of refraction is a consequence of electronic polarization of the atoms or ions, which is induced by the electric field component of the light wave.
- 2. **Reflection:** When light passes from one transparent medium to another having a different index of refraction, some of it is reflected at the interface. The degree of the reflectance depends on the indices of refraction of both media, as well as the angle of incidence.
- **3. Absorption:** Nonmetallic materials are either intrinsically transparent or opaque. Opacity results in relatively narrow-band gap materials as a result of absorption whereby a photon's energy is

sufficient to promote valence band-conduction band electron transitions. Transparent nonmetals have band gaps greater than about 3 eV. Some light absorption occurs in even transparent materials as a consequence of electronic polarization.

- 4. Colour: For wide-band gap insulators that contain impurities, decay processes involving excited electrons to states within the band gap are possible with the emission of photons having energies less than the band gap energy. These materials appear colored, and the color depends on the distribution of wavelength ranges in the transmitted beam.
- 5. Opacity and Translucency in Insulators: Normally transparent materials may be made translucent or even opaque if the incident light beam experiences interior reflection and/or refraction. Translucency and opacity as a result of internal scattering may occur, (1) in polycrystalline materials that have an anisotropic index of refraction, (2) in two-phase materials, (3) in materials containing small pores, and (4) in highly crystalline polymers.

Application in Communications

Optical Fibers is used in modern telecommunications. This is because using fiber-optic technology, transmission of information is interference free, rapid, and intense.

7.2 MAGNETIC PROPERTIES OF MATERIALS

Magnetism is the phenomenon by which materials assert an attractive or repulsive force or influence on other materials. Magnetic forces are generated by moving electrically charged particles; these magnetic forces are in addition to any electrostatic forces that may prevail. Many of our modern technological devices rely on magnetism and magnetic materials; these include electrical power generators and transformers, electric motors, radio, television, telephones, computers, and components of sound and video reproduction systems. Iron, some steels, and the naturally occurring mineral lodestone are well-

known examples of materials that exhibit magnetic properties. Not so familiar, however, is the fact that all substances are influenced to one degree or another by the presence of a magnetic field.



Diamagnetism and Paramagnetism

Diamagnetism is a very weak form of magnetism that is nonpermanent and persists only while an external field is being applied. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. The magnitude of the induced magnetic moment is extremely small, and in a direction opposite to that of the applied field.

Ferromagnetism

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations. These are the characteristics of ferromagnetism, and they are displayed by the transition metals: iron (as BCC ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as are possible for ferromagnetic materials. Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to electron spin - uncancelled electron spins as a consequence of the electron structure. There is also an orbital magnetic moment contribution that is small in comparison to the spin moment. Furthermore, in a ferromagnetic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. The maximum possible magnetization, or saturation magnetization of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field.

Diamagnetism and Paramagnetism

Diamagnetism results from changes in electron orbital motion induced by an external field. The effect is extremely small and in opposition to the applied field. All materials are diamagnetic. Paramagnetic materials are those having permanent atomic dipoles, which are acted on individually and are aligned in the direction of an external field. Since the magnetizations are relatively small and persist only while an applied field is present, diamagnetic and paramagnetic materials are considered to be nonmagnetic.

Classification of Magnetic Materials

(1.)Soft Magnetic Materials: Both ferromagnetic and ferromagnetic materials are classified as either soft or hard on the basis of their hysteresis characteristics. Soft magnetic materials are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low. Example is transformer cores. Due to this, the relative area within the hysteresis loop must be small. Consequently, a soft magnetic material must have a high initial permeability and a low coercivity. A material possessing these properties may reach its saturation magnetization with a relatively low applied field (i.e., is easily magnetized and demagnetized) and still has low hysteresis energy losses. Another property consideration for soft magnetic materials is electrical resistivity. In addition to the hysteresis energy losses, energy losses may result from electrical currents that are induced in a magnetic material by a magnetic field that varies in magnitude and direction with time; these are called eddy currents. It is most desirable to minimize these energy losses in soft magnetic materials by increasing the electrical resistivity.

(2.)Hard Magnetic Materials: Hard magnetic materials are utilized in permanent magnets, which must have a high resistance to demagnetization. It has a high remanence, coercivity, and saturation flux density, as well as a low initial permeability, and high hysteresis energy losses. The hard magnet steels are normally alloyed with tungsten and/or chromium. Under the proper heat-treating conditions these two elements readily combine with carbon in the steel to form tungsten and chromium carbide precipitate particles, which are especially effective in obstructing domain wall motion.

Application of Magnetic Property

Magnetic Storage: Information storage is accomplished using magnetic materials in both needleshaped particulate and thin-film forms. It is applied in the area information storage; in fact, magnetic recording has become virtually the universal technology for the storage of electronic information such as audio tapes, VCRs, disk storage media, credit cards, and so on. In computers, semiconductor elements serve as primary memory, but magnetic disks are used for secondary memory because they are capable of storing larger quantities of information and at a lower cost. Furthermore, the recording and television industries rely heavily on magnetic tapes for the storage and reproduction of audio and video sequences.

7.3 EFFECTS OF SERVICE CONDITIONS ON MATERIALS

The stability and effectiveness in the performance of materials in service is subject to the environment of operation of the material. Materials operate under different types of loading, at varied temperatures as well as different atmosphere and/or media. Some of the environmental factors that affect the behaviour of materials include: load, temperature, radiation, atmosphere and corrosive agents.

1. Load: The type of force or load acting on a material may dramatically change its behaviour. In this respect, the most important property is the yield strength of the material. However, a material that displays high yield strength may fail rather easily at lower loads if the loading is cyclical (fatigue) or applied suddenly (impact). The engineer must recognize the type of loading to which a material is exposed.

2. <u>Temperature:</u> Changes in temperature dramatically alter the properties of material. The strength of most materials decreases as the temperature increases. Likewise, sudden catastrophic changes may occur when heating above critical temperatures. Metals that have been strengthened by certain heat treatments or forming techniques may suddenly lose their strength when heated. Very low temperature (Sub-Zero) may cause a metal to fail in a brittle manner even though the applied loads are low. High temperatures can also change the structure of ceramics or cause polymers to melt or char.

3. Most metals and polymers react with oxygen or other gases of the atmosphere, particularly at high temperatures. Metals and ceramics may catastrophically disintegrate or be chemically attacked, while others may be protected. Corrosive agents may attack metals in their service environment and cause them to be uniformly or selectively consumed, or may develop cracks or pits leading to premature failure. High energy radiation, such as neutrons produced in nuclear reactors, can affect the internal structure of all materials, producing a loss of strength, embrittlement, or critical alteration of physical properties. External dimensions may also change, causing swelling or even cracking.

CHAPTER EIGHT

8.0 MECHANICAL PROPERTIES OF MATERIALS

To be of value to the engineer a material must have suitable mechanical properties. Hence, we should have the knowledge of **mechanical properties of materials**. These properties include strength, ductility, hardness, impact, creep, fatigue and wear, the value of which vary greatly from material to material and are independent on the metallurgical condition of the material.

Several tests are carried out to measure these properties. These tests are carried out for one purpose or the other some of which include

- (a) To determine the quality of a material
- (b) To determine such properties as strength, hardness and ductility.
- (c) To check flaws within a material or in a finished product.
- (d) To assess the likely performance of the material in a particular service conditions.

Most common tests are tensile, compression, torsion, hardness, creep, impact and fatigue tests. Except for hardness test, all other tests are destructive in nature and they often require the test piece be prepared to standard dimensions. For flaws detection, defects within part of processed stock materials or finished components, there available several non-destructive tests techniques. Other special tests have been devised for the purpose of material quality assessment or for the information gathering on the behaviour of a component or assembly in service.

8.1 HARDNESS

This is the **ability of a material to withstand scratching (abrasion) or indentation by another hard body** by resisting a permanent shape change due to external stress. It is an indication of the wear resistance of a material. There are various measure of hardness – scratch Hardness, indentation hardness and rebound hardness

(a). Scratch Hardness is the ability of material to oppose scratch by outer surface layer due to external force.

(b). Indentation Hardness It is ability of material to oppose the dent due to punch of external load and sharp object.

(c). Rebound Hardness which is also called dynamic hardness is determined by the height of "bounce" of a diamond tipped hammer dropped from a fixed height on the material.

8.1.1 Hardness Tests

Three main methods of test commonly used are: Brinell, Vicker and Rockwell

8.1.1.1 The Brinell Test

In the Brinell test, a small indenter, usually a hardened steel ball or diamond cone, 10mm in diameter is forced into the surface of the material or test piece using a suitable load. This force is maintained for the diameter of the impression left on the surface is measured and converted to a hardness number. Brinell hardness number is calculated from the formula

BHN = F/(
$$\pi D_b/2$$
)($D_b - \sqrt{D_b^2 - D_i^2}$) or $HB = \frac{2F}{\pi D_b (D_b - \sqrt{D_b^2 - D_i^2})}$

Where: HB = Brinell Hardness Number (BHN), $F = indentation load (kg); D_b = diameter of ball (mm)$

and D_i = diameter of indentation/impression left on the material's surface (mm)

F = Applied load in Kg (1Kg = 9.81 N)

There is a standard table relating the hardness to the diameter of the indention from where the Brinell hardness number may be read directly

Conditions for Brinell Test

- (a) The depth of indentation must not be too great relative to the material or test piece thickness.
- (b) For soft materials. The thickness of the test piece should be at least 15 times the indentation depth while for hard materials the thickness should be at least 7 times the indentation depth

The HB is not constant for a given specimen under test but depends on the load and size of the ball used. Balls of different diameters are available enabling one of the suitable size for the thickness of the test piece to be chosen. It is to be noted that the larger the ball it is possible to use, the more accurate the

suit is likely to be. For different materials, the ratio F/D^2 has been standardized in order to obtain reliable comparable results.

8.1.1.2 The Vickers Test

The Vickers hardness test eliminates the need for deciding the correct ratio of F/D^2 by using a squarebased diamond pyramid indenter. This offers advantages over Brinell test in that all indentations made are geometrically similar and the hardness value obtained is independent of the value of the indenting force applied. Since there is no plastic deformation of the indenter as in the case of brinell, the test may be used for very hard materials. The accuracy of the test result will not vary with the indentation depth, though the relationship between indentation dept and test piece thickness is still observed. The diamond indenter in the form of right pyramid with a square base and an angle of 136° between opposite faces is forced into the prepared surface of the test piece under a selected load. Held for 15 second, the indentation made is measured by means of microscope and the reading obtained converted to a Vickers hardness number (HV) by reference to tables. Like brinell test, the Vickers hardness is defined as

> $HV = \underline{load \ kgf}$ Surface area of indentation (mm²)

$$= \underline{2FSin0/2}_{d^{2}} = \underline{f}_{d^{2}/2} = 1.854 \underline{f}_{d^{2}/2}$$

where:

and d = diagonal length of the indentation in min.

8.1.1.3 The Rockwell Test

F = Load in kg

This test is based on the measurement of the penetration depth of the indenter. This is directly indicated on a dial as a hardness value. A load of 10kg (minor load) is first applied to the indenter and the penetration depth then reached is taken as the zero for further measurements. A further major load is applied and the depth, dmm of the indenter relative to the zero position is recorded on a suitable dial gauge. Different scales of hardness using difference shapes used are Rockwell B (HRB) and Rockwell C (HRC) whose indenters are 1.6mm diameter steel ball and 120° diamond cone called brale respectively depending on the degree of hardness of the material.



For soft materials the 1.6mm diameter steel ball is used, the major load is 90 kg (100 kg total load) and the hardness is

$$HRB = 130 - \underline{d}$$
$$0.002$$

for harder materials, a conical shaped diamond of 120° apex angle is used. The major load is 140 kg (total load 150 kg) and the hardness is

$$HRC = 100 - \underline{d}$$
$$0.002$$

8.2 STRENGTH

It is the property of material which opposes the deformation or breakdown of material in presence of external forces or load. The loading systems are of different types which include:

(a) Tensile Strength: This is the ability of a material to withstand tensile (stretching) loads without rupture occurring. The material is in tension.

(b) Compressive strength: This is the ability of a material to withstand compressive (squeezing) loads without being crushed or broken. The material is in compression.

(c) Shear Strength: This is the ability of a material to withstand offset or transverse loads without rupture occurring. For instance, a rivet connecting two bars is in **shear** and the bars themselves are in **tension.** Note that the rivet would still be in *shear* if the bars were in *compression*.

8.2.1 Tensile Test

The tensile test measures the resistance of material to a static or slowly applied force. The test is carried out by placing a specimen in the testing machine and force or load F is then applied. A strained gauge or extensometer is used to measure the amount that the specimen stretches between the gauge marks when the force is applied. The result obtained in this process is usually expressed in graphical form of load versus gauge length.

Typical Engineering Stress-Strain Plot

For a typical engineering stress-strain plot in a tensile test of a metal, there are two regions:

1. Elastic region and 2. Plastic region



8.2.1 Engineering Stress and Strain

The result of a single test apply to all sizes and shapes of specimens for a given material provided the force and distance between gauge marks are converted to stress and strain respectively.

Engineering stress and engineering strain are defined as follows

Engineering Stress = $\sigma_e = F/A_o$ and

Engineering Strain $\varepsilon_e = \underline{L-Lo}$ Lo

Where A_o – original cross sectional area of the specimen before the test begins.

L_o - Original distance between gauge marks

L - Distance between the gauge marks after the load F is applied.

The stress - strain curve is usually used to record the tensile fest results

8.2.2 Features of Stress-Strain Curve

1.) Gauge length of the test piece is defined as that portion of the parallel part which is used for measuring the extension either during or after testing. Experimentally, it has been shown that material deform in a particular manner if the relationship

	<u>Gauge length</u> Cross sectional area	is a constant
	i.e $\mathbf{L}_{\mathbf{o}} = \mathbf{k} \mathbf{A}_{\mathbf{o}}$	(Barba's law)
Where:	L _o = original gauge leng	th and $A_o = original cross sectional area$

This allows for gauge length variation with the cross sectional area of the test piece. K has been standardised at 5.65 and a test piece conforming to barba's law is known as a proportional round test piece with initial diameter d.

- 1. Elastic strength σ is the stress at the point at which the test specimen returns to its shape following an applied stress.
- 2. Elastic deformation is the deformation of a material that is recovered when the applied load is removed.
- 3. Yield strength Y on the curve is the point indicating the strength at which the test specimen experiences a sudden relatively large extension. At that point, the slip becomes noticeable and significant. Yield strength, therefore is the stress applied to a material that just causes permanent plastic deformation. Yield point marks the beginning of plastic deformation in

which the stress-strain relationship is no longer guided by Hooke's Law. As load is increased beyond *Y*, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically.

- 4. Tensile Strength is indicated by TS. It is the stress obtained at the highest applied force and thus the maximum stress on the stress-strain curve. It is also the stress at which necking begins. Necking is a term used to describe the locally deformed region of test specimen occurring as a result of large decrease of cross sectional area of that region. Localized deformation of a ductile metal during a tensile test produces a necked region.
- 5. Breaking Strength the stress at which the test specimen becomes completely plastically deformed.

8.2.3 True Stress and Strain

The decrease in engineering stress beyond the tensile point occurs because the definition of the engineering stress in which the original area A_o is used in the calculation. In practical cases, original area A_o is not precise because the area changes continuously. True stress and true strain are defined as

True stress
$$\sigma$$
 = F/A and
True Strain ε = $\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln \frac{L}{L_o}$
True strain - = $\frac{dL}{L_o}$ $\ln \frac{L}{L_o} = \ln \frac{A}{A_o}$
 $\ln \frac{L}{L_o} = \ln \frac{A_o}{A_o}$

Where: where σ = true stress; *F* = force; and *A* = actual (instantaneous) area resisting the load

Note: The expression $\ln A_o/A$ become applicable only when necking begins.

Example 8.1

A 2.5 diameter copper wire having yield strength of 140 MPa is subjected to a tensile load of 120kg. Determine whether the wire will deform plastically under this load.

Cross-sectional area of wire, $A = \pi d^2/4$

A = $\frac{\pi}{4}d^2 = \frac{\pi}{4}(2.5 \text{ x } 10^{-3})^2 = 4.91 \text{ x } 10^{-6} \text{ m}^2$

Stress, $\sigma = \frac{F}{A} = \frac{120 \times 9.8N}{4.91 \times 10^{-6} M^2} = 2.40 \times 10^8 \text{ Nm}^{-2} = 240 \text{ MPa}$

Since $\sigma > \sigma_y$, the wire will deform plastically.

Example 8.2

Compute the engineering stress and strain to the true stress and strain of an Al alloy whose gauge lengths before and after test

a) maximum load of 3628.8N are 0.0508m and 0.05385m respectively.

b) fracture load 3447.36N are 0.0508m and 0.05601m respectively.

The diameters at maximum load and fracture are 0.01262m and 0.01011m respectively. Initial diameter of the test piece is 0.01283m

Solution

At maximum load

Engineering stress
$$\sigma_e$$
 = F/A_o = 3628.8
 $\pi/4 (0.01283)^2$ = 2.808 x 10⁷ N/m²

True stress =	F/A	=	ln <u>3628.8</u>	
			$\pi/4 (0.01262)^2$	$= 2.90 \text{ x } 10^7 \text{ N/m}^2$

Engineering strain = $\underline{L} - \underline{Lo} =$	0.05385-0.0508	
Lo	0.0508	= 0.060 m/m

True strain =
$$\ln L/Lo = \ln 0.05385$$

0.0508 = 0.058 m/m

b) At fracture

Engineering stress =
$$F/A = \underline{3447.36}$$

 $\pi/4 (0.01283)^2 = 2.67 \times 10^7 \text{ N/m}^2$

True stress
$$F/A = 3447.36$$

 $\pi/4 (0.01011)2 = 4.29 \times 10^7 \text{ N/m}^2$
Engineering strain $= \underline{L} - \underline{L}_0 = 0.05601 - 0.0508$
 $L = 0.0508 = 0.1026 \text{ m/m}$
True strain $= \text{In } \underline{A}_0 = \ln 0.0508$
 $A = 0.05601$

8.2.4 Modulus of Elasticity

The modulus of elasticity or young modulus is the slope of the stress-strain curve in the elastic region. The relationship is defined by hooke's law (between stress and strain) and is linear

Hooke's Law: $\sigma = E\varepsilon$ where E =modulus of elasticity

Modulus is closely related to the forces bonding the atoms in the material. The material returns to its original length when stress is removed. E is a measure of the inherent stiffness of a material and its value differs for different materials.

At equilibrium spacing, a steep slope of the curve indicates that high forces are elastically stretched. This explains why the modulus is therefore a measure of the stiffness of the material. A very stiff material having a high modulus of elasticity, maintain its size and shape even under an elastic load.

8.2.5 Relationship between Hardness and Tensile Strength

The hardness numbers is used primarily as a basis for comparison of materials' specification for manufacturing and heat treatment, quality control and correlation with other properties and behaviour of materials. For examples, brinell hardness is closely related to the tensile strength of ferrous materials by the relationship

Tensile strength (psi) = 500 BHN (BHN)

Therefore, one pound per square inch is approximately 6894.757 Pa.

and tensile strength is related to the endurance limit by the expression

Endurance limit = 0.5 tensile strength.

Also, the Vickers hardness is related to the tensile strength by the relationship.

Tensile strength (MPa) = 3.45 HV or Tensile strength (kgf/mm²) = 0.346 HV

Design/Safety Factors

To take into account variability of properties, engineering components designers usually use, instead of an average value of, say, the tensile strength, the probability that the yield strength is above the minimum value tolerable. This leads to the use of a *safety factor* N > 1 (typically. 1.2 - 4). Thus, a working value for the tensile strength would be $\sigma_W = \sigma_{TS} / N$.

Example 8.3

Calculate the tensile strength and the endurance limit of the steel whose BHN is 363 kgf/mm².

Solution

Tensile strength (psi) = 500 BHN = 500 x 363 = 181,500 psi Endurance limit = $0.5 \times T.S$ = (0.5) (181,500) = 90,750 psi

8.1.5 Nomenclature

Some nomenclatures are adopted in tabulating data on material properties. For instance, in collating data on hardness of materials, the following nomenclature are adopted

- 248 HS 10/3000 indicates a brinell hardness of 248 was obtained by using 10 mm diameter ball with a load of 3000 kgf
- 2. 650 HV/30 indicates Vickers hardness number of 650 obtained with a load of 30kgf
- 3. 70 HRC means a Rockwell hardness of 70 measured on scale C with a diamond indenter and a total load of 150kgf.

8.3 Ductility

This is the term used when plastic deformation occurs as the result of applying a tensile load. It indicates how easily a material gets deformed. It is also the ability of material to get stretched into a wire through a die by pulling or drawing. A *ductile* material combines the properties of a plasticity and tenacity (tensile strength) so that it can be stretched or drawn to shape. With rise of temperature, the ductility of material increases.

Ductility is expressed in two ways:-

a) By measuring the distance between the gauge marks of a test piece before and after the test. The % elongation describes the executing the specimen is subjected as the total percent increase in the length of a test piece during a tensile test.

% Elongation =
$$\underline{L}_{\underline{f}}$$
 - L_{o} x 100 L_{o}

Where L_f is the distance between gauge marks after the specimen breaks

b) By measuring the percentage change in cross sectional area at the point of fracture before and after the test and amount of thinning that the test piece undergoes during the test is described by the % reduction is area.

% Reduction in Area = is the total percent decrease in the cross sectional area of a test piece during tensile test.

i.e % Reduction in Area = $\underline{A_o-A_f}$

 A_{o}

Where A_f is the final cross sectional area at the fracture surface

Example 8.4

The gauge length of a metal alloy of diameter 0.01283 is 0.05080m. Calculate the ductility of the alloy if the final length and final diameter are 0.05575m and 0.010011m respectively.

Solution

% Elongation =
$$\underline{L}_{\underline{f}}$$
-Lo x 100 = $\underline{0.05575} - \underline{0.0508}$ x 100
L₀ 0.0508 = 9.75%

% Reduction in Area =
$$\underline{A_o - A_f}$$
 x 100 = $\pi (0.01283)^2 / 4 - \pi (0.010011)^2 / 4$
 A_o $\pi (0.01283)^2 / 4$ = 39.11%

Example 8.5 A cylinder tensile specimen of original gauge length 50 mm and diameter 12.0 mm is pulled in tension until it fractures. The final (fractured) gauge length is 70.5 mm and the diameter at the fracture surface is 6.50 mm. Calculate the ductility in terms of (a) percent elongation and (b) percent reduction in area.

Solution

- $L_o = 50 \text{ mm}, L_f = 70.5 \text{ mm}, d_o = 12.0 \text{ mm}, d_f = 6.50 \text{ mm}$
- (a) Percent elongation = $\frac{l_f l_0}{l_o} \ge 100\% = \frac{70.5 50}{50} \ge 100\% = 41\%$

(b) Percent reduction in area
$$=\frac{d_0^2 - d_f^2}{d_0^2} \ge 100 \left(1 - \frac{d_f^2}{d_0^2}\right) \ge 100$$

 $= \left[1 - \left(\frac{6.50}{12.0}\right)\right] \ge 100 = 71\%$

Note: The ductility larger in the case of reduction in area because of substantial local deformation due to necking. If the specimen fails without necking, the two values should be identical

8.4 Toughness or Impact Resistance

It is the ability of material to absorb energy and gets plastically deformed without fracturing i.e to resist being shatter when subjected to an impact load. It is the ability to hinder the spread of surface cracks from occurring or only occurs to a limited extent. Its numerical value is determined by the amount of energy per unit volume. It unit is Joule/ m³. Value of toughness of a material can be determines by stress-strain characteristics of material. For good toughness, material should have good strength as well as ductility. For example: brittle materials, having good strength but limited ductility are not tough enough. Conversely, materials having good ductility but low strength are also not tough enough. Therefore, to be tough, material should be capable to withstand both high stress and strain.

In the test, heavy pendulum is allowed to swings from its high elevation, \mathbf{h}_{0} , through its arc to strike and break the test piece at its lower final elevation \mathbf{h}_{f} . By knowing the initial and final elevation of the pendulum, the difference in potential energy can be calculated. This energy difference is called the impact energy and it is the energy required to fracture a standard test piece when the load is suddenly applied.

Many test procedures have been devised but the two most common ones are those of **charpy and Izod**. The test piece may be either notched or unnotched; the v- notched pieces being used to measure the resistance of the material to crack propagation.

The type of failure which occurs depends on a numbers of factors, such factors include:

- a) The nature of the material and its metallurgical condition
- b) The type of stressing c) The rate of stressing
- d) Temperature e) Environment

For example at high temperature, a material behaves in a ductile manner with extensive deformation and stretching of the test piece prior to failure, but on low temperature, the material is brittle and little deformation at the point of fracture is observed. The transition temperature is the temperature at which the material changed from ductile to brittle fracture.

8.5 Fatigue

Fatigue is the measure of the weakening or failure of material caused by the repeated loading of material. When a material is subjected to cyclic loading, and loading greater than certain threshold value but much below the strength of material (ultimate tensile strength limit or yield stress limit,

microscopic cracks begin to form at grain boundaries and interfaces. Eventually the crack reached to a critical size. This crack propagates suddenly and the structure gets fractured. The shape of structural effect of fatigue varies much. Square holes and sharp corners lead to elevated stresses where the fatigue crack initiates.

8.5.1 Fatigue Test

The fatigue test measures the resistance of a material to failure when a stress below the yield strength is repeatedly applied. The fatigue life or endurance is the number of stress cycles to failure usually stated as a decimal proportional or multiple of 10^8 .

This can be measured by subjecting a load –bearing specimen material to rotation. Initially, the upper half portion of the specimen is in compression while the other half or lower part is in tension. Upon rotating through 180°, the part which was originally in compression will now be in tension and vice versa. The stress at any point within the sample thus cycles from a positive value through zero to a negative and back to positive value. For a given stress, the number of cycles required to cause failure is counted. Several samples will be tested at different stress amplitudes and the results are displayed as a plot of stress amplitude (S) against number of cycles to failure (N). The curve thus obtained in refer to as S-N for the material

The fatigue or endurance limit is the value of the stress below which a material may withstand an infinite number of stress cycles.

Fatigue testing usually involves the application of an alternating stress cycles with a mean stress value of zero. A common method to measure the resistance to fatigue is the rotating cantilever beam. Test the result of fatigue is summarized as S-N curve which has a form.

8.5.2 Factors Affecting Fatigue Strength

Fatigue failure is influenced by a number of engineering and metallurgical factors, some of which are:

- a) Mean stress: Majority of engineering applications usually involve a mean stress which is not zero contrary to what obtains in a fatigue testing. As the mean stress is increased in tension, fatigue limit is increased and the endurance limit decreased.
- b) Surface Finish: A smooth surface is essential for high fatigue strength and test pieces for fatigue testing are usually polished. Scratches result in easy formation of fatigue cracks and lead to lower resistance to fatigue while ground surface gives a significantly lower limit or fatigue.

- c) Component Design: Care must be taken in design to avoid sharp changes in section because these act as stress raisers from which fatigue cracks start.
- d) Surface Treatment: Fatigue cracks are normally initiated at the surface, thus surface hardening e.g nitriding, cold working influence the fatigue life. The effect of surface hardening is to introduce residual compressive stresses into the surface and so to improve fatigue life.
- e) The presence of Inclusions: Non metallic inclusions at or near the surface may act as starting points for cracks and hence reduce the fatigue life.
- f) Temperature: Lowering the temperature below that of the atmosphere usually increases the fatigue limit. It is however difficult to generalize on the effect of temperature increase because of the possibility of structural changes in the material.
- **g) Environment:** Presence of an aggressive environment may cause small corrosion pits on the surface and these act as points of stress points and thus starting for fatigue cracks.

8.6 Creep and Slip

Creep is the property of material which indicates the tendency of material to move slowly and deform permanently under the influence of external mechanical stress. It results due to long time exposure to large external mechanical stress with in limit of yielding. Creep is more severe in material that are subjected to heat for long time. Slip in material is a plane with high density of atoms.

8.6.1 Creep Test

It measures the resistance of a material to deformation and failure when subjected to at static load below the yield strength at an elevated temperature

Most creep testing uses tensile stressing of a conventional tensile test piece. The test pieces are enclosed in electric resistance tube type furnace which are accurately maintained a fixed temperature over long period of taken by the test. During the test, the strain or elongation is measured as a function of time and plotted. The time required for failure to occur is the rupture time which is the indicates the time required for a test piece to fail by creep at a particular temperature and stress.

Creep is important in the following applications:

a) Soft metals used at about room temperatures e.g. lead pipes and white metal bearings.

b) Plant operating at high temperatures e.g. furnace equipment, gar turbines steam and chemical processing plant.

8.7 Malleability: Malleability is property of solid material which indicates how easily a material gets deformed under compressive stress. It is often categorized by the ability of material to be formed in the form of a thin sheet by hammering or rolling. This mechanical property is an aspect of plasticity of material. Malleability of material is temperature dependent. With rise of temperature, the malleability of material increases.

8.8 Elasticity: This is the ability of a material to deform under load and return to its original size and shape when the load is removed.

8.9 Plasticity: This property is the exact opposite of elasticity. It is the state of a material which has been loaded beyond its elastic state. Under a load beyond that required to cause elastic deformation (the elastic limit) a material possessing the property of plasticity deforms permanently. It takes a permanent set and will not recover when the load is removed.

8.10 Resilience: Resilience is the ability of material to absorb the energy when it is deformed elastically by applying stress and release the energy when stress is removed. Proof resilience is defined as the maximum energy that can be absorbed without permanent deformation. The modulus of resilience is defined as the maximum energy that can be absorbed per unit volume without permanent deformation. It can be determined by integrating the stress-strain cure from zero to elastic limit. Its unit is joule/m³.

8.11 Brittleness: Brittleness of a material indicates how easily it gets fractured when it is subjected to a force or load. When a brittle material is subjected to a stress, it absorbs very less energy and gets fractures without significant strain. Brittleness is converse to ductility of material. Brittleness of material is temperature depended. Some metals which are ductile at normal temperature become brittle at low temperature.

Exercise 1: In a single tensile test of a 0.01283 in diameter of Al alloy test bar, the force 453.6kg was applied to the bar of initial gauge length of 0.0508m. at the end of the test, the stress and engineering strain.

Exercise 2: A strain of 8.89 x 10^{-5} m/m is produced in an Al alloy when a stress of 2.41 x 10^{8} N/m² is applied. Calculate the modulus of elasticity and use it to determine the length of a 1.27m bar to which a stress of 2.07 x 10^{8} N/m² is applied.

Exercise 3: An aluminium alloy plate of cross-section 25 mm by 3 mm is subjected to a tensile load. Taking the yield strength of the alloy as 40 MPa and its modulus of elasticity as 70 GPa, determine (a) the maximum load that the plate can withstand without permanently deforming (b) the strain in the plate under this load.

Exercise 4: A steel wire with yield strength of 500 MPa and tensile strength of 800 MPa is loaded in tension. What is the minimum diameter of the wire if it is to withstand a load of (a) 100 KN without plastic deformation? (b) 120 KN without fracturing? (Assume uniform deformation until fracture).

Exercise 5: A steel rod of diameter 2.5 cm deforms elastically under a tensile load of 4,500 N. Calculates the diameter of an aluminium rod which will produce the same elastic strain in both materials under the same load. [$E_{steel} = 205$ GPa, $E_{Al} = 70$ GPa]

CHAPTER NINE

PHYSICAL PROPERTIES OF MATERIALS

For a material to be suitable for an engineering product or application, we should have the knowledge of **physical properties of materials**. The physical properties of a material are those which can be observed without change of the identity of material. Some of these typical properties of a material include:

1. Density	2. Specific gravity	3. State Chang	e temperatures
4. Coefficients of	of thermal expansion	5. Specific Hea	at 6. Latent heat
7. Fluidity	8. Weld ability	9. Elasticity	10. Plasticity
11. Porosity	12. Thermal conduct	tivity 13. Ele	ctrical Conductivity

1. Density of Materials: This is defined as "the mass per unit volume". It is represented as the ratio of mass with volume of a material. It is denoted by " ρ ". Its unit in SI system is Kg/m³. If, m is the mass of material in Kg, V is the volume of material in meter³. Then the Density of

 $\rho = \frac{m}{V} \ Kg/m^3$

material is:

- 3. **State Change Temperatures:** Generally a substance is having three states called solid state, liquid state and gaseous state. State change temperature is the temperature at which the substance changes from one state to another state. They are of following types:
- 1. Melting point It is the temperature (in °C or K) at which the substance changes from solid state to liquid state.
- 2. Boiling point It is the temperature (in °C or K) at which the substance changes from liquid state to gaseous state.
- 3. Freezing point It is the temperature (in °C or K) at which a liquid changes from liquid to solid state.

4. Coefficient of Thermal Expansion: When a material is heated, it expands due to which its dimensions change. Coefficient of thermal expansion represents the expansion in material with increase of temperature. They are of three types:

a). Coefficient of Linear Thermal Expansion: This is change in length of an object due change in temperature. It is denoted by " α_L "

$$\alpha_L = \frac{\Delta l}{l \times \Delta t}$$
 Unit of α_L is per °C.

Where: 'l' is the initial length of object, ' Δ l' is the change in length, ' Δ t' is the change in the temperature.

b). Coefficient of Area Thermal Expansion: This is change in area of an object due change in temperature and is related by " αA "

$$\alpha_A = \frac{\Delta A}{A \times \Delta t}$$
 Unit of α_A is per °C

Where: 'A' is the initial area of object, ' Δ A' is the change in area, ' Δ t' is the change in the temperature.

c). Coefficient of Volume Thermal Expansion: This is change in volume of an object due change in temperature which is related by " α_V "

$$\alpha_V = \frac{\Delta V}{V \times \Delta t}$$
 Unit of α_A is per °C

Where: 'V' is the initial volume of object, ' Δ V' is change in volume, ' Δ t' is the change in temperature.

5. Specific Heat of Materials: This is defined as the amount of heat required to increase the temperature of unit mass of material by 1°C. It is denoted by 'S'

$$S = \frac{Q}{m \cdot \Delta t}$$
 Unit of specific heat in SI system is, Joule/Kg °C

Where: 'm' is the mass of material in Kg. 'Q' is the amount of heat given to material in Joule. ' Δt ' is rise in temperature.

6. Latent Heat of Materials: It is defined as the amount of heat required / released due to change in the unit mass of material from one state to another state (Phase change). It is denoted by 'L'.

and is given by:
$$L = \frac{Q}{m}$$
 Unit of Latent heat in SI system is Joule / Kg.

Where, 'Q' is the amount of heat required/released by material (J), 'm' is mass of material (Kg).

- 7. Fluidity of Materials: It is a property of material which represents how easily a material can flow in liquid state. It is the reciprocal to viscosity of a liquid material.
- 8. Weld-ability of Materials: It is the property of a material which presents how easily the two pieces of the material can be welded together by applying pressure or heat or both.
- **9. Elasticity of Materials:** It is the property of a material by which it regains its original dimensions on removal of load or force.
- **10. Plasticity of Materials:** When we keep on increasing the load beyond limit of elasticity material retains it molded state. This property of material is called plasticity.
- 11. **Porosity of Materials:** When a material is in melting condition, it contains some dissolved gases within it. When the material solidifies, these gases get evaporated and leave behind voids. The Porosity of material represents the quantity of voids in solid materials.
- 12. Thermal Conductivity of Materials: It is the property of a material which represents how easily heat can be conducted by the material. It can be defined as "the amount of heat transmitted by unit thickness of material normal to the unit surface area in unit time when the temperature gradient across the material piece is unity in steady state condition. Its unit in SI system is watts per meter per °K.
- 13. Electrical Conductivity of Materials: It is the property of material which represents how easily it can conduct electricity and is denoted by ' σ '. It is the reciprocal of <u>resistivity</u> of material. Its unit is ohm-meter.

CHAPTER TEN

10.1 SELECTION OF MATERIAL FOR ENGINEERING APPLICATION

For every engineering product, the quality, performance and life span are affected by the engineering material being used for manufacturing that product. Hence it becomes necessary to select suitable engineering materials for a successful engineering product. For selection of suitable materials for any engineering application / product, the following factors should be considered –

1. Mechanical strength	2. Stability	3. Ductility	4. Availability
5. Fabricability	6. Design	7 Corrosion Resig	stance 8. Cost

- Mechanical Strength: Mechanical strength is primary criteria for selection of suitable materials for any Engineering application/product. Mechanical strength is the ability of materials to withstand with load or forces. Materials selected for any engineering application, should have appropriate mechanical strength to be capable to withstand with loads or forces developed in structure of engineering product during operation.
- 2. **Stability:** Stability of engineering material is defined by the ability of engineering product manufactured by using that material to with stand with following operating conditions-
- a. Temperatureb. Fluctuations in temperaturec. During of operationd. Radiatione. Atmospheric conditions
- 3. **Ductility:** Ductility of engineering material is the property of material makes the material suitable for fabrication by rolling, drawing, extrusion and other mechanical processes. Basically it is the ability of material that how much the materials can be stretched plastically without breakdown or failure. Ductility of materials is related to the strength of material. Considerable ductility can be obtained at a sacrifice of strength or vice versa. For example, by increase of temperature ductility of material increased and strength decreased. By cold rolling the mechanical strength is increased whereas the ductility is decreased. It is not necessary the material being used for all product should have high ductility.

- 4. Availability: Material selected for engineering product should be easily available in desired form and at appropriate cost. So that the product can be produced economically to make its price competitive in market. Material may be available in any form such as casting, forging, rolled sheets etc. But the availability of material in suitable form is necessary to facilitate the manufacturing the product with desired quality.
- 5. Fabricability: Fabricability of an Engineering material is the ability of material, which indicates that how easily it can be fabricated in desired form and shape in order to manufacture an engineering product. Fabricability of material makes it suitable for mechanical processing to convert it in desired form and shape.
- 6. Design: The selection of material for any engineering product is also governed by the design of product. The design of engineering product decides the strength and ductility required for in materials being selected for that product. Hence, the engineering product should be designed with consideration of properties of engineering material.
- 7. Corrosion Resistance: When the Engineering product is used in an industrial atmospheric environment, there are chances that the base materials of product gets corroded. Corrosion of refined material is a natural process which converts the refined material in more stable oxides. This corrosion makes the material gradually weak with time. Hence, for the satisfactory operation, performance and life of engineering product, it becomes necessary that material being selected for that product should have sufficient corrosion resistance.
- 8. **Cost:** To make the engineering product commercially successful and profitable, its price should be reasonable and competitive in market. The price value of any engineering product is governed by many factors such as material cost, labour cost, processing cost etc. Hence, the keep the price of product low, it becomes necessary that the material cost, labour cost and processing cost should by as minimum as possible. Therefore, the cost of engineering material selected for engineering product must be low.

10.2

DIFFERENCE BETWEEN METALS AND NON METALS

SI.	Property	Metals	Non-Metals
No.			
1.	Structure	All metals are having crystalline	All Non-metals are having amorphic &
		structure	mesomorphic structure
2.	State	Generally metals are slid normal	State varies material to material. Some
		temperature	are gas state and some are in solid state
			at normal temperature.
3.	Valance	Valance electrons are free to	Valence electrons are tightly bound with
	electrons and	move within metals which makes	nucleuses which are not free to move.
	conductivity	them good conductor of heat &	This makes them bad conductor of heat
		electricity	& electricity
4.	Density	High density	Low density
5.	Strength	High strength	Low strength
6.	Hardness	Generally hard	Hardness is generally varies
7.	Malleability	Malleable	Non malleable
8.	Ductility	Ductile	Non ductile
9.	Brittleness	Generally non brittle in nature	Brittleness varies material to material
10.	Lustre	Metals possess metallic lustre	Generally do not possess metallic lustre
			(Except graphite & iodine)

10.3 ENGINEERING PROPERTIES OF POLYMERS AND WOOD

10.3.1 Engineering Properties of Polymers: Some of the useful properties of various engineering polymers are high **strength** or **modulus** to weight ratios (light weight but comparatively stiff and strong), **toughness**, resilience, resistance to corrosion, lack of **conductivity** (heat and electrical), color, transparency, processing, and low cost.

10.3.2 Engineering Properties of Wood: Physical properties refer to density and moisture relations that affect its use, while the mechanical properties refer to the strength characteristics of wood. Therefore generally, the properties include: strength, density, moisture content

Density: Wood is a porous material made up of cells of various kinds. Depending on the nature of these cells, some woods have more or less solid wood substance for a given sized piece.