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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – I – Fundamentals of Material Science – SMEA1201

1. Material Technology

Materials technology is a relatively comprehensive discipline that begins with the production of goods from raw materials to processing of materials into the shapes and forms needed for specific applications.

Materials - metals, plastics and ceramics - typically have completely different properties, which mean that the technologies involved in their production are fundamentally different. Materials technology is a constantly evolving discipline, and new materials with interesting properties lead to new applications. For example, the combination of different materials into composites gives rise to entirely new material properties.

1.1 Material Science

Materials Science is closely related to materials technology. Materials Science is a multidisciplinary field that connects material properties to the material's chemical composition, micro-structure and crystal structure. Crystal structure is a description of the ordered arrangement of atoms, ions or molecules in a crystalline material. The crystalline lattice, is a periodic array of the atoms. When the solid is not crystalline, it is called amorphous. Examples of crystalline solids are metals, diamond and other precious stones, ice, graphite. Examples of amorphous solids are glass, amorphous carbon (a-C), amorphous Si, most plastics

1.2. Polymorphism and Allotropy

Some materials may exist in more than one crystal structure, this is called polymorphism. If the material is an elemental solid, it is called allotropy. An example of allotropy is carbon, which can exist as diamond, graphite, and amorphous caCrystallography

Crystallography, branch of science that deals with discerning the arrangement and bonding of atoms in crystalline solids and with the geometric structure of crystal lattices.

1.3. Crystalline and Amorphous Solids

The atoms, molecules or ions which make up solids may be arranged in an orderly repeating pattern, or irregularly.

Crystalline, if long-range ordering exists.

I. Single Crystal: long-range order in the entire volume. A single-crystal, or monocrystalline, solid is a material in which the crystal lattice of the entire sample is continuous and unbroken to the edges of the sample, with no grain boundaries. (e.g. quartz).

II. Polycrystalline: long-range order within grains but orientation differs. Polycrystalline materials, or polycrystals, are solids that are composed of many crystallites of varying size and orientation. Most inorganic solids are polycrystalline, including all common metals, many ceramics, rocks, and ice.

III. Almost all common metals, and many ceramics, are polycrystalline.

IV. Amorphous, if short-range ordering exists.(e.g. glass). In condensed matter physics and materials science, an amorphous or non-crystalline solid is a solid that lacks the long-range order that is characteristic of a crystal.

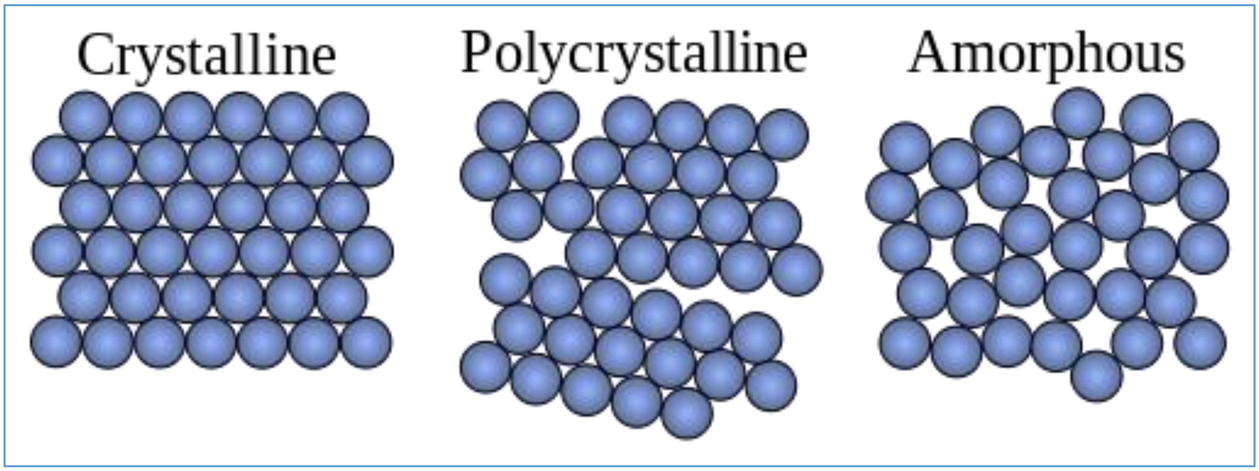


Fig 1.1: Crystalline and amorphous maaterials

1.4. Crystal Geometry

Crystal: A 3D Periodic arrangement of atoms in space. Ex:NaCl shown in figure

Lattice: 3D Periodic arrangement of points in space. Geometrical concepts can be applied.

Motif or Basis: An atom or a group of atoms associated with each lattice point. Physical object possessing properties like weight, density, conductivity etc.

Lattice translation: A lattice translation operator is defined as a displacement of a crystal with a crystal translation operator.

UnitCell: The unit cell completely reflects the symmetry and structure of the entire crystal, which is built up by repetitive translation of the unit cell along its principal axes.

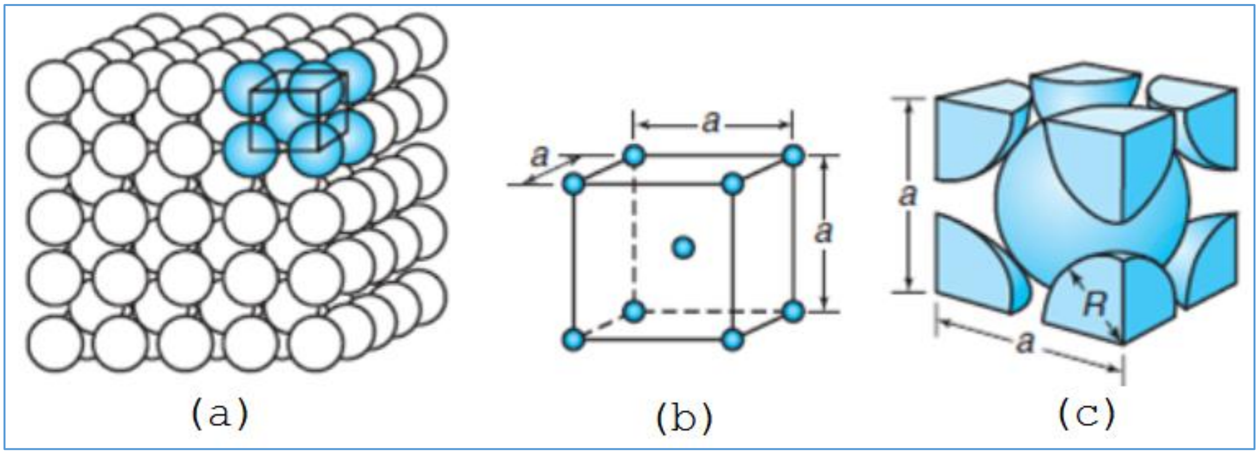


Fig 1.2: (a) Single Crystal with many unit cells; (b) Unit Cell; (c) Hard-ball Model

Primitive Cell: A primitive cell is a unit cell that contains exactly one lattice point. Non-primitive unit cells contain additional lattice points, either on a face of the unit cell or within the unit cell, and so have more than one lattice point per unit cell.

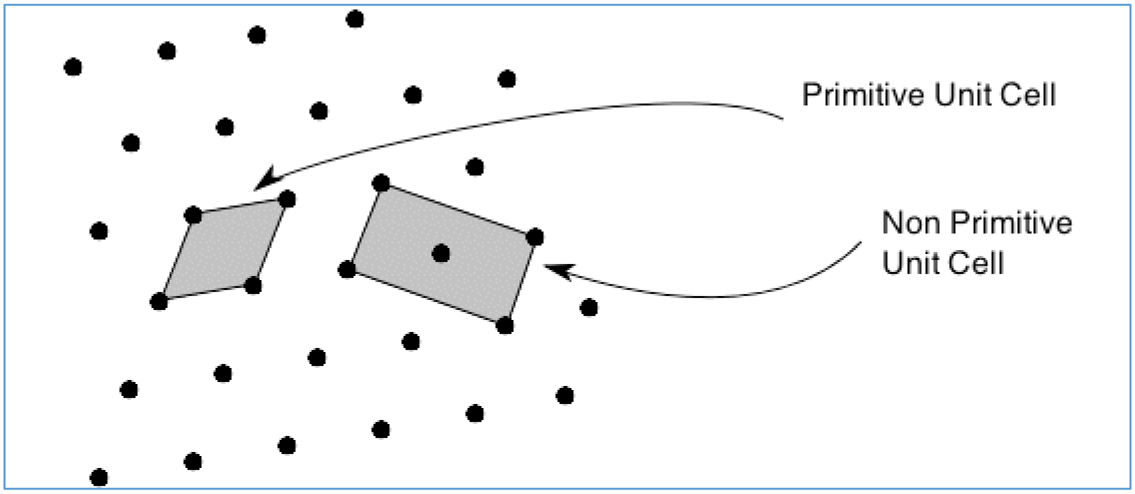


Fig 1.3: Primitive and non-primitive unit cells

Crystal Coordinate system: Select a corner of the unit cell as the origin, the vectors from the corner along the edges of the unit cell define basis vectors of the lattice.

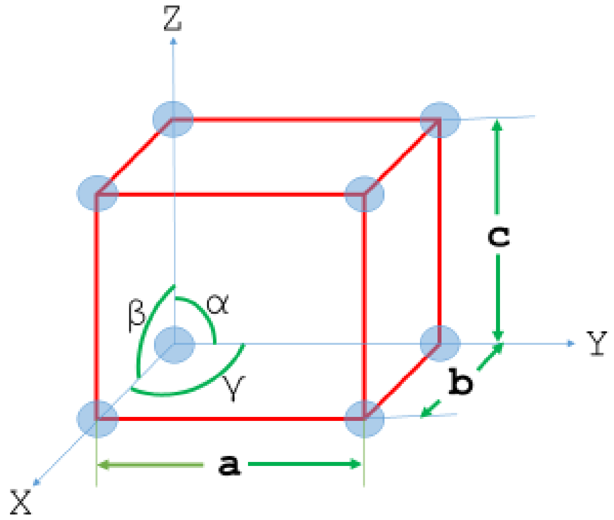


Fig 1.4: Coordinate systems and lattice parameters

The length of 3 edges of the unit cell (or of the 3 basis vectors) and the 3 interaxial angles between them are called the lattice parameters.

a, b, c

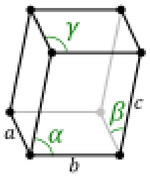
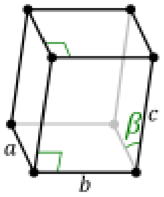
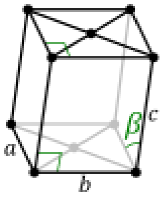
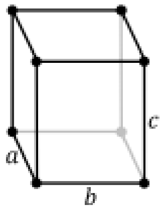
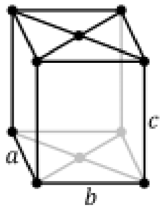
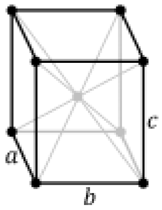
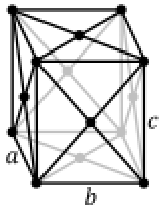
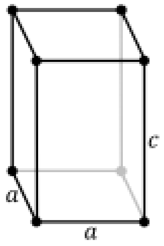
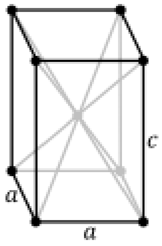
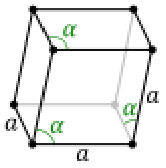
Γ = angle b/w x & y

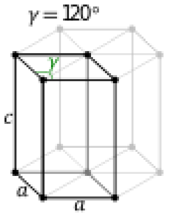
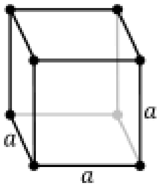
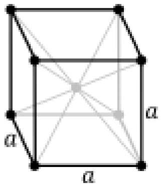
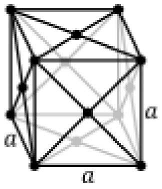
B = angle b/w x & Z

α = angle b/w x & Y

For the special case of simple cubic crystals, the lattice vectors are orthogonal and of equal length (usually denoted a); similarly for the reciprocal lattice. So, in this common case, the Miller indices (ℓmn) and [ℓmn] both simply denote normals/directions in Cartesian coordinates.

1.5. Classification of Braivais Lattices

Crystal family	Lattice system	14 Bravais Lattices			
		Primitive	Base-centered	Body-centered	Face-centered
triclinic					
monoclinic					
orthorhombic					
tetragonal					
hexagonal	rhombohedral				

	hexagonal				
cubic					

1.6. Atomic packing factor

Atomic Radius: It is the half the distance between two nearest atoms in a crystal.

Coordination Number or Kissing Number: It is the maximum number atoms that can touch a given atom.

Number of atoms per unit cell: It is the product of (the number of atoms per lattice point) and (the number of lattice points per unit cell).

Atomic Packing Factor (APF):

$$\text{APF} = \frac{\text{Volume of atoms in a unit cell}}{\text{Volume of the unit cell}} \text{ (or)}$$

$$\text{APF} = \frac{\text{No. of atoms in a unit cell x Volume of } sphere}{\text{Volume of the unit cell}}$$

1.7. Atomic Packing Factor for simple cubic

For a simple cubic packing, the number of atoms per unit cell is one. The side of the unit cell is of length 2*r*, where *r* is the radius of the atom.

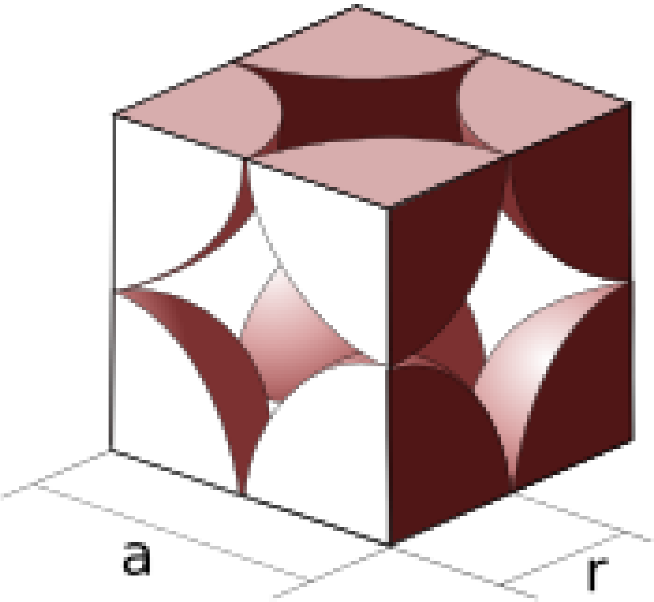


Fig 1.5: Simple cubic model

Number of atoms per unit cell: = (8 corner atoms)$\left(\frac{1}{8}\right)$ = 1

Relationship between atomic radius (r) and lattice constant (a): r = $\frac{a}{2}$

$$\text{APF} = \frac{\text{No. of atoms in a unit cell x Volume of } sphere}{\text{Volume of the unit cell}} = \frac{1\left(\frac{4}{3}\right)\pi r3}{\text{a}3} \qquad = \frac{1\left(\frac{4}{3}\right)\pi\,(\frac{a}{2})3}{(\text{a})3}$$

$$= 1\,\left(\frac{4}{3}\right)\pi\,\left(\frac{1}{8}\right) = \frac{\pi}{6} = 0.52$$

1.8. Body centered cubic

The primitive unit cell for the body-centered cubic crystal structure contains several fractions taken from nine atoms (if the particles in the crystal are atoms): one on each corner of the cube and one atom in the center. Because the volume of each of the eight corner atoms is shared between eight adjacent cells, each BCC cell contains the equivalent volume of two atoms (one central and one on the corner).

Number of atoms per unit cell: = (8 corner atoms)$\left(\frac{1}{8}\right)$ + (1 centre atom) = 1 + 1 = 2

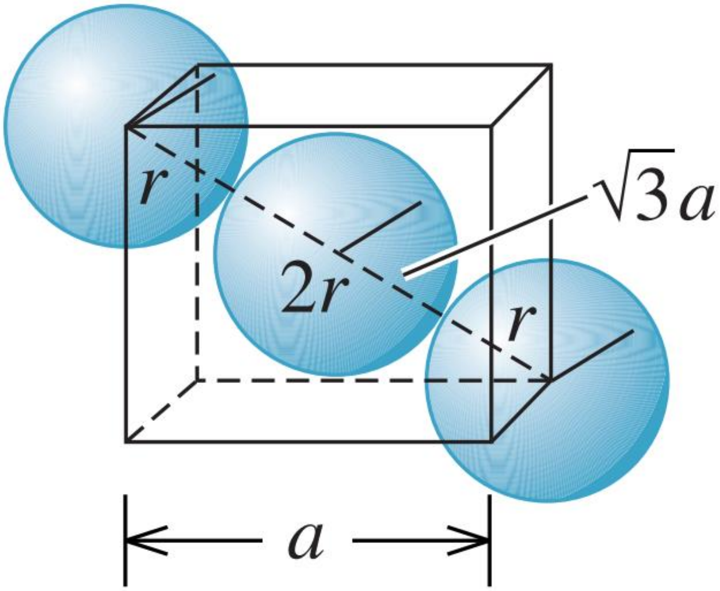


Fig 1.6: BCC structure

Relationship between atomic radius (r) and lattice constant (a):

$\text{AC}^2 \;=\; (AB2 + BC2) \;=\; (a)2 + (a)2 = 2\text{a}^2$

$\text{DC}^2 \;=\; (DA2 + AC2) \;=\; (a)2 + (2a)2 = 3\text{a}^2$

$\text{DC} = \text{a}\sqrt{3} \;= 4\text{r}$

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

$$\text{APF} = \frac{\text{No. of atoms in a unit cell x Volume of } sphere}{\text{Volume of the unit cell}} = \frac{2\left(\frac{4}{3}\right)\pi r3}{\text{a3}} = \frac{2\left(\frac{4}{3}\right)\pi\,(\frac{a\sqrt{3}}{4})3}{\text{a3}}$$

$$= 2\left(\frac{4}{3}\right)\pi\,(\frac{3\sqrt{3}}{64}) \;= \frac{\pi\sqrt{3}}{8} = 0.68$$

1.9. Atomic packing factor for FCC

Number of atoms per unit cell: $=(8 \text{ corner atoms})\left(\frac{1}{8}\right) + (6 \text{ Face-centre atoms})\left(\frac{1}{2}\right) \;= 1 + 3 = 4$

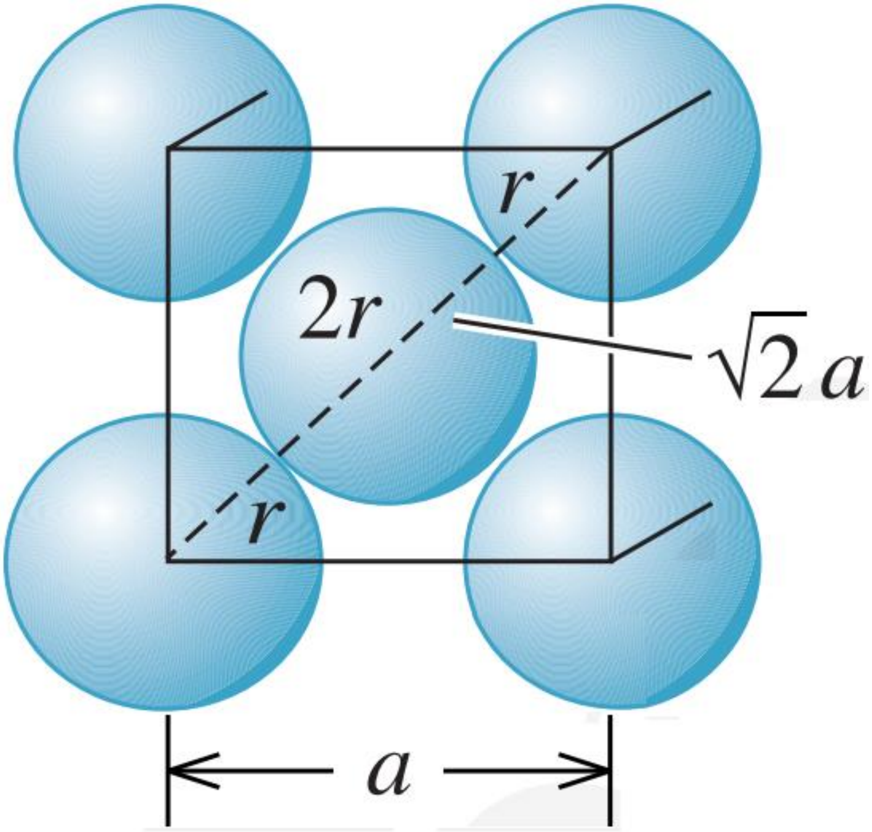


Fig 1.7: FCC structure

Relationship between atomic radius (r) and lattice constant (a):

$$AC^2 = (AB2 + BC2) = (a)2 + (a)2 = 2a^2$$

$$AC = a\sqrt{2} = 4r$$

$$r = \frac{a\sqrt{2}}{4}$$

$$APF = \frac{\text{No. of atoms in a unit cell x Volume of } sphere}{\text{Volume of the unit cell}} = \frac{4\left(\frac{4}{3}\right)\pi r3}{a3} = = \frac{4\left(\frac{4}{3}\right)\pi\,(\frac{a\sqrt{2}}{4})3}{(a)3}$$

$$= 4\left(\frac{4}{3}\right)\pi\,(\frac{2\sqrt{2}}{64}) = \frac{\pi\sqrt{2}}{6} = 0.74$$

1.10. Hexagonal Close Packed Structure

For the hexagonal close-packed structure the derivation is similar. Here the unit cell (equivalent to 3 primitive unit cells) is a hexagonal prism containing six atoms (if the particles in the crystal are atoms). Indeed, three are the atoms in the middle layer (inside the prism); in addition, for the top and bottom layers (on the bases of the prism), the central atom is shared with the adjacent cell, and each of the six atoms at the vertices is shared with other five adjacent cells. So the total number of atoms in the cell is 3 + (1/2)×2 + (1/6)×6×2 = 6. Each atom touches other twelve atoms. The latter is twice the distance between adjacent layers, i. e., twice the height of the regular tetrahedron whose vertices are occupied by (say) the central atom of the lower layer, two adjacent non-central atoms of the same layer, and one atom of the middle layer "resting" on the previous three.

$$\text{APF} = \frac{\text{No. of atoms in a unit cell x Volume of } sphere}{\text{Volume of the unit cell}}$$

$$= \frac{6\ \left(\frac{4}{3}\right)\pi r3}{\text{a3}} \qquad = \frac{6\left(\frac{4}{3}\right)\pi\ (\frac{a}{2})3}{(\frac{3\sqrt{3}}{2})\text{a}^2\text{c}}$$

$$= \frac{16\ \pi\ a3}{8\ x\ 3\sqrt{3}\ a2x\ 1.633a}$$

$$= \frac{2\ \pi}{3\sqrt{3}\ x\ 1.633} = 0.74$$

1.11. Allotropy

Allotropy is the property of some chemical elements to exist in more than one type of space lattice in the solid state.

Solid solution: A homogeneous mixture of two or more solid elements. Vary in composition. Has the crystal structure of one of the constituent elements. Intermediate alloy phase or compound

Compounds formed by atoms or ions of two or more elements by strong bonding, similar like pure metals. Definite composition, which is intermediate between the pure elements. Has the crystal structure different from the constituent elements.

1.12. Diffusion

Diffusion is a process of mass transport by atomic movement under the influence of thermal energy and a concentration gradient. Atoms move from higher to lower concentration region. If this movement is from one element to another e.g. Cu to Ni, then it is termed *inter-diffusion*. If the movement is within similar atoms as in pure metals, it is termed *self-diffusion*.

Diffusion of atoms involves movement in steps from one lattice site to the another. An empty adjacent site and breaking of bonds with the neighbor atoms are the two necessary conditions for this.

Vacancy Diffusion: This mechanism involves movement of atoms from a regular lattice site to an adjacent vacancy. Since vacancy and atoms exchange position, the vacancy flux is in the opposite direction.

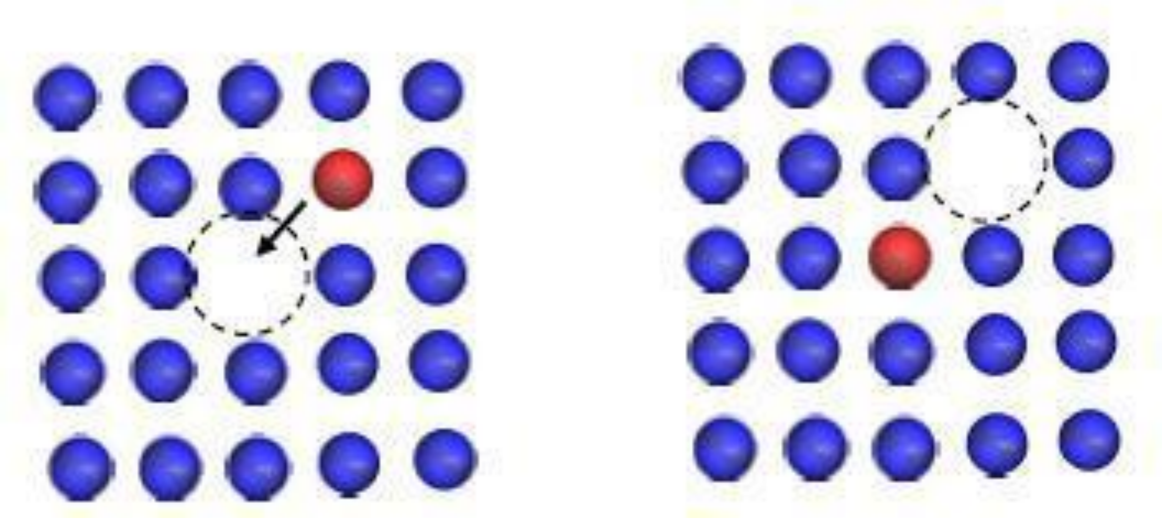


Fig 1.8: Vacancy diffusion

Interstitial Diffusion: This mechanism involves migration of atoms from one interstitial site to a neighbouring empty interstitial site. This mechanism is more prevalent for impurity atoms such as hydrogen, carbon, nitrogen, oxygen which are small enough to fit in to an interstitial position. For substitutional diffusion atoms exchange their places directly or along a ring (ring diffusion mechanism).

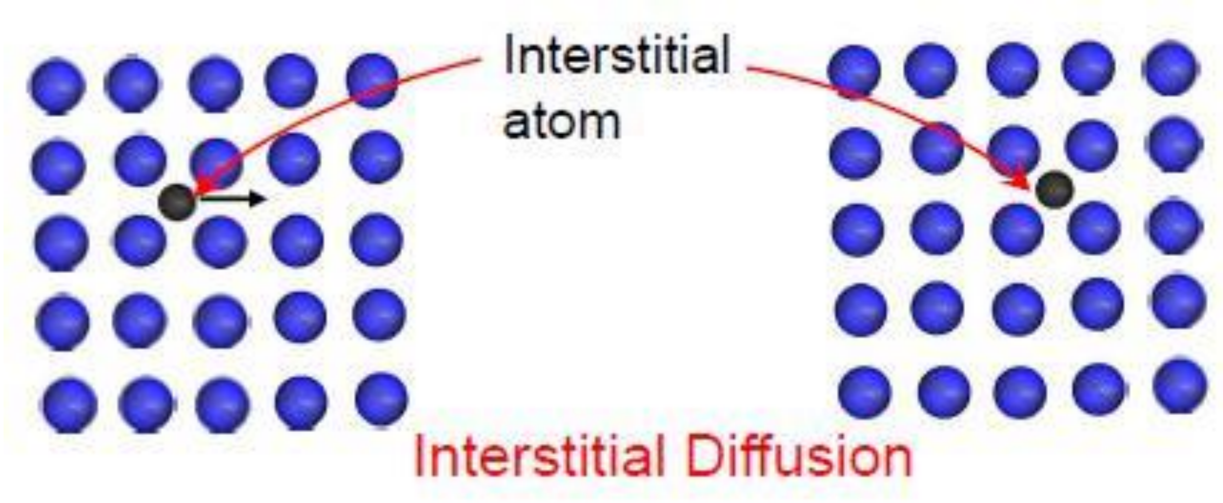


Fig 1.9: Interstitial diffusion

Inter Diffusion or Impurities Diffusion: Interdiffusion (or impurity diffusion) occurs in response to a concentration gradient.

1.13. The Phase Rule

The *Phase Rule* expresses the relation between phases, phase compositions, and intensive variables (temperature and pressure) in a system of a given composition at equilibrium.

System: A substance that are isolated from their surrounding. (e.g. Iron-Carbon System)

Component: Pure metals or compounds of which an alloy is made (Fe and C are the components, in Fe-C system).

Phase: A physically and chemically homogeneous portion of a system that has uniform physical and chemical characteristics (e.g. Solid, Liquid and Gas).

Equilibrium: A system is at equilibrium if its free energy is at minimum under some specified combination of temperature, pressure and composition.

State: It is a physical condition governed by quantities such as pressure, temperature, mass etc.

Degree of Freedom: Number of independent variables available to describe a state of the system.

Phase Diagram Graphical representations that show the phases in equilibrium present in the system at various specified compositions, temperatures, and pressures. Also known as equilibrium diagram. By the word 'equilibrium, we mean very slow heating and cooling rates are used to generate data for their construction. For any constitution point (x, T), a phase diagram answers: What are the phases present? What are the compositions of the phases? What are the relative amounts of phases?

1.14. Gibbs Phase Rule

The Gibbs phase rule describes the degrees of freedom available to describe a particular system with various phases and substances.

System: An assemblage of materials that is isolated in some manner from rest of the universe.
isolated system: one that does not exchange matter or energy with its surroundings.

Equilibrium: The lowest energy state of a system in which there is no tendency for a spontaneous change.

Metastable Equilibrium: state of a system which is not in its lowest energy state at the imposed conditions, but cannot spontaneously change due to high activation energy for change.

The Phase Rule is given by:

$F=C-P+2$, where

P - a phase is any portion of a system that is chemically and physically homogenous and can be mechanically isolated from any other portion of the system.
C -: minimum number of chemically distinct constituents necessary to describe the composition of each phase in the system.
“2” stands for temperature and pressure. Temperature (*T*) and pressure (*P*) are *intensive* parameters of a system. Intensive parameters do not depend on amount or mass. *Extensive* parameters (e.g., volume, number of moles) depend on mass.

F (degrees of freedom; variance): number of attributes of a system (*T*, *P*, phase composition) that can be changed independently without creating or destroying a phase, or ...
number of parameters (*T*, *P*, system composition) that need to be described to completely define the composition and identity of each phase.
F = 3 : trivariant
F = 2 : divariant
F = 1 : univariant
F = 0 : invariant
if F < 0 then there must be disequilibrium.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – II – Ferrous and Nonferrous Alloys – SMEA1201

2. Ferrous and Non Ferrous Alloys

2.1. The Iron–Iron Carbide (Fe–Fe3C) Phase Diagram

Solidification begins with nucleation and growth of crystals of iron at 1539°C. It is BCC (body centered cubic). At 1394°C it transforms into FCC (face centered cubic) structure. This is stable till 910°C where it again transforms into BCC. Each of these transformations appears as steps on the cooling curve. Apart from this there is another transformation which may not get detected by thermal analysis. This is the transformation from paramagnetic to ferromagnetic state. It occurs at 770°C. This is known as its Curie temperature. The property which is most sensitive to detect it, is magnetic permeability. The three different forms of iron are known as ferrite, stable until 910°C, austenite, stable from 910°-1394°C and ferrite, stable from1394°– 1539°C. Note that the BCC form of iron is known as ferrite. Therefore in order to distinguish between the two, the high temperature form is termed as delta ferrite. If carbon atoms are introduced into iron these are likely to occupy the interstitial sites because the atoms carbon are much smaller than those of iron atoms. The solubility of carbon in iron is a function of temperature and crystal structure.

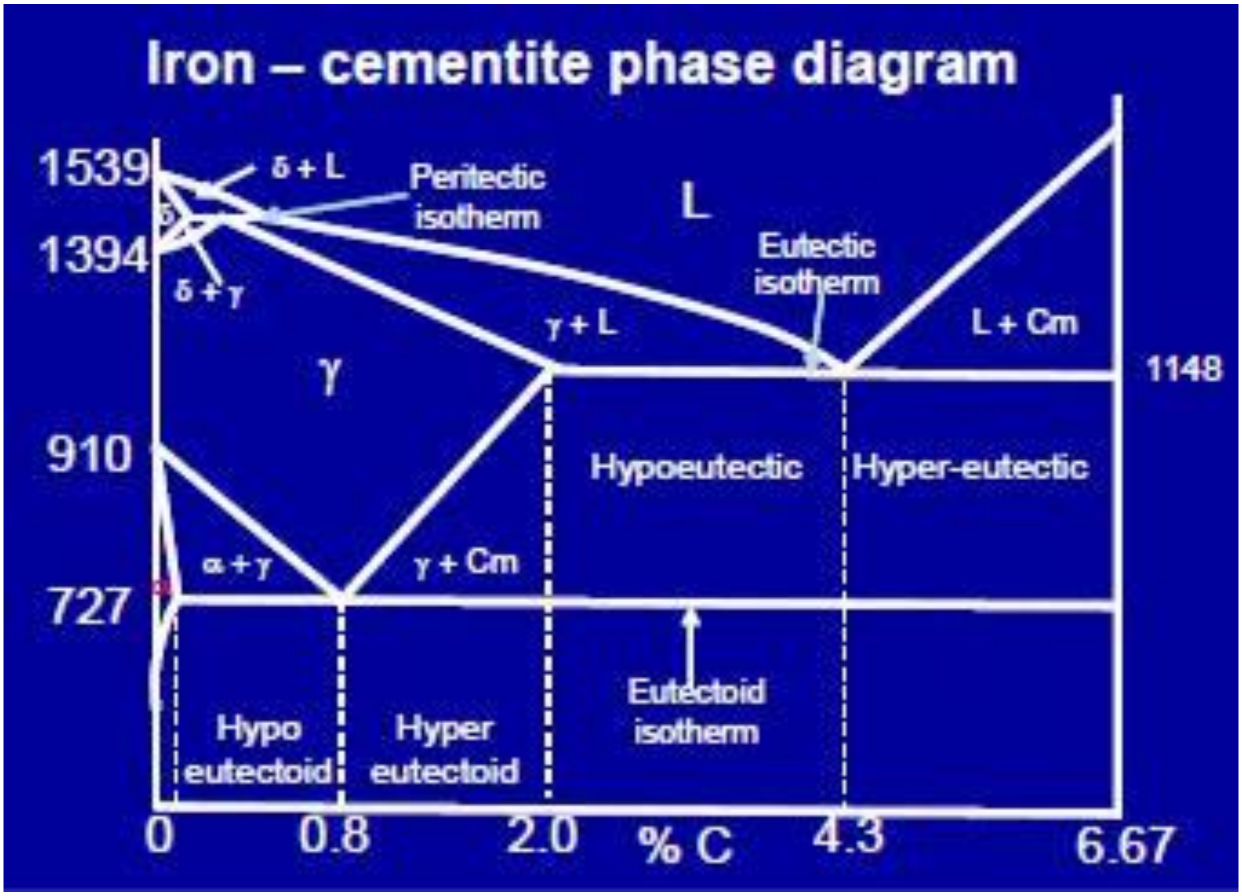

Fig 2.1: Phase diagram of Fe-Fe3C

Iron can exist in three different crystalline forms each having limited solubility of carbon. The stability of these depends on temperature and composition. The two high temperature forms of iron are ferrite which is BCC (stable above 1394°C) and austenite (stable above 910°C) which is FCC. The room temperature form of iron is ferrite which is BCC. The solubility of carbon in ferrite is limited. The maximum solubility is around 0.025wt% as against this the solubility of carbon in austenite is a little more. It is about 2wt%. Apart from this iron carbon system may have iron carbide (Fe3C) called cementite. It has 6.67% carbon. It is considered as an inter-metallic compound having relatively more complex crystal structure than those of ferrite and austenite. It is a meta-stable phase. It may exist for indefinite periods of time at room temperature. However on prolonged thermal exposure at 600°C or beyond it transforms into ferrite and graphite. Therefore iron carbon alloys of commercial importance may be considered as a binary alloy of iron and cementite. Let us first look at its phase diagram. It is also known as iron cementite meta-stable phase diagram. Although it is a binary system there are five different phases including the liquid. This is likely to have more than one invariant reaction involving three phases.

It has 3 invariant reactions (transformation). These are given in slide 4. The one occurring at 1495°C is the peritectic reaction. The delta ferrite reacts with liquid to form austenite. The one at 1148°C is known as the eutectic reaction where the liquid transforms into a mixture of austenite and cementite. The eutectic is known as Ledeburite. The one at 727°C is known as eutectoid transformation where austenite decomposes into a mixture of ferrite and cementite. This is known as Pearlite. On the basis of this diagram iron – carbon alloys having less than 2.0% carbon are known as steel, whereas those having more than 2.0% carbon are known as cast iron. This classification is based on their ability to undergo large plastic deformation. Steel is ductile but cast iron is brittle.

Steel:

It is an iron carbon alloy where most of the carbon is present as meta-stable iron carbide called cementite. The upper limit of carbon content is 2%. Phase diagram helps us guess the structure of alloys and their properties. Let us look at what kinds of structure steel could have depending on its composition. We would only consider the structure that develops under equilibrium rate of cooling. The steel on solidification is expected to have fully austenitic structure. It may be assumed to be homogeneous since the rate of cooling is considered to be slow. Depending on its composition we may have three types of structures. (i) % carbon < 0.02 (ii) 0.02 < % carbon < 0.8 (iii) 0.8 < % Carbon < 2.0.

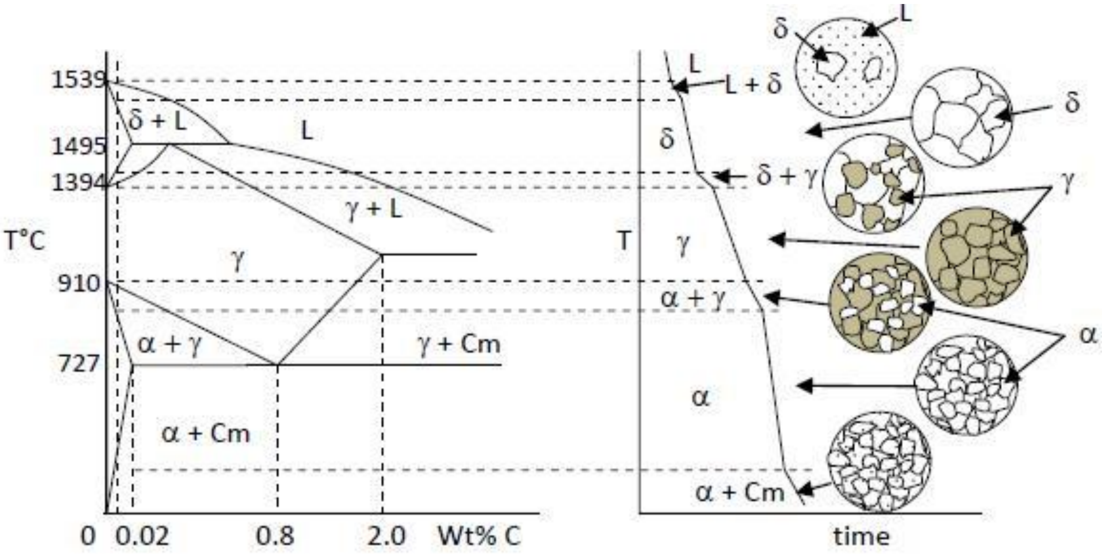

Fig 2.2: Phase formation

The above figure explains the solidification behavior of steel having less than 0.02% carbon with the help of schematic diagrams. The sketch on the left shows a part of the equilibrium diagram (Fe-Fe3C) with the location of the alloy by a vertical dotted line. It intersects the liquidus, solidus, and a set of solvus curves. These are projected on to the cooling curve shown on the right with the help of a set of horizontal lines. The cooling curve exhibits inflection points at each of these intersections. Solidification begins with precipitation of a few grains of δ ferrite. The top most microstructure corresponds to this stage. The solidification takes place by nucleation and growth. The composition of the liquid and the solid keeps changing during this stage. When solidification is complete the entire liquid is replaced by δ ferrite having the same composition as that of the alloy. This is shown by the second schematic structure from the top Figure. The structure remains unchanged until the temperature crosses the boundary between δ /δ + γ phase fields. Thereafter austenite precipitates from δ ferrite. The grain corners and boundaries are the preferred sites where grains of austenite nucleate. The third microstructure from the top in Figure represents its main features. It consists of grains of δ (white) and a few grains of γ (grey). There is partition of carbon between these two phases. Bulk of the carbon goes into austenite. The composition of the two keeps changing as the temperature drops. The volume fraction of γ increases at the cost of δ. When the %carbon in austenite becomes equal to that of the steel δ ferrite disappears. The structure now consists of 100% austenite. Note the main features of the fourth microstructure from the top in Figure. The grain size is finer than that of 100% δ ferrite. The structure remains as 100% austenite until the temperature drops below the line representing the boundary between γ and α + γ phase fields of the equilibrium diagram. This is where α ferrite starts precipitating from austenite. The grain boundaries and the grain corners are the preferred sites for precipitation. The fifth sketch from the top of Figure is a typical representation of its microstructure at this stage. Ferrite grains are shown as white and austenite grains are shown as grey. This continues through nucleation of new grains and growth of the existing ones until the temperature drops below the line between α + γ and α phase fields of the phase diagram. At this stage the structure is 100% ferrite (α). The 6th sketch in Figure is a typical representation of the microstructure. This remains unchanged till the temperature drops below the solvus. At this stage excess carbon precipitates as cementite. The last sketch in Fig 2 is a typical representation of its microstructure. The amount of cementite keeps increasing as the room temperature drops. It can be estimated by lever rule. From the phase diagram it is evident that the steel at room temperature would consist of ferrite with a few specks of cementite. If % carbon in the steel is 0.01 the amount of cementite is given by (0.01/6.67)x100 = 0.15%. The grains are relatively finer than that after solidification.

2.2. Cast Iron (C.I)

Cast Iron is the name applied to a family of high-carbon content Fe-C alloys, specifically, those containing more than 2.14 wt. % C. Generally, most cast irons fall within the 3.0 to 4.2 wt. % range. Many contain silicon. Many cast irons are strong, but also brittle. As such, they find uses as small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases, diesel engine casting.. There are four types of cast irons: gray, nodular, white, and malleable. Cast irons melt between ~ 1150oC and 1300oC; since this range is lower than for steels, they are easier to melt and cast than steels. Cast irons consists of varying amounts of ferrite, cementite (Fe3C), and graphite (C). In most cast irons, the carbon-rich phase is graphite, not cementite.

2.3. Gray Cast iron

Gray Cast iron contains 2.5 to 4.0 wt. % C and also 1.0 to 3.0 wt. % silicon. The Si promotes formation of graphite instead of cementite. Graphite is dispersed throughout a ferrite or pearlite matrix in the form of flakes. The graphite flakes have sharp edges and tips. Consequently, the flakes act as stress raisers which can induce fracture near their tips. For this reason, gray iron is brittle in tension. It is also good at damping vibrations. Gray iron is inexpensive and relatively easy to cast with minimal shrinkage.

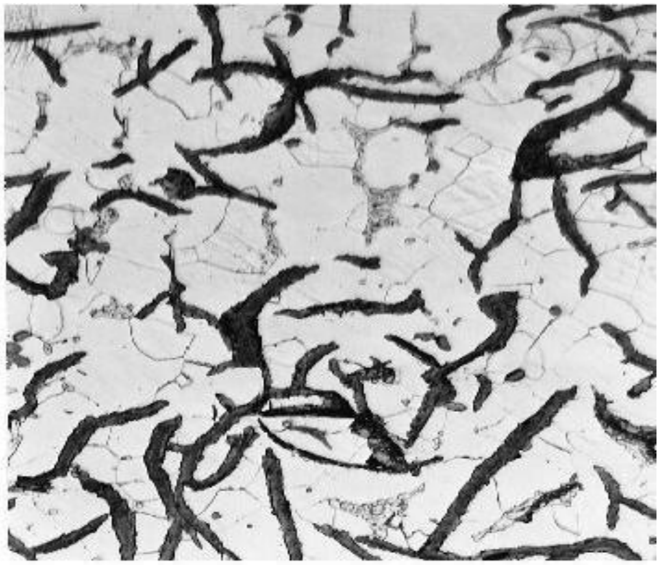

Fig 2.3: Microstructure of gray cast iron

2.4. Nodular Cast iron:

The nodular cast iron contains 2.5 to 4.0 wt. % C, 1.0 to 3.0 wt. % Si, plus Mg &/or Ce. The Mg &/or Ce cause the flakes to spherodize (hence nodular). Graphite is dispersed throughout a ferrite or pearlite matrix in the form of spheres or nodules. The graphite nodules have no sharp features; therefore, the resulting material is much more ductile than gray iron. The mechanical properties of nodular iron are similar to steel. Nodular iron is frequently used in valves, crankshafts, gears, and other automotive components.

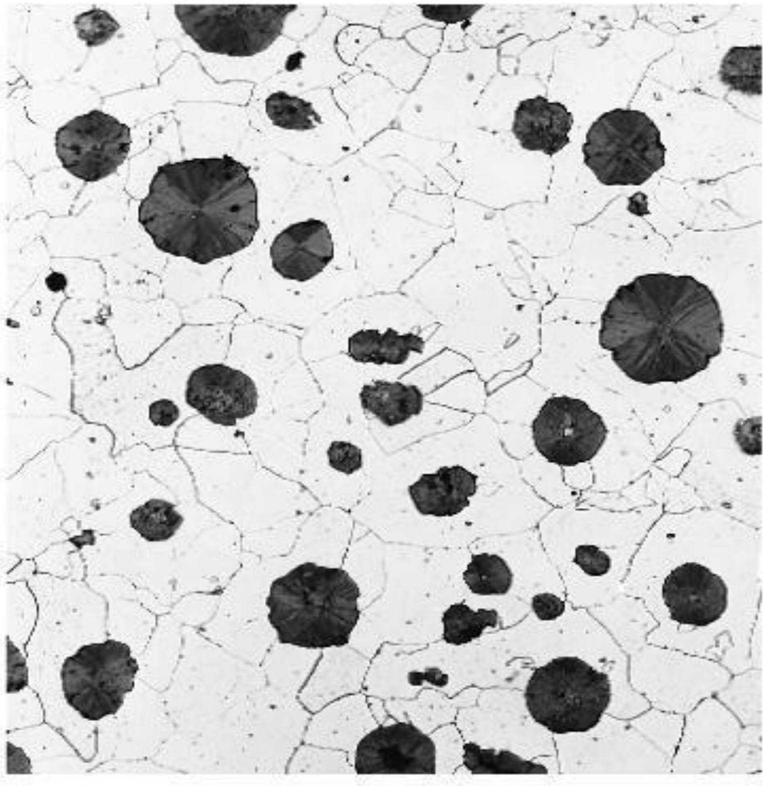

Fig 2.4: Microstructure of noduar cast iron

2.5. White Cast Iron:

White iron contains 2.5 to 4.0 wt. % C and less than 1.0 wt. % Si. Because of the low Si content, the carbon forms Fe3C instead of graphite. Cementite is dispersed throughout pearlite (ferrite + cementite) matrix. White iron contains a considerable volume fraction of cementite (Fe3C), a hard and brittle compound. Because of the amount of cementite, white iron is extremely hard and extremely brittle. Limited usage - mainly applications requiring hardness and wear resistance (such a rollers in rolling mills). Also used as a precursor to malleable iron.

Fig 2.5: Microstructure of white cast iron

2.6. Malleable Cast Iron:

Malleable iron (just like white iron) contains 2.5 to 4.0 wt. % C and less than 1.0 wt. % Si. Unlike white iron, the C exists in the form of graphite instead of cementite. Graphite rosettes are dispersed throughout a ferrite (or pearlite) matrix. Malleable iron is produced by heating white iron in order to decompose the cementite into graphite. The graphite forms clusters, similar to nodular iron. Reduction in the amount of cementite causes the material to become relatively ductile (or malleable). Used in connecting rods, transmission gears, differential cases, flanges, pipe fittings.

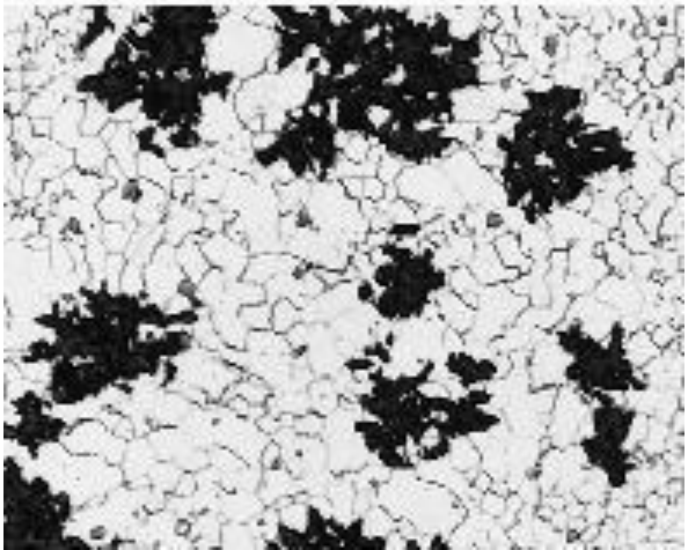

Fig 2.6: Microstructure of malleable cast iron

2.6. Steel

The term steel is used for many different alloys of iron. These alloys vary both in the way they are made and in the proportions of the materials added to the iron. All steels, however, contain small amounts of carbon and manganese. In other words, it can be said that steel is a crystalline alloy of iron, carbon and several other elements, which hardens above its critical temperature. Like stated above, there do exist several types of steels which are (among others) plain carbon, stainless steel, alloyed steel and tool steel.

2.7. Plain carbon steel.

Carbon steel is by far the most widely used kind of steel. The properties of carbon steel depend primarily on the amount of carbon it contains. Most carbon steel has a carbon content of less than 1%. Carbon steel is made into a wide range of products, including structural beams, car bodies, kitchen appliances, and cans. In fact, there are three types of plain carbon steel and they are low carbon steel, medium carbon steel, high carbon steel, and as their names suggests all these types of plain carbon steel differs in the amount of carbon they contain. Indeed, it is good to precise that plain carbon steel is a type of steel having a maximum carbon content of 1.5% along with small percentages of silica, sulphur, phosphorus and manganese.

Generally, with an increase in the carbon content from 0.01 to 1.5% in the alloy, its strength and hardness increases but still such an increase beyond 1.5% causes appreciable reduction in the ductility and malleability of the steel.

Low carbon steel or mild steel, containing carbon up to 0.25% responds to heat treatment as improvement in the ductility is concerned but has no effect in respect of its strength properties.

Medium carbon steels, having carbon content ranging from 0.25 to 0.70% improves in the machinability by heat treatment. It must also be noted that this steel is especially adaptable for machining or forging and where surface hardness is desirable.

High carbon steels, is steel-containing carbon in the range of 0.70 to 1.05% and is especially classed as high carbon steel. In the fully heat-treated condition it is very hard and it will withstand high shear and wear and will thus be subjected to little deformation.

Moreover, at maximum hardness, the steel is brittle and if some toughness is desired it must be obtained at the expense of hardness. Depth hardening ability (normally termed as hardenability) is poor, limiting the use of this steel.

Furthermore, as it has been seen that hardness, brittleness and ductility are very important properties as they determine mainly the way these different carbon content steels are used. Considering the microstructure of slowly cooled steel; for mild steel, for instance, with 0.2% carbon. Such steel consists of about 75% of proeutectoid ferrite that forms above the eutectoid temperature and about 25% of pearlite (pearlite and ferrite being microstructure components of steel). When the carbon content in the steel is increased, the amount of pearlite increases until we get the fully pearlitic structure of a composition of 0.8% carbon. Beyond 0.8%, high carbon steel contain proeutectoid cementide in addition to pearlite. However, in slowly cooled carbon steels, the overall hardness and ductility of the steel are determined by the relative proportions of the soft, ductile ferrite and the hard, brottle cementite. The cementite content increases with increasing carbon content, resulting in an increase of hardness and a decrease of ductility, as we go from low carbon to high carbon steels.

2.8. Aluminum and its Alloys

Pure aluminum is a silvery-white metal with many desirable characteristics. It is light, nontoxic (as the metal), nonmagnetic and nonsparking. It is easily formed, machined, and cast. Pure aluminum is soft and lacks strength, but alloys with small amounts of copper, magnesium, silicon, manganese, and other elements have very useful properties. Aluminum is an abundant element in the earth's crust, but it is not found free in nature. The Bayer process is used to refine aluminum from bauxite, an aluminum ore. Because of aluminum's mechanical and physical properties, it is an extremely convenient and widely used metal. Aluminium alloys can be classified as; cast or wrought alloys, examples are; Al--Li, Al-Cu-Si etc

The Properties are:

- Very lightweight (about 1/3 the mass of an equivalent volume of steel or copper) but with alloying can become very strong.
- excellent thermal conductor
- excellent electrical conductor (on a weight-for-mass basis, aluminium will conduct more than twice as much electricity as copper)
- highly reflective to radiant energy in the electromagnetic spectrum highly corrosion resistant in air and water (including sea water). highly workable and can be formed into almost any structural shape non-magnetic, non-toxic

The applications are:

- door and window frames
- high tension power lines, wires, cables, bus bars, components for television, radios, refrigerators and air-conditioners
- beverage cans, bottle tops
- propellers, airplane and vehicle body sheet, gear boxes, motor parts Al-Cu food/ chemicals handing and storage equipments.
- Al-Cu-Mn-Zn- Cooking utensils.
- Al-Zn-Mg-Cu-Cr Aircraft structural parts

2.9. Copper and its Alloys

Copper alloys are metal alloys that have copper as their principal component. They have high resistance against corrosion. There are as many as 400 different copper and copper-alloy compositions loosely grouped into the categories: copper, high copper alloy, brasses, bronzes, copper nickels, copper–nickel–zinc (nickel silver), leaded copper, and special alloys. The best known traditional types are bronze, where tin is a significant addition, and brass, using zinc instead.

Brasses: Brass A brass is an alloy of copper with zinc. Brasses are usually yellow in color. The zinc content can vary between few % to about 40%; as long as it is kept under 15%, it does not markedly decrease corrosion resistance of copper. Brasses can be sensitive to selective leaching corrosion under certain conditions, when zinc is leached from the alloy (dezincification), leaving behind a spongy copper structure.

Bronzes: A bronze is an alloy of copper and other metals, most often tin, but also aluminium and silicon. Aluminium bronzes are alloys of copper and aluminium. The content of aluminium ranges mostly between 5-11%. Iron, nickel, manganese and silicon are sometimes added. They have higher strength and corrosion resistance than other bronzes, especially in marine environment, and have low reactivity to sulfur compounds. Aluminium forms a thin passivation layer on the surface of the metal. Example: Bell metal Phosphor bronze Nickel bronzes, e.g. nickel silver and cupronickel Speculum metal

The Properties are

- Good thermal and electrical conductivity Ease of forming, ease of joining, and color.
- However, copper and its alloys have relatively low strength-to-weight ratios Low strengths at elevated temperatures.
- Copper is resistant to corrosion in most atmospheres including marine and industrial environments. It is corroded by oxidizing acids, halogens, sulphides and ammonia based solutions
- Copper and its alloys -- the brasses and bronzes -- are available in rod, plate, strip, sheet, tube shapes, forgings, wire, and castings.

The Applications are

- Pure Cu Electrical and thermal conductors (cast Cu), transistor components, coaxial cables rectifiers, lead in wires (cold--worked Cu)
- Cu- Be- Co moulds for plastic parts, bearings, valves, gears(cast Cu)
- Cu--30Zn & Cu --40Zn (cold --work brass) fasteners, locks, heal exchange components, large nuts and bolts, plumbing accessories, pints and rivets.
- Cu--4Si bearing, belts, marine fittings

2.10. Titanium and its Alloys

Titanium alloys are metals that contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, medical devices, highly stressed components such as connecting rods on expensive sports cars and some premium sports equipment and consumer electronics. Although "commercially pure" titanium has acceptable mechanical properties and has been used for orthopedic and dental implants, for most applications titanium is alloyed with small amounts of aluminium and vanadium, typically 6% and 4% respectively, by weight.

Titanium alloys are generally classified into four main categories:

[1] Alpha alloys which contain neutral alloying elements (such as tin) and/ or alpha stabilisers (such as aluminium or oxygen) only. These are not heat treatable. Examples include: Ti-5AL-2SN-ELI, Ti-8AL-1MO-1V.

[2] Near-alpha alloys contain small amount of ductile beta-phase. Besides alpha-phase stabilisers, near-alpha alloys are alloyed with 1–2% of beta phase stabilizers such as molybdenum, silicon or vanadium. Examples include: Ti-6Al-2Sn-4Zr-2Mo, Ti-5Al-5Sn-2Zr- 2Mo, IMI 685, Ti 1100.

[3] Alpha and beta alloys, which are metastable and generally include some combination of both alpha and beta stabilisers, and which can be heat treated. Examples include: Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-6Al-6V-2Sn.

[4] Beta and near beta alloys, which are metastable and which contain sufficient beta stabilisers (such as molybdenum, silicon and vanadium) to allow them to maintain the beta phase when quenched, and which can also be solution treated and aged to improve strength. Examples include: Ti-10V-2Fe-3Al, Ti-13V-11Cr-3Al, Ti-8Mo-8V-2Fe-3Al, Beta C, Ti-15-3.

The Properties are

Low density metal (4.5 g/cm cm3) High melting point = 1668oC elastic modulus = 107MPa

Chemical reactivity with other material at elevated temperatures Corrosion resistance

The Applications are

- Pure Ti - Jet engine cases and airframe skins, corrosion--resistance equipment for marine's applications chemical processing, industries.
- Ti--5Al--2.55Sn – Gas turbine engine casing
- Ti--6Al-4V – High strength prosthetic implants, orthopedics, airframe structured components

2.11. Nickel and nickel alloys

Nickel is a versatile element and will alloy with most metals. Complete solid solubility exists between nickel and copper. Wide solubility ranges between iron, chromium, and nickel make possible many alloy combinations. It has strength, toughness, and corrosion resistance to metals. It is used in stainless steels and nickel-base alloys. Nickel alloys are used for high temperature applications, such as jet-engine components and rockets.

The types of resistance alloys containing nickel include:

Cu-Ni alloys containing 2 to 45% Ni Ni-Cr-Al alloys containing 35 to 95% Ni Ni-Cr-Fe alloys containing 35 to 60% Ni Ni-Cr-Si alloys containing 70 to 80% Ni

The types of resistance heating alloys con-taining nickel include:

Ni-Cr alloys containing 65 to 80% Ni with 1.5% Si Ni-Cr-Fe alloys containing 35 to 70% Ni with 1.5% Si + l% Nb

Soft Magnetic Alloys: Two broad classes of magnetically soft materials have been developed in the Fe-Ni system. The high-nickel alloys (about 79% Ni with 4 to 5% Mo; bal Fe) have high initial permeability and low saturation induction.

Shape Memory Alloys: Metallic materials that demonstrate the ability to return to their previously defined shape when subjected to the appropriate heating schedule are referred to as shape memory alloys. Nickel- titanium alloys (50Ni-50Ti) are one of the few commercially important shape memory alloys.

Superalloys: Superalloys are high-temperature alloys use in jet engines, gas turbines and reciprocating engines.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – III – Strengthening Mechanisms – SMEA1201

3. Strengthening Mechanisms

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics. Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material.

3.1. TTT and CCT Diagrams

There are two main types of transformation diagram that are helpful in selecting the optimum steel and processing route to achieve a given set of properties. These are time-temperature transformation (TTT) and continuous cooling transformation (CCT) diagrams. CCT diagrams are generally more appropriate for engineering applications as components are cooled (air cooled, furnace cooled, quenched etc.) from a processing temperature as this is more economic than transferring to a separate furnace for an isothermal treatment. Time-temperature transformation (TTT) diagrams measure the rate of transformation at a constant temperature. In other words a sample is austenitised and then cooled rapidly to a lower temperature and held at that temperature whilst the rate of transformation is measured, for example by dilatometry. Obviously a large number of experiments is required to build up a complete TTT diagram. Continuous cooling transformation (CCT) diagrams measure the extent of transformation as a function of time for a continuously decreasing temperature. In other words a sample is austenitised and then cooled at a predetermined rate and the degree of transformation is measured, for example by dilatometry.

Obviously a large number of experiments is required to build up a complete CCT diagram. TTT diagrams are time temperature transformation or isothermal transformation diagrams.

The essential difference between both the diagrams is the method of cooling. In TTT diagrams, after cooling to a transformation temperature, you keep the temperature constant until the transformation of austenite to the required transformation product (usually pearlite or bainite) is complete and then cool to the room temperature. One such process is austempering in which austenite is transformed to bainite isothermally.

The red lines form the transformation diagram and blue line denote the process. In this case the component which had an austenitic structure was cooled to just above Ts temperature; held at that temperature until the transformation was complete and then cooled further to the room temperature.

In CCT diagrams, there is continuous cooling i.e. there is no holding of temperature. The components are cooled at a constant or varying rates. The end products are usually martensite or pearlite depending on the cooling media as well as the material of components. Fully bainitic structure cannot be obtained using continuous cooling.

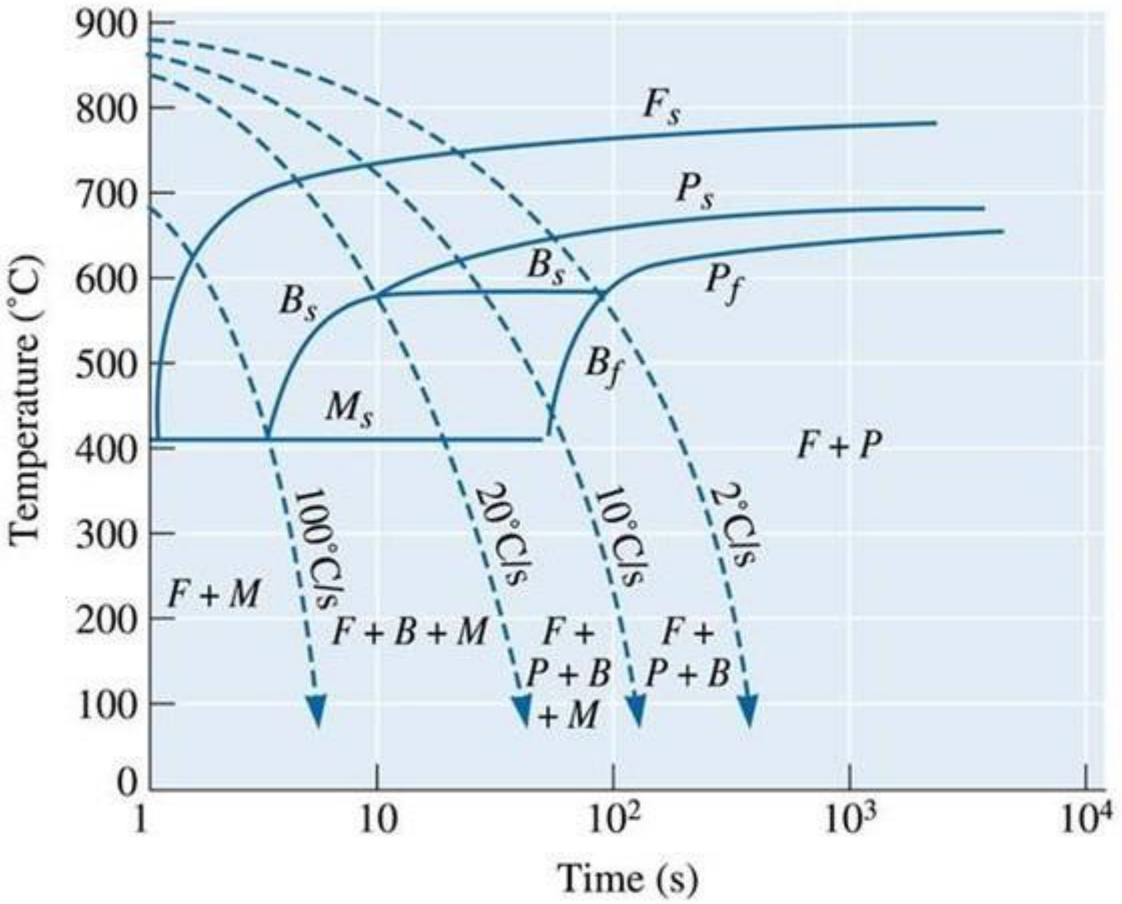

Fig 3.1: Phases at different cooling rates

In the above figure: F – Ferrite, P – Pearlite: B – Bainite: M – Martensite: s subscript denotes start temperature and f subscript denotes finish temperature. So a CCT diagrams simply gives the various transformation products which will be obtained at different cooling rates. It can be seen from the diagram that at cooling rates of more than 100 degrees celsius, ferrite and martensite will be obtained; for cooling rates between 20 and 100 degrees celsius, ferrite, bainite and martensite will be obtained and so on. These cooling rates are dependent on the cooling media. CCT diagrams are more practical than TTT diagrams as most of the processes employ continuous cooling rather than isothermal transformation. Also it is more difficult to hold the temperature constant.

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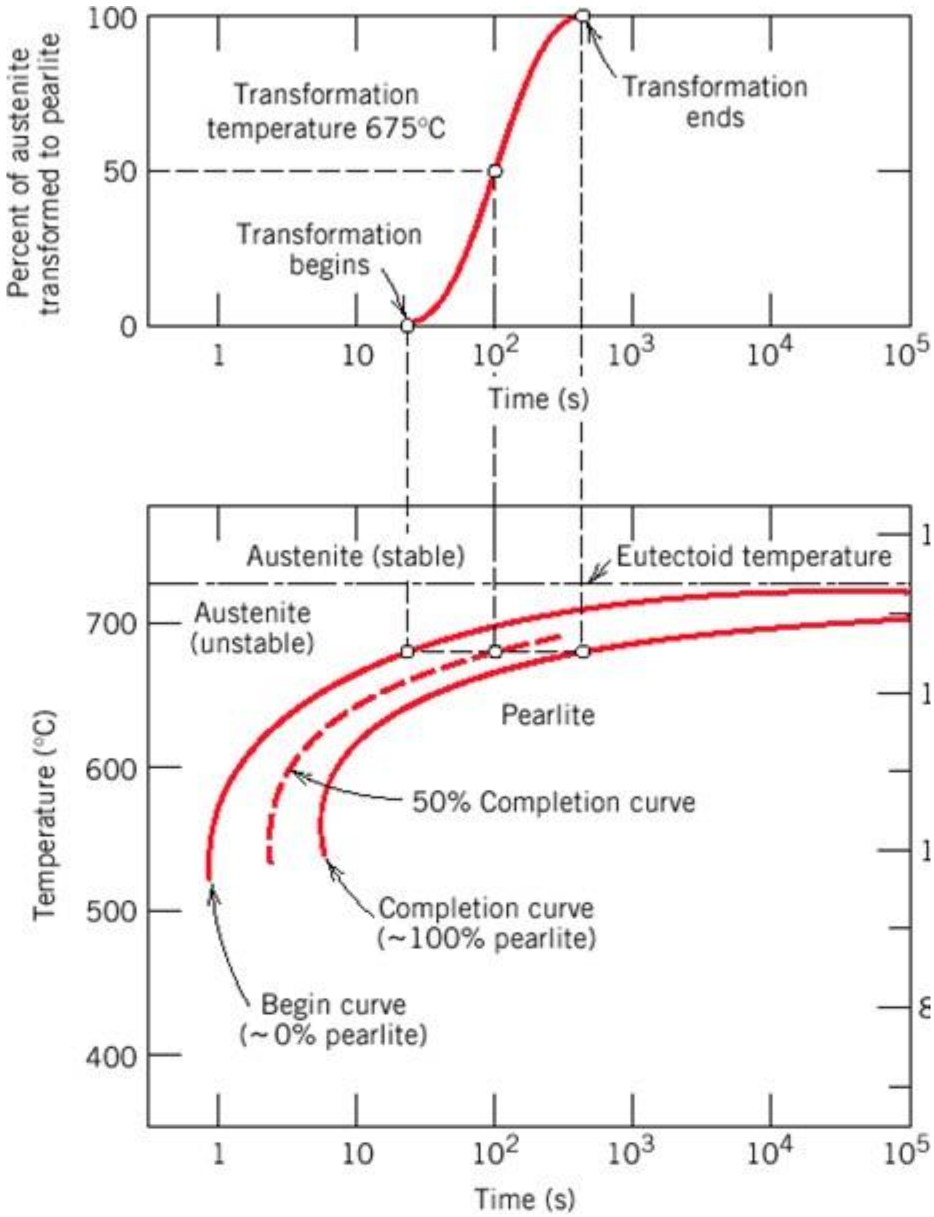

Fig 3.2: TTT diagram

Then these transformation start times and transformation end times are plotted for different temperatures as shown. These points, when joined, give us the TTT diagrams. For continuous cooling, the time required for the transformation to begin and end is delayed. Thus the TTT diagram's curves are shifted to longer times and lower temperatures.

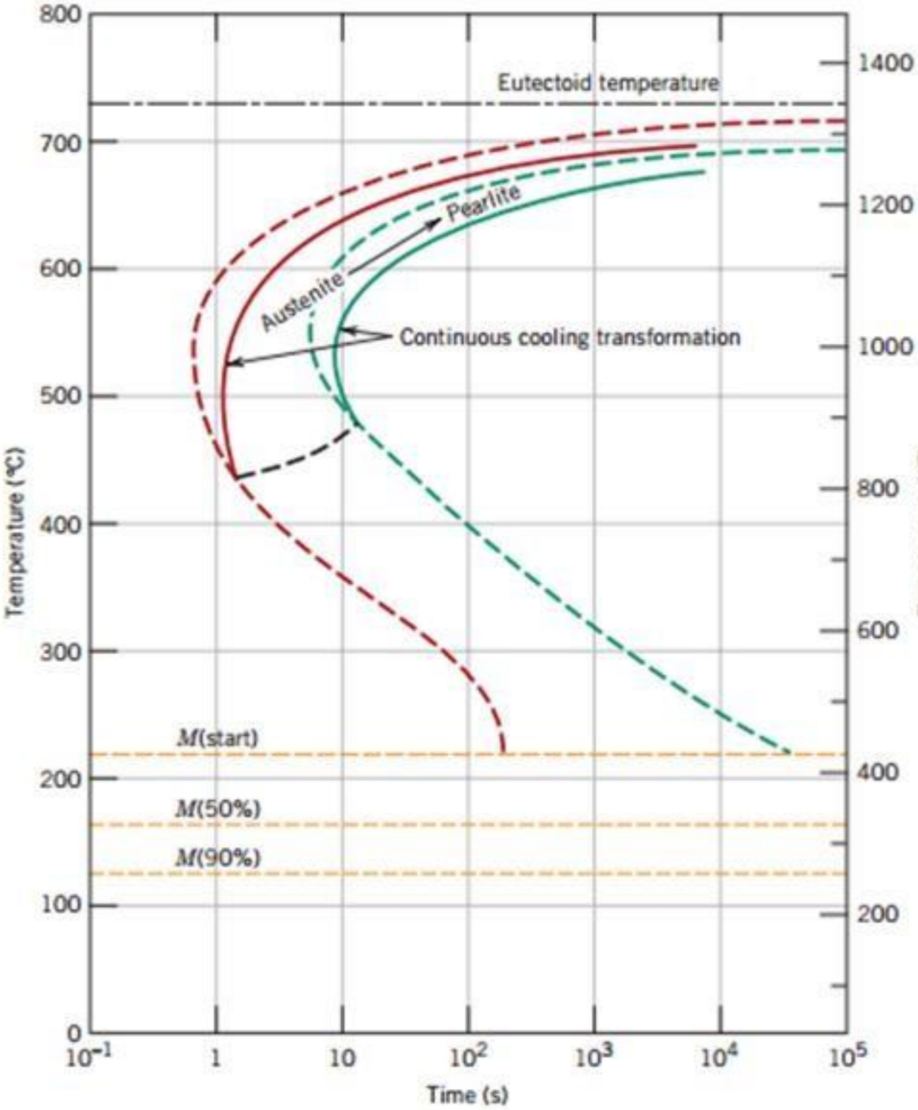

Fig 3.3: CCT diagram

The dashed lines form TTT diagrams and the solid lines form the CCT diagrams. It can be seen that CCT diagram can be obtained by moving the TTT curves a little to the downward right.

3.2. Heat Treatment of Steels

Heat treatment of steels can be heat treated to produce a great variety of microstructures and properties. Generally, heat treatment uses phase transformation during heating and cooling to change a microstructure in a solid state. In heat treatment, the processing is most often entirely thermal and modifies only structure. Thermomechanical treatments, which modify component shape and structure, and thermochemical treatments which modify surface chemistry and structure, are also important processing approaches which fall into the domain of heat treatment. The iron-carbon diagram is the base of heat treatment.

According to cooling rate we can distinguish two main heat treatment operations: • annealing – upon slow cooling rate (in air or with a furnace) • quenching – upon fast cooling (in oil or in water) annealing - produces equilibrium structures according to the Fe-Fe_3C diagram quenching - gives non-equilibrium structures Among annealing there are some important heat treatment processes like: • normalising • spheroidising • stress relieving

Normalising: The temperature depends on carbon content. After soaking the alloy is cooled in still air. This cooling rate and applied temperature produces small grain size. The small grain structure improve both toughness and strength (especially yield strenght). During normalising we use grain refinement which is associated with allotropic transformation upon heating $\gamma \rightarrow \alpha$

Spheroidising: The process is limited to steels in excess of 0.5% carbon and consists of heating the steel to temperature about A1 (727°C). At this temperature any cold worked ferrite will recrystallise and the iron carbide present in pearlite will form as spheroids or ―ball up‖. As a result of change of carbides shape the strength and hardness are reduced.

Quenching: Material is heated up to the suitable temperature and then quenched in water or oil to harden to full hardness according to the kind of steels. Material is heated to the suitable temperature for hardening, then cooled rapidly by immersing the hot part is water, oil or another suitable liquid to transform the material to a fully hardened structure. Parts which are quenched usually must be aged, tempered or stress relieved to achieve the proper toughness, final hardness and dimensional stability. Alloys may be air cooled, or cooled by quenching in oil, water, or another liquid, depending upon the amount of alloying elements in the material and final mechanical properties to be achieved. Hardened materials are tempered to improve their dimensional stability and toughness.

Tempering: Tempering is done to develop the required combination of hardness, strength and toughness or to relieve the brittleness of fully hardened steels. Steels are never used in the as quenched condition. The combination of quenching and tempering is important to make tough parts. This treatment follows a quenching or air cooling operation. Tempering is generally considered effective in relieving stresses induced by quenching in addition to lowering hardness to within a specified range, or meeting certain mechanical property requirements. Tempering is the process of reheating the steel at a relatively low temperature leading to precipitation and spheroidization of the carbides present in the microstructure. The tempering temperature and times are generally controlled to produce the final properties required of the steel. The result is a component with the appropriate combination of hardness, strength and toughness for the intended application. Tempering is also effective in relieving the stresses induced by quenching.

Critical Temperatures: The "critical points" of carbon tool steel are the temperatures at which certain changes in the chemical composition of the steel take place, during both heating and cooling. Steel at normal temperatures has its carbon (which is the chief hardening element) in a certain form called pearlite carbon, and if the steel is heated to a certain temperature, a change occurs and the pearlite becomes martensite or hardening carbon. If the steel is allowed to cool slowly, the hardening carbon changes back to pearlite. The points at which these changes occur are the decalescence and recalescence or critical points, and the effect of these molecular changes is as follows: When a piece of steel is heated to a certain point, it continues to absorb heat without appreciably rising in temperature, although its immediate surroundings may be hotter than the steel. This is the decalescence point. Similarly, steel cooling slowly from a high heat will, at a certain temperature, actually increase in temperature, although its surroundings may be colder. This takes place at the recalescence point. The recalescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F., and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite carbon is changed into a hardening carbon, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalescence point, thus preventing the changing back again from hardening to pearlite carbon, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests in each case. It is the variation in the critical points that makes it necessary to heat different steels to different temperatures when hardening.

Hardening: The use of this treatment will result in an improvement of the mechanical properties, as well as an increase in the level of hardness, producing a tougher, more durable item. Alloys are heated above the critical transformation temperature for the material, then cooled rapidly enough to cause the soft initial material to transform to a much harder, stronger structure. Alloys may be air cooled, or cooled by quenching in oil, water, or another liquid, depending upon the amount of alloying elements in the material. Hardened materials are usually tempered or stress relieved to improve their dimensional stability and toughness. Steel parts often require a heat treatment to obtain improved mechanical properties, such as increasing increase hardness or strength. The hardening process consists of heating the components above the critical (normalizing) temperature, holding at this temperature for one hour per inch of thickness cooling at a rate fast enough to allow the material to transform to a much harder, stronger structure, and then tempering. Steel is essentially an alloy of iron and carbon; other steel alloys have other metal elements in solution. Heating the material above the critical temperature causes carbon and the other elements to go into solid solution. Quenching "freezes" the microstructure, inducing stresses. Parts are subsequently tempered to transform the microstructure, achieve the appropriate hardness and eliminate the stresses.

Annealing Heat Treatment: Annealing heat treatment process is heating the material above the critical temperature, holding long enough for transformation to occur and slow cooling. Full annealing heat treatment differs from normalizing heat treatment in that the annealing temperature is typically 150-200F lower than the normalizing temperature and the cooling rate is slower. This establishes a soft microstructure and thus a soft product.

Austenitizing: Austenitizing heat treatment is heating a steel above the critical temperature, holding for a period of time long enough for transformation to occur. The material will be hardened if austenitizing is followed by quenching at a rate that is fast enough to transform the austenite into martensite.

Normalizing: Normalizing Heat Treatment process is heating a steel above the critical temperature, holding for a period of time long enough for transformation to occur, and air cooling. Normalized heat treatment establishes a more uniform carbide size and distribution which facilitates later heat treatment operations and produces a more uniform final product. Solution Annealing - Solution

Heat Treatment Definition Some alloys (aluminum, PH stainless steels, Ti) harden by precipitating microscopic particles during aging. Solution heat treatment solution annealing takes these particles and puts them back into solution. In the solution annealing process, the alloy is heated to a high temperature, held for a period of time related to the section size of the material and air cooled or faster. This traps the precipitates in solution.

Steel Aging (also referred to as Precipitation Hardening): Precipitation Hardening is the heating of alloys, in the solution treated condition, to a lower temperature, which allows a relatively uniform distribution of microscopic particles throughout the alloy. The aging process results in alloy strengthening.

Stress Relieving Heat Treatment: Stress Relieving heat treatment process is heating to a temperature in order to relieve internal stresses in the material and lower the hardness of the surface of the material.

Austempering: Austempering is a technique used to form pure bainite, a transitional microstructure found between pearlite and martensite. In normalizing, both upper and lower bainite are usually found mixed with pearlite. To avoid the formation of pearlite or martensite, the steel is quenched in a bath of molten metals or salts. This quickly cools the steel past the point where pearlite can form, and into the bainite-forming range. The steel is then held at the bainite-forming temperature, beyond the point where the temperature reaches an equilibrium, until the bainite fully forms. The steel is then removed from the bath and allowed to air-cool, without the formation of either pearlite or martensite. Depending on the holding-temperature, austempering can produce either upper or lower bainite. Upper bainite is a laminate structure formed at temperatures typically above 350 °C (662 °F) and is a much tougher microstructure. Lower bainite is a needle-like structure, produced at temperatures below 350 °C, and is stronger but much more brittle.In either case, austempering produces greater strength and toughness for a given hardness, which is determined mostly by composition rather than cooling speed, and reduced internal stresses which could lead to breakage. This produces steel with superior impact resistance. Modern punches and chisels are often austempered. Because austempering does not produce martensite, the steel does not require further tempering.

Martempering: Martempering is similar to austempering, in that the steel is quenched in a bath of molten metal or salts to quickly cool it past the pearlite-forming range. However, in martempering, the goal is to create martensite rather than bainite. The steel is quenched to a much lower temperature than is used for austempering; to just above the martensite start temperature. The metal is then held at this temperature until the temperature of the steel reaches an equilibrium. The steel is then removed from the bath before any bainite can form, and then is allowed to air-cool, turning it into martensite. The interruption in cooling allows much of the internal stresses to relax before the martensite forms, decreasing the brittleness of the steel. However, the martempered steel will usually need to undergo further tempering to adjust the hardness and toughness, except in rare cases where maximum hardness is needed but the accompanying brittleness is not. Modern files are often martempered

Embrittlement: Embrittlement occurs during tempering when, through a specific temperature range, the steel experiences an increase in hardness and a reduction in ductility, as opposed to the normal decrease in hardness that occurs to either side of this range. The first type is called tempered martensite embrittlement (TME) or one-step embrittlement. The second is referred to as temper embrittlement (TE) or two-step embrittlement.

Recrystallization: Recrystallization is a process by which deformed grains are replaced by a new set of defects-free grains that nucleate and grow until the original grains have been entirely consumed. Recrystallization is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility. Thus, the process may be introduced as a deliberate step in metals processing or may be an undesirable byproduct of another processing step. The most important industrial uses are the softening of metals previously hardened by cold work, which have lost their ductility, and the control of the grain structure in the final product.

3.3. Hardenability

To achieve a full conversion of austenite into hard martensite, cooling needs to be fast enough to avoid partial conversion into perlite or bainite. If the piece is thick, the interior may cool too slowly so that full martensitic conversion is not achieved. Thus, the martensitic content, and the hardness, will drop from a high value at the surface to a lower value in the interior of the piece. Hardenability is the ability of the material to be hardened by forming martensite.

Hardenability is measured by the Jominy end-quench test (shown in figure). Hardenability is then given as the dependence of hardness on distance from the quenched end. High hardenability means that the hardness curve is relatively flat.

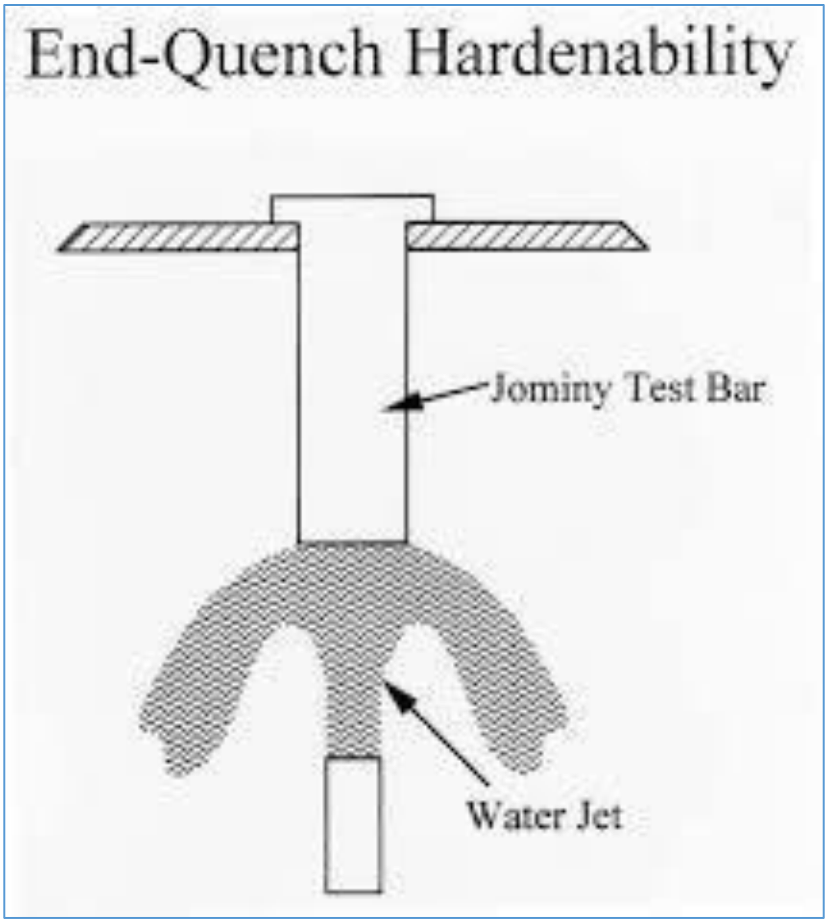

Fig 3.4: End Quench Test Apparatus

The cooling rate depends on the cooling medium. Cooling is fastest using water, then oil, and then air. Fast cooling brings the danger of warping and formation of cracks, since it is usually accompanied by large thermal gradients. The shape and size of the piece, together with the heat capacity and heat conductivity are important in determining the cooling rate for different parts of the metal piece. Heat capacity is the energy content of a heated mass, which needs to be removed for cooling. Heat conductivity measures how fast this energy is transported to the colder regions of the piece.

3.4. Precipitation Hardening

Hardening can be enhanced by extremely small precipitates that hinder dislocation motion. The precipitates form when the solubility limit is exceeded. Precipitation hardening is also called age hardening because it involves the hardening of the material over a prolonged time. Precipitation hardening is achieved by: solution heat treatment where all the solute atoms are dissolved to form a single-phase solution, rapid cooling across the solvus line to exceed the solubility limit. This leads to a supersaturated solid solution that remains stable (metastable) due to the low temperatures, which prevent diffusion, precipitation heat treatment where the supersaturated solution is heated to an intermediate temperature to induce precipitation and kept there for some time (aging). If the process is continued for a very long time, eventually the hardness decreases. This is called overaging.

3.5. Carburizing

Carburizing, also referred to as Case Hardening, is a heat treatment process that produces a surface which is resistant to wear, while maintaining toughness and strength of the core. This treatment is applied to low carbon steel parts after machining, as well as high alloy steel bearings, gears, and other components.

Carburizing increases strength and wear resistance by diffusing carbon into the surface of the steel creating a case while retaining a substantially lesser hardness in the core. This treatment is applied to low carbon steels after machining. Strong and very hard-surface parts of intricate and complex shapes can be made of relatively lower cost materials that are readily machined or formed prior to heat treatment.

Most carburizing is done by heating components in either a pit furnace, or sealed atmosphere furnace, and introducing carburizing gases at temperature. Gas carburizing allows for accurate control of both the process temperature and carburizing atmosphere (carbon potential). Carburizing is a time/temperature process; the carburizing atmosphere is introduced into the furnace for the required time to ensure the correct depth of case. The carbon potential of the gas can be lowered to permit diffusion, avoiding excess carbon in the surface layer.

After carburizing, the work is either slow cooled for later quench hardening, or quenched directly into oil. Quench selection is made to achieve the optimum properties with acceptable levels of dimensional change. Hot oil quenching may be used for minimal distortion, but may be limited in application by the strength requirements for the product. Alternatively, bearing races may be press quenched to maintain their dimensional tolerances, minimizing the need for excessive post heat treatment grinding. In some cases, product is tempered, then cryogenically processed to convert retained austenite to martensite, and then retempered.

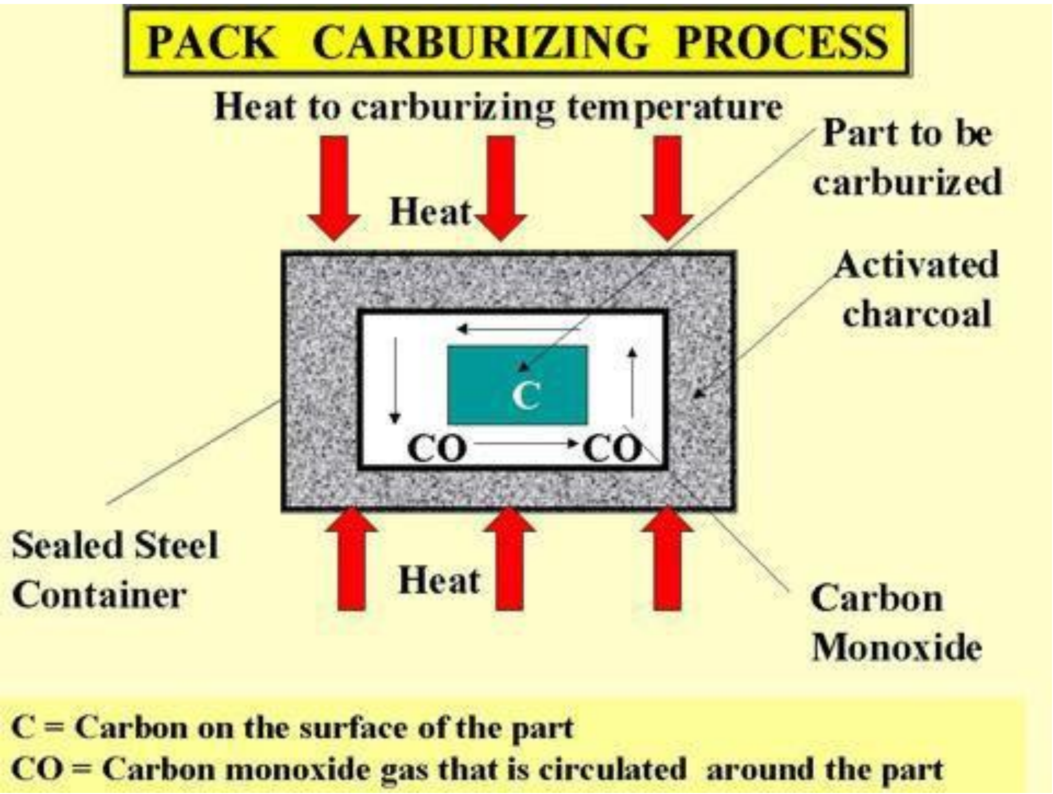

Fig 3.5: Carburizing

3.6. Nitrading

Gas nitriding is a surface hardening process, where nitrogen is added to the surface of steel parts using dissociated ammonia as the source. Gas nitriding develops a very hard case in a component at relatively low temperature, without the need for quenching.

Nitriding is carried out at temperatures below the transformation temperature of alloy steels, so that with proper manufacturing techniques, there is little or no distortion as a result of the process. Parts to be nitrided are heat treated to the proper strength level, and final machined. The parts are then exposed to active nitrogen at a carefully controlled temperature, typically in the range of 925°F to 985°F. This temperature is typically below the final tempering temperature of the steel so that nitriding does not affect the base metal mechanical properties. As a result, a very high strength product with extremely good wear resistance can be produced, with little or no dimensional change.

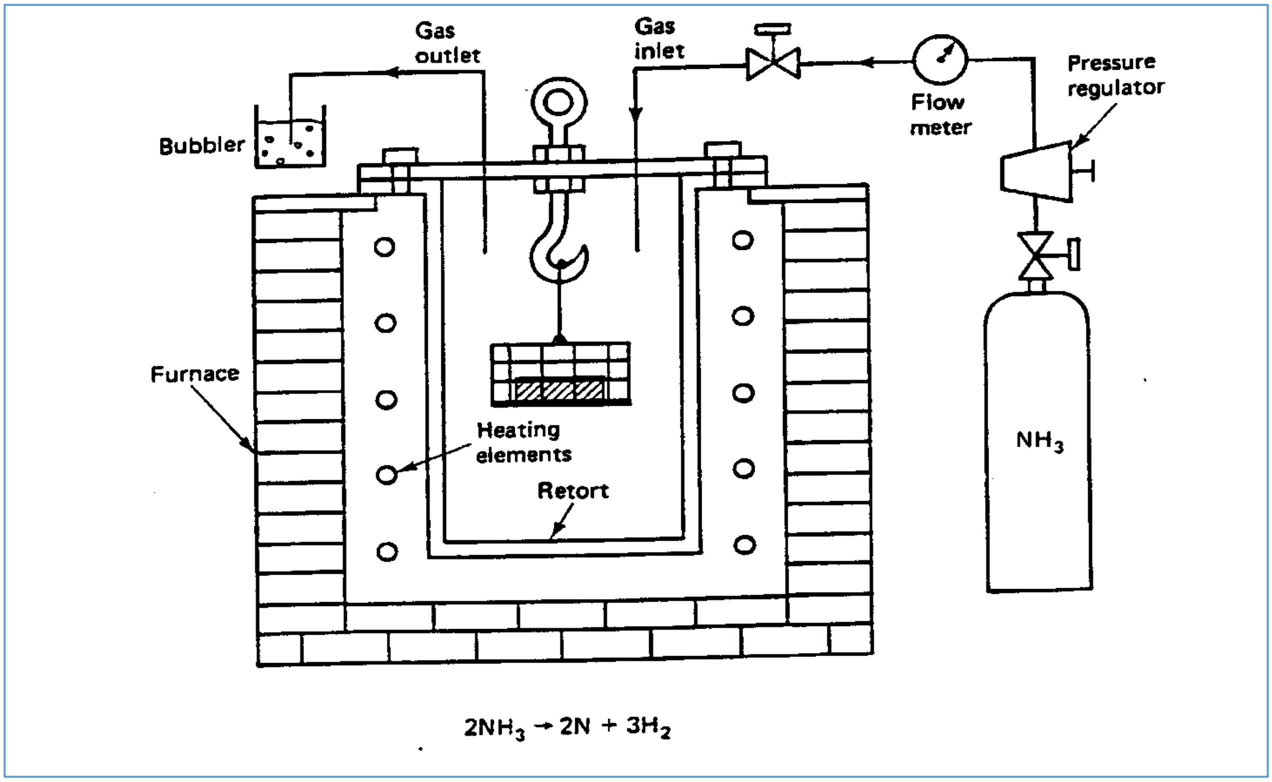

Fig 3.6: Nitriding Apparatus

The components to be nitrided are often stress relieved prior to final machining so that the only size changes observed are growth of about 0.0005". In some cases, nitrided components are surface ground after nitriding to remove the most outermost brittle layer produced by the process, or to bring parts into a tight tolerance.

3.7. Induction Hardening

Induction hardening is a process used for the surface hardening of steel and other alloy components. The parts to be heat treated are placed inside a water cooled copper coil and then heated above their transformation temperature by applying an alternating current to the coil. The alternating current in the coil induces an alternating magnetic field within the work piece, which if made from steel, caused the outer surface of the part to heat to a temperature above the transformation range. Parts are held at that temperature until the appropriate depth of hardening has been achieved, and then quenched in oil, or another media, depending upon the steel type and hardness desired. The core of the component remains unaffected by the treatment and its physical properties are those of the bar from which it was machined or preheat treated. The hardness of the case can be HRC 37 - 58. Carbon and alloy steels with a carbon content in the range 0.40 - 0.45% are most suitable for this process. In some cases, parts made from alloy steels such as 4320, 8620 or 9310, like steel and paper mill rolls, are first carburized to a required case depth and slow cooled, and then induction hardened. This is to realize the benefit of relatively high core mechanical properties, and surface hardness greater than HRC 60, which provides excellent protection.

While induction hardening is most commonly used for steel parts, other alloys such as copper alloys, which are solution treated and tempered, may be induction hardened as well. Applications include hardening bearing races, gears, pinion shafts, crane (and other) wheels and treads, and threaded pipe used for oil patch drilling.

3.8. Flame Hardening

Flame hardening is similar to induction hardening, in that it is a surface hardening process. Heat is applied to the part being hardened, using an oxy- acetylene (or similar gas) flame on the surface of the steel being hardened and heating the surface above the upper critical temperature before quenching the steel in a spray of water. The result is a hard surface layer ranging from 0.050" to 0.250" deep. As with induction hardening, the steel component must have sufficient carbon (greater than 0.35%). The composition of the steel is not changed; therefore core mechanical properties are unaffected. Flame hardening produces results similar to conventional hardening processes but with less hardness penetration. Applications for flame hardening are similar to those for induction hardening, although an advantage of flame hardening is the ability to harden flat surfaces. Flat wear plates, and knives can be selectively hardened using this process.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – IV – Failure of Materias and Testing – SMEA1201

4. Failure of Materials and Testing

4.1. Elastic/Plastic Deformation

When a sufficient load is applied to a metal or other structural material, it will cause the material to change shape. This change in shape is called deformation. A temporary shape change that is self-reversing after the force is removed, so that the object returns to its original shape, is called elastic deformation. In other words, elastic deformation is a change in shape of a material at low stress that is recoverable after the stress is removed. This type of deformation involves stretching of the bonds, but the atoms do not slip past each other. When the stress is sufficient to permanently deform the metal, it is called plastic deformation.

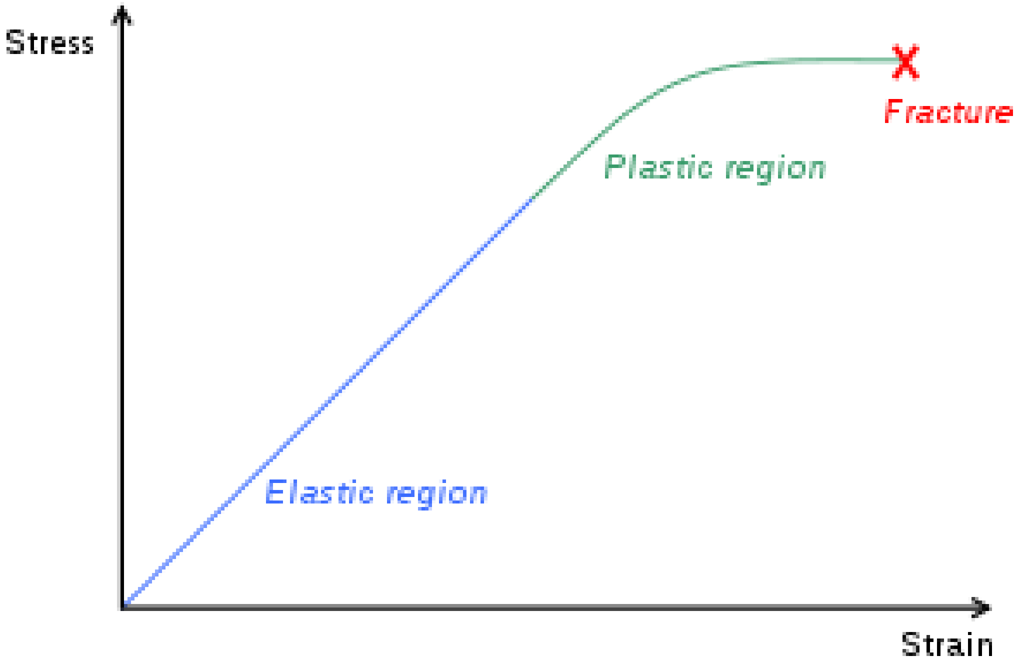


Fig 4.1: Stress-Strain Curve

However, an object in the plastic deformation range will first have undergone elastic deformation, which is reversible, so the object will return part way to its original shape.

Fracture: This type of deformation is also irreversible. A break occurs after the material has reached the end of the elastic, and then plastic, deformation ranges. At this point forces accumulate until they are sufficient to cause a fracture. All materials will eventually fracture, if sufficient forces are applied.

4.2. Deformation by slip

When the stress is sufficient to permanently deform the metal, it is called plastic deformation. The plastic deformation involves the breaking of a limited number of atomic bonds by the movement of dislocations. The force needed to break the bonds of all the atoms in a crystal plane all at once is very great. However, the movement of dislocations allows atoms in crystal planes to slip past one another at a much lower stress levels. Since the energy required to move is lowest along the densest planes of atoms, dislocations have a preferred direction of travel within a grain of the material. This results in slip that occurs along parallel planes within the grain. These parallel slip planes group together to form slip bands, which can be seen with an optical microscope. A slip band appears as a single line under the microscope, but it is in fact made up of closely spaced parallel slip planes as shown in the image.

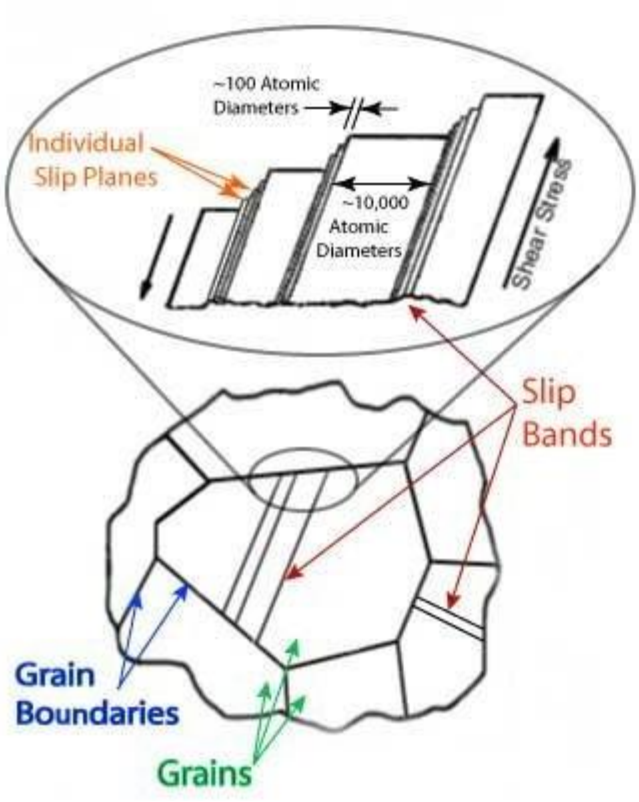


Fig 4.2: Deformation by slip

4.3. Fatigue

Another deformation mechanism is fatigue, which occurs primarily in ductile metals. It was originally thought that a material deformed only within the elastic range returned completely to its original state once the forces were removed. However, faults are introduced at the molecular level with each deformation. After many deformations, cracks will begin to appear, followed soon after by a fracture, with no apparent plastic deformation in between. Fatigue has been a major cause of aircraft failure, especially before the process was well understood . There are two ways to determine when a part is in danger of metal fatigue; either predict when failure will occur due to the material/force/shape/iteration combination, and replace the vulnerable materials before this occurs, or perform inspections to detect the microscopic cracks and perform replacement once they occur. Selection of materials not likely to suffer from metal fatigue during the life of the product is the best solution, but not always possible. Avoiding shapes with sharp corners limits metal fatigue by reducing stress concentrations, but does not eliminate it.

4.4. Mechanical Properties

In the course of operation or use, all the articles and structures are subjected to the action of external forces, which create stresses that inevitably cause deformation. To keep these stresses, and, consequently deformation within permissible limits it is necessary to select suitable materials for the Components of various designs and to apply the most effective heat treatment. i.e. a Comprehensive knowledge of the chief character tics of the semi-finished metal products & finished metal articles (such as strength, ductility, toughness etc) are essential for the purpose.

For this reason the specification of metals, used in the manufacture of various products and structure, are based on the results of mechanical tests or we say that the mechanical tests conducted on the specially prepared specimens (test pieces) of standard form and size on special machines to obtained the strength, ductility and toughness characteristics of the metal.

The conditions under which the mechanical test are conducted are of three types:

(1) Static: When the load is increased slowly and gradually and the metal is loaded by tension, compression, torsion or bending.

(2) Dynamic: when the load increases rapidly as in impact

(3) Repeated or Fatigue: (both static and impact type) . i.e. when the load repeatedly varies in the course of test either in value or both in value and direction Now let us consider the uniaxial tension test.

4.5. Uniaxial Tension Test

This test is of static type i.e. the load is increased comparatively slowly from zero to a certain value. A typical tensile test curve for the mild steel has been shown below

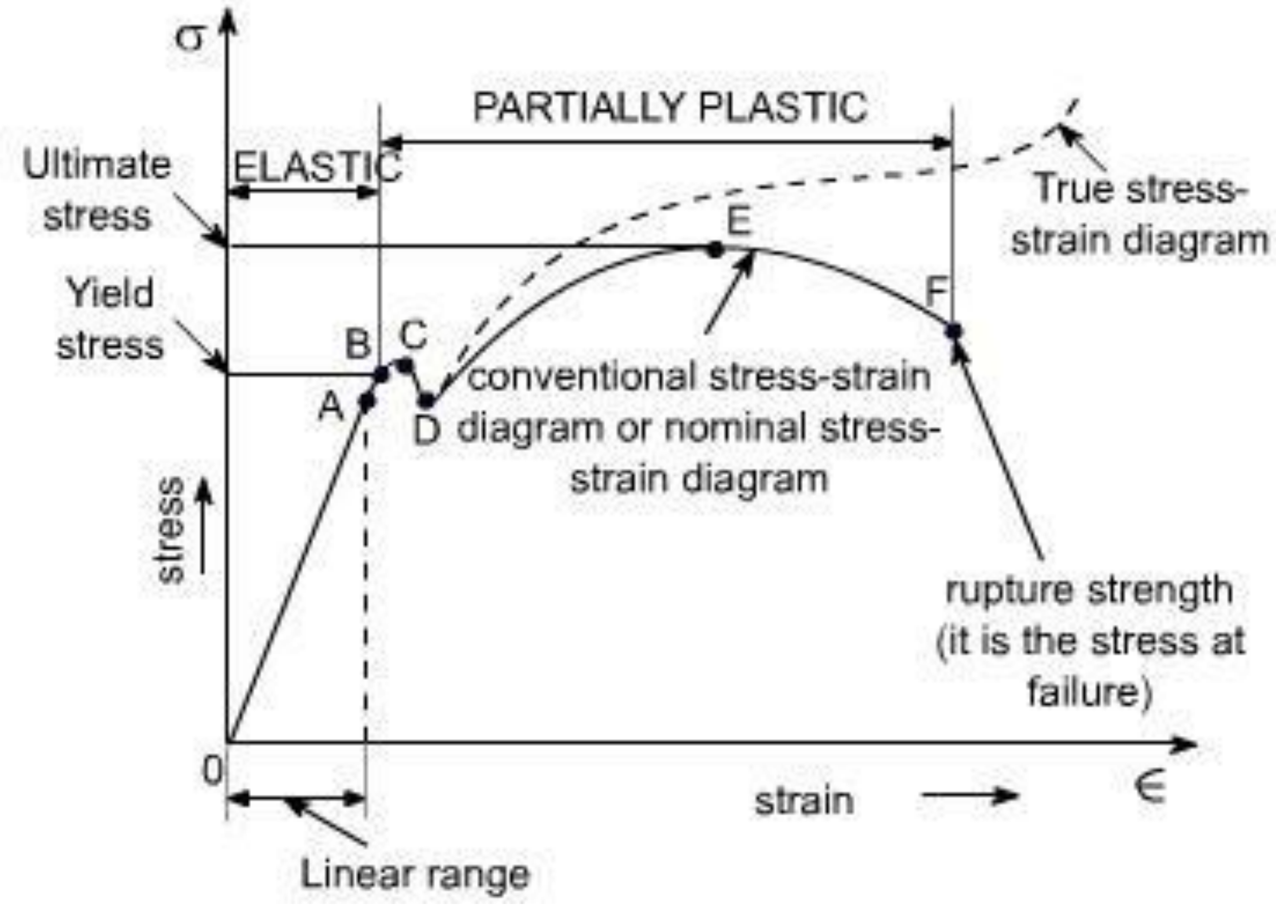


Fig 4.3: Stress-Strain curve plot

Nominal stress – Strain OR Conventional Stress – Strain diagrams: Stresses are usually computed on the basis of the original area of the specimen; such stresses are often referred to as conventional or nominal stresses.

True stress – Strain Diagram: Since when a material is subjected to a uniaxial load, some contraction or expansion always takes place. Thus, dividing the applied force by the corresponding actual area of the specimen at the same instant gives the so called true stress.

It is evident form the graph that the strain is proportional to strain or elongation is proportional to the load giving a st.line relationship. This law of proportionality is valid upto a point A. We can say that point A is some ultimate point when the linear nature of the graph ceases or there is a deviation from the linear nature. This point is known as the limit of proportionality or the proportionality limit. For a short period beyond the point A, the material may still be elastic in the sense that the deformations are completely recovered when the load is removed. The limiting point B is termed as Elastic Limit. Beyond the elastic limit plastic deformation occurs and strains are not totally recoverable. There will be thus permanent deformation or permanent set when load is removed. These two points are termed as upper and lower yield points respectively. The stress at the yield point is called the yield strength. A study a stress – strain diagrams shows that the yield point is so near the proportional limit that for most purpose the two may be taken as one. However, it is much easier to locate the former. For material which do not posses a well define yield points, In order to find the yield point or yield strength, an offset method is applied. In this method a line is drawn parallel to the straight line portion of initial stress diagram by off setting this by an amount equal to 0.2% of the strain as shown as below and this happens especially for the low carbon steel.

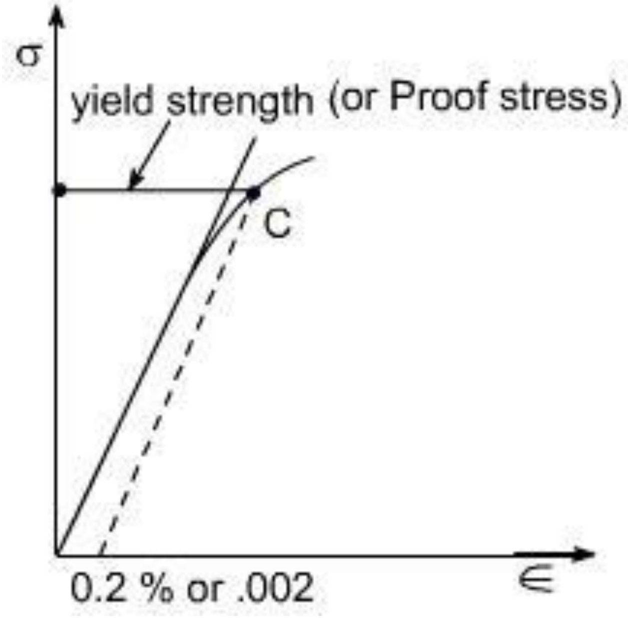


Fig 4.4: Offsetting

A further increase in the load will cause marked deformation in the whole volume of the metal. The maximum load which the specimen can with stand without failure is called the load at the ultimate strength. The highest point ‘E' of the diagram corresponds to the ultimate strength of a material. Beyond point E, the bar begins to forms neck. The load falling from the maximum until fracture occurs at F.

The ductility of a material in tension can be characterized by its elongation and by the reduction in area at the cross section where fracture occurs. It is the ratio of the extension in length of the specimen after fracture to its initial gauge length, expressed in percent.

$$\delta = \frac{(l_1 - l_g)}{l_1} \times 100$$

l_I = gauge length of specimen after fracture(or the distance between the gage marks at fracture)
l_g= gauge length before fracture(i.e. initial gauge length)

4.6. Hardness Testing

The tem ‘hardness' is one having a variety of meanings; a hard material is thought of as one whose surface resists indentation or scratching, and which has the ability to indent or cut other materials.

The hardness test is a comparative test and has been evolved mainly from the need to have some convenient method of measuring the resistance of materials to scratching, wear or in dentation this is also used to give a guide to overall strength of a materials, after as an inspection procedure, and has the advantage of being a non – destructive test, in that only small indentations are lift permanently on the surface of the specimen.

Four hardness tests are customarily used in industry namely

(i) Brinell
(ii) Vickers
(iii) Rockwell
(vi) Shore Scleroscopy

4.6.1. Brinell Hardness test

In the Brinell hardness test, a hardened steel ball is pressed into the flat surface of a test piece using a specified force. The ball is then removed and the diameter of the resulting indentation is measured using a microscope.

The Brinell Hardness no. (BHN) is defined as

BHN = P / A

Where

P = Force applied to the ball. A = curved area of the indentation

It may be shown that $A = \frac{1}{2}\pi D\left[D - \sqrt{D^2 - d^2}\right]$

D = diameter of the ball,

d = the diameter of the indentation.

In the Brinell Test, the ball diameter and applied load are constant and are selected to suit the composition of the metal, its hardness, and selected to suit the composition of the metal, its hardness, the thickness etc. Further, the hardness of the ball should be at least 1.7 times than the test specimen to prevent permanent set in the ball.

The main disadvantage of the Brinell Hardness test is that the Brinell hardness number is not independent of the applied load. This can be realized from. Considering the geometry of indentations for increasing loads. As the ball is pressed into the surface under increasing load the geometry of the indentation charges.

4.6.2. Vickers Hardness test

The Vicker's Hardness test follows a procedure exactly a identical with that of Brinell test, but uses a different indenter. The steel ball is replaced by a diamond, having the from of a square – based pyramid with an angle of 136^0 between opposite faces. This is pressed into the flat surface of the test piece using a specified force, and the diagonals of the resulting indentation measured is using a microscope. The Hardness, expressed as a Vicker's pyramid number is defined as the ratio F/A, where F is the force applied to the diamond and A is the surface area of the indentation.

$$A = \frac{\frac{1}{2}l^2}{\sin\frac{1}{2}(136^0)}$$

$$= \frac{l^2}{.854v_x} \Rightarrow H_V = \frac{F}{\frac{l^2}{.854}}$$

$$H_V = \frac{.854F}{l^2}$$

where l is the average lengthof the diagonal is $l = \frac{1}{2}(l_1 + l_2)$

It may be shown that

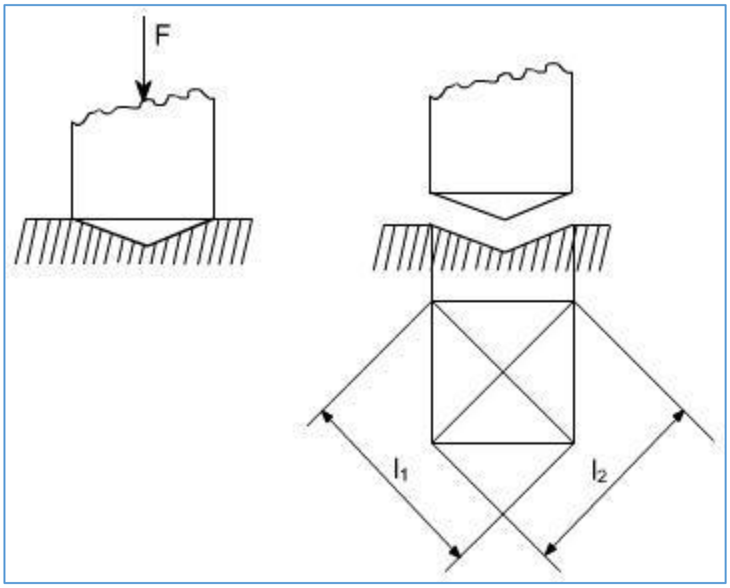


Fig 4.5. Indentation of Vicker's testing

In the Vicker Test the indenters of pyramidal or conical shape are used & this overcomes the disadvantage which is faced in Brinell test i.e. as the load increases, the geometry of the indentation's does not change

4.6.3. Rockwell Hardness Test

The Rockwell Hardness test also uses an indenter when is pressed into the flat surface of the test piece, but differs from the Brinell and Vicker's test in that the measurement of hardness is based on the depth of penetration, not on the surface area of indentation. The indenter may be a conical diamond of 120^0 included angle, with a rounded apex. It is brought into contact with the test piece, and a force F is applied.

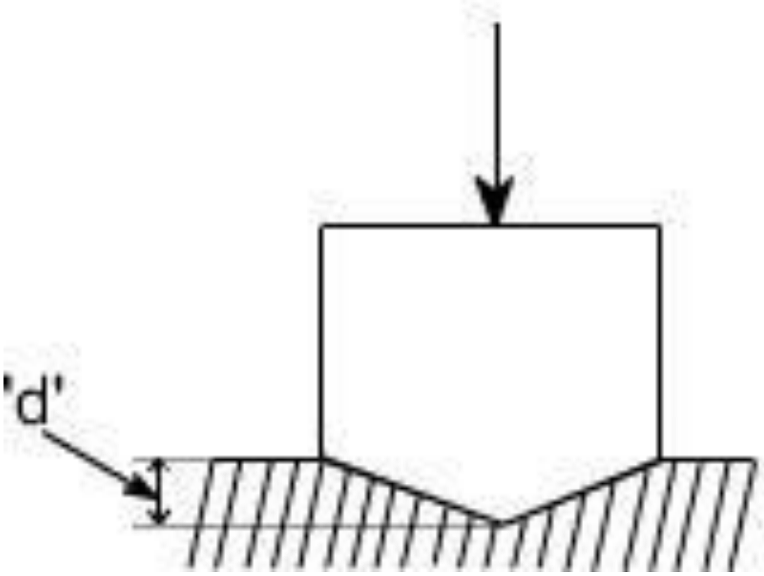


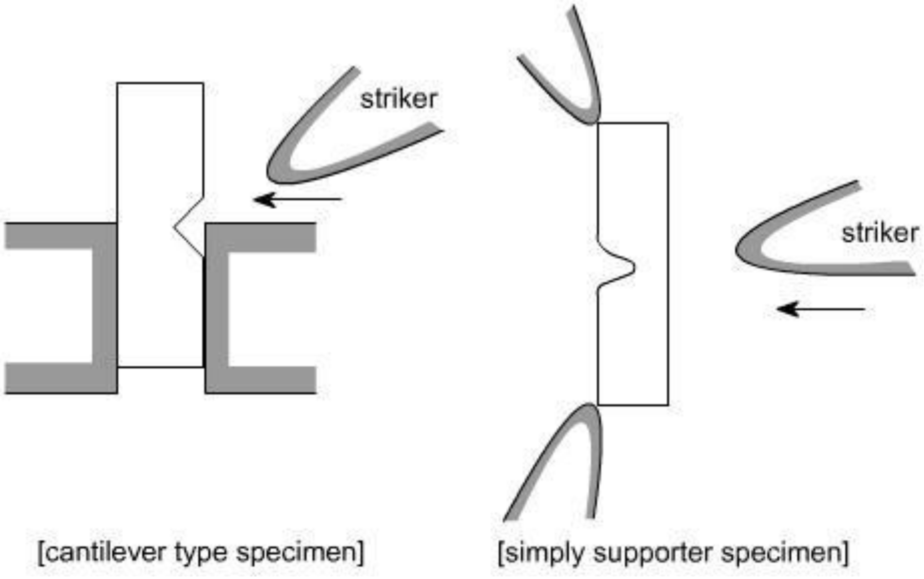
Fig 4.6: Indentation of Rockwell Test

Rockwell tests are widely applied in industry due to rapidity and simplicity with which they may be performed, high accuracy, and due to the small size of the impressions produced on the surface.

4.7. Impact testing

In an ‘impact test' a notched bar of material, arranged either as a cantilever or as a simply supported beam, is broken by a single blow in such a way that the total energy required to fracture it may be determined. The energy required to fracture a material is of importance in cases of “shock loading' when a component or structure may be required to absorb the K.E of a moving object. Often a structure must be capable of receiving an accidental ‘shock load' without failing completely, and whether it can do this will be determined not by its strength but by its ability to absorb energy. A combination of strength and ductility will be required, since large amounts of energy can only be absorbed by large amounts of plastic deformation. The ability of a material to absorb a large amount of energy before breaking is often referred as toughness, and the energy absorbed in an impact test is an obvious indication of this property.

Impact tests are carried out on notched specimens, and the notches must not be regarded simply as a local reduction in the cross – sectional area of the specimen, Notches – and , in fact, surface irregularities of many kind – give rise to high local stresses, and are in practice, a potential source of cracks.



[cantilever type specimen]

[simply supporter specimen]

Fig 4.7: Specimen configuration in impact testing

The specimen may be of circular or square cross – section arranged either as a cantilever or a simply supported beam.

4.8. Defects in materials

Crystallographic defects are interruptions of regular patterns in crystalline solids. They are common because positions of atoms or molecules at repeating fixed distances determined by the unit cell parameters in crystals, which exhibit a periodic crystal structure, are usually imperfect

Point defects: A Point Defect involves a single atom change to the normal crystal array. There are three major types of point defect: Vacancies, Interstitials and Impurities. They may be built-in with the original crystal growth, or activated by heat. They may be the result of radiation, or electric current etc, etc.

Vacancies: A Vacancy is the absence of an atom from a site normally occupied in the lattice.

Interstitials: An Interstitial is an atom on a non-lattice site. There needs to be enough room for it, so this type of defect occurs in open covalent structures, or metallic structures with large atoms.

Impurities: An Impurity is the substitution of a regular lattice atom with an atom that does not normally occupy that site. The atom may come from within the crystal, (e.g. a Chlorine atom on a Sodium site in a NaCl crystal) or from the addition of impurities.

Dislocation: A Dislocation is a line discontinuity in the regular crystal structure. There are two basic types: Edge dislocations, and Screw dislocations.

An Edge dislocation in a Metal may be regarded as the insertion (or removal) of an extra half plane of atoms in the crystal structure.

Screw Dislocation: changes the character of the atom planes. The atom planes no longer exist separately from each other. They form a single surface, like a screw thread, which "spirals" from one end of the crystal to the other. (It is actually a helical structure because it winds up in 3D, not like a spiral that is flat.)

Planar Defects: A Planar Defect is a discontinuity of the perfect crystal structure across a plane.

Grain Boundaries: A Grain Boundary is a general planar defect that separates regions of different crystalline orientation (i.e. grains) within a polycrystalline solid. The atoms in the grain boundary will not be in perfect crystalline arrangement. Grain boundaries are usually the result of uneven growth when the solid is crystallising. Grain sizes vary from 1 µm to 1 mm.

Tilt Boundaries: A Tilt Boundary, between two slightly mis-aligned grains appears as an array of edge dislocations.

Twin Boundaries: A Twin Boundary happens when the crystals on either side of a plane are mirror images of each other. The boundary between the twinned crystals will be a single plane of atoms. There is no region of disorder and the boundary atoms can be viewed as belonging to the crystal structures of both twins. Twins are either grown-in during crystallisation, or the result of mechanical or thermal work.

Volume Defects: Volume defects are Voids, i.e. the absence of a number of atoms to form internal surfaces in the crystal. They have similar properties to microcracks because of the broken bonds at the surface.

4.9. Failure Mechanism

Failure can be defined, in general, as an event that does not accomplish its intended purpose. Failure of a material component is the loss of ability to function normally. Components of a system can fail one of many ways, for example excessive deformation, fracture, corrosion, burning-out, degradation of specific properties (thermal, electrical, or magnetic), etc. Failure of components, especially, structural members and machine elements can lead to heavy loss of lives, wealth and even may jeopardize the society! This chapter deals with the study of failures by mechanical means i.e. application stresses.

Even though the causes of failure are known, prevention of failure is difficult to guarantee. Causes for failure include: improper materials selection, improper processing, inadequate design, misuse of a component, and improper maintenance. It’s the engineer’s responsibility to anticipate and prepare for possible failure; and in the event of failure, to assess its cause and then take preventive measures.

Structural elements and machine elements can fail to perform their intended functions in three general ways: excessive elastic deformation, excessive plastic deformation or yielding, and fracture. Under the category of failure due to excessive elastic deformation, for example: too flexible machine shaft can cause rapid wear of bearing. On the other hand sudden buckling type of failure may occur. Failures due to excessive elastic deformation are controlled by the modulus of elasticity, not by the strength of the material. The most effective way to increase stiffness of a component is by tailoring the shape or dimensions. Yielding or plastic deformation may render a component useless after a certain limit. This failure is controlled by the yield strength of the material. At room temperature, continued loading over the yielding point may lead to strain hardening followed by fracture. However at elevated temperatures, failure occurs in form of time- dependent yielding known as creep. Fracture involves complete disruption of continuity of a component. It starts with initiation of a crack, followed by crack propagation. Fracture of materials may occur in three ways – brittle/ductile fracture, fatigue or progressive fracture, delayed fracture. Ductile/brittle fracture occurs over short period of time, and distinguishable. Fatigue failure is the mode in which most machine parts fail. Fatigue, which is caused by a critical localized tensile stress, occurs in parts which are subjected to alternating or fluctuating stress. Stress-rupture occurs when a metal has been statically loaded at an elevated temperature for a long time, and is best example for delayed fracture.

4.10. Fracture

Fracture is a form of failure, and is defined as the separation or fragmentation of a solid body into two or more parts under the action of stress. Fracture that occurs over a very short time period and under simple loading conditions (static i.e. constant or slowly changing) is considered here. Fracture under complex condition, for example alternating stress, is considered in later sections.

The process of fracture can be considered to be made up of two components, crack initiation followed by crack propagation. Fractures are classified w.r.t. several characteristics, for example, strain to fracture, crystallographic mode of fracture, appearance of fracture, etc. Table gives a brief summary of different fracture modes.

Shear fracture, promoted by shear stresses, occurs as result of extensive slip on active slip plane. On the other hand, cleavage fracture is controlled by tensile stresses acting normal to cleavage plane. A shear fracture surface appears gray and fibrous, while a cleavage fracture surface appears bright or granular. Actual fracture surfaces often appear as mixture of fibrous and granular mode. Based on metallographic examination of fracture surfaces of polycrystalline materials, they are classified as either transgranular or intergranular. Transgranular fracture, as the name go by, represents crack propagation through the grains, whereas intergranular fracture represents the crack that propagated along the grain boundaries.

The fracture is termed ductile or brittle depending on the ability of a material to undergo plastic deformation during the fracture. A ductile fracture is characterized by considerable amount of plastic deformation prior to and during the crack propagation. On the other hand, brittle fracture is characterized by micro-deformation or no gross deformation during the crack propagation. Plastic deformation that occurs during ductile fracture, if monitored, can be useful as warning sign to the fracture that may occur in later stages. Thus brittle fracture shall be avoided as it may occur without warning!

Since deformation of a material depends on many conditions such as stress state, rate of loading, ambient temperature, crystal structure; ductile and brittle are relative terms. Thus the boundary between a ductile and brittle fracture is arbitrary and depends on the situation being considered. A change from the ductile to brittle type of fracture is promoted by a decrease in temperature, an increase in the rate of loading, and the presence of complex state of stress (for example, due to a notch). Under the action of tensile stresses, most metallic materials are ductile, whereas ceramics are mostly brittle, while polymers may exhibit both types of fracture. Materials with BCC or HCP crystal structure can be expected to experience brittle fracture under normal conditions, whereas materials with FCC crystal structure are expected to experience ductile fracture.

Figure depicts characteristic macroscopic fracture profiles. The profile shown in figure-(a) is representative of very high ductility represented by close to 100% reduction in cross-sectional area. This kind of failure is usually called rupture. It is observed in very soft metals such as pure gold and lead at room temperature and other metals, polymers, glasses at elevated temperatures. Most ductile metals fracture preceded by a moderate amount of necking, followed by formation of voids, cracks and finally shear. This gives characteristic cup-and-cone fracture as shown by figure-(b). In this central interior region has an irregular and fibrous appearance. Figure -(c) presents the typical profile of brittle fracture which is usually transgranular. It occurs in most ceramics and glasses at room temperature, long-chain polymers below their glass transition temperatures, certain metals and alloys below their ductile-to-brittle transition temperatures.

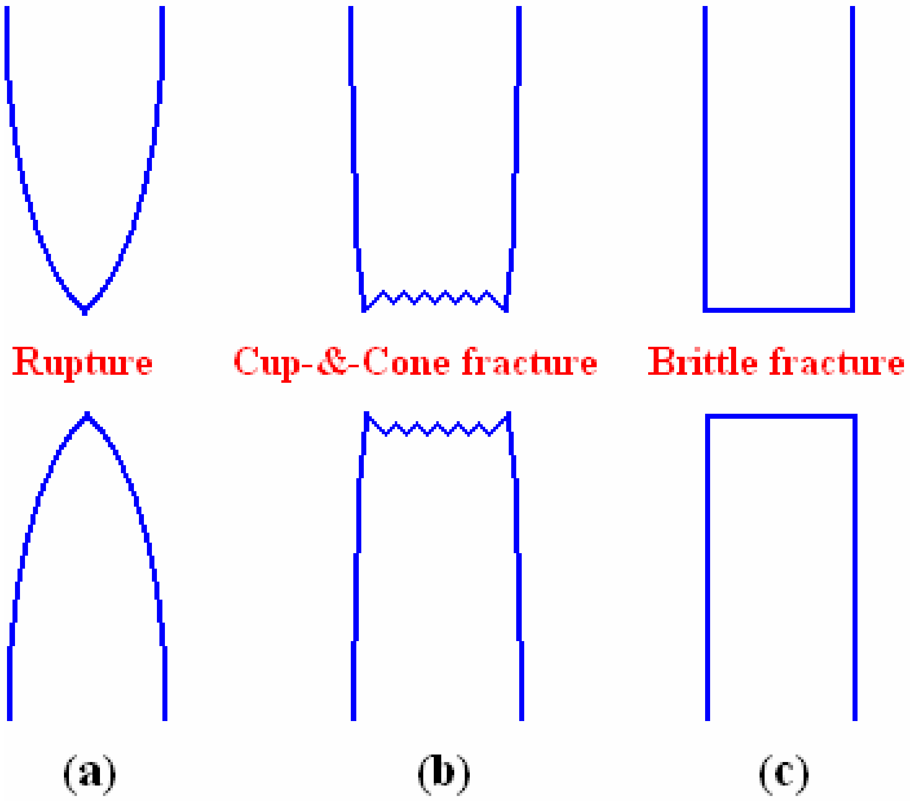


Fig 4.8: Fracture profiles.

Detailed and important information on the mechanism of fracture can be obtained from microscopic examination of fracture surfaces. This study is known as fractography. This study is most commonly done using SEM (scanning electron microscope). Common microscopic modes of fracture observed include cleavage, quasi-cleavage, and dimpled rupture. Characteristic feature of cleavage fracture is flat facets, and these exhibit river marking caused by crack moving through the crystal along number of parallel planes which form a series of plateaus and connecting ledges. Quasi-cleavage fracture is related but distinct from cleavage in the sense that fracture surfaces are not true cleavage planes. This often exhibit dimples and tear ridges around the periphery of the facets. Dimpled rupture is characterized by cup-like depressions whose shape is dependent on stress state. The depressions may be equi-axial, parabolic, or elliptical. This dimpled rupture represents a ductile fracture. Table distinguishes two common modes of fracture.

4.11. Ductile fracture

Most often ductile fracture in tension occurs after appreciable plastic deformation. It occurs by a slow tearing of the metal with the expenditure of considerable energy. It can be said that ductile fracture in tension is usually preceded by a localized reduction in cross-sectional area, called necking. Further it exhibits three stages - (1) after on set of necking, cavities form, usually at inclusions at second-phase particles, in the necked region because the geometrical changes induces hydrostatic tensile stresses, (2) the cavities grow, and further growth leads to their coalesce resulting in formation of crack that grows outward in direction perpendicular to the application of stress, (3) final failure involves rapid crack propagation at about 45° to the tensile axis. This angle represents the direction of maximum shear stress that causes shear slip in the final stage. During the shear slip, crack propagates at a rapid speed around the outer perimeter of neck leaving one surface in form of cup, and the other in form of cone. Thus it is known as cup-and- cone fracture. In this central interior region has an irregular and fibrous appearance, which signifies plastic deformation. Different progressive stages of ductile fracture are shown in figure.

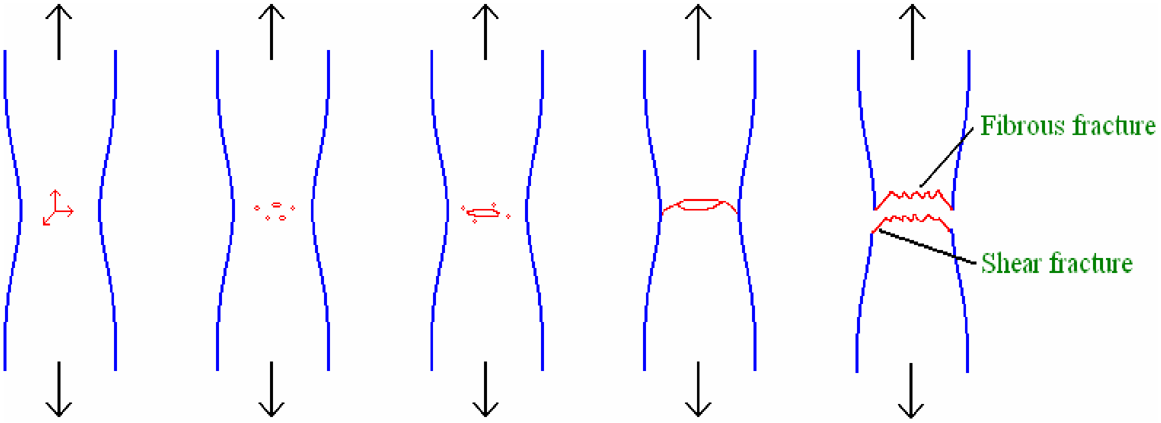


Fig 4.9: Stages of ductile tensile fracture.

The voids are thought to be nucleated heterogeneously at sites where further deformation is difficult. These preferred sites mainly consists of foreign inclusions, second-phase particles like oxide particles, or even voids those can form at grain boundary triple points in high-purity metals. It has been observed that concentration of nucleating sites had a strong influence on ductile fracture as true strain to fracture decreases rapidly with increasing volume fraction of second phase particles. In addition, particle shape also has an important influence. When the particles are more spherical than plate-like, cracking is more difficult and the ductility is increased. This is because dislocations can cross slip around spherical particles with ease than around plate-like particles thus avoids buildup of high stresses.

More details of fracture mechanism can be obtained from fractographic study of the fracture surface. At high magnification under microscope, numerous spherical dimples separated by thin walls are found on the ductile fractured surface. This is an indication that surface had formed from numerous holes which were separated by thin walls until it fractures. Dimples formed on shear lip of cup-and-cone fracture will be elongated attaining parabolic shape which is indication that shear failure took place.

4.12. Ductile-to-Brittle transition

It is well understood that ductile and brittle are relative, and thus interchange between these two modes of fracture is achievable with ease. The term Ductile-to-Brittle transition (DBT) is used in relation to the temperature dependence of the measured impact energy absorption. For a material, as the temperature is lowered, the impact energy drops suddenly over a relatively narrow temperature range, below which the energy has a considerably lower value as a representative of brittle fracture.

The temperature where DBT occurs is termed as Ductile-to-Brittle Transition Temperature (DBTT). A typical variation of energy expended as a function of temperature is shown in figure-8.6. From the figure it can be concluded that there is no single criterion that defines the transition temperature. Above the DBTT, the yield strength (σ_y) is lower than the tensile stress necessary to cause brittle failure (σ_f) i.e. $\sigma_y < \sigma_f$. With decreasing temperature, the yield strength increases rapidly to the point where it equals the tensile stress for brittle failure, and below this temperature, fracture usually occurs in brittle/cleavage mode. So, at and below the DBTT, $\sigma_y = \sigma_f$. At the transition temperature, the micro-cracks that form are of critical size for crack propagation, and at lower temperatures these cracks exceed the critical size. Over a temperature range just above DBTT, micro-cracks formed are initially sub-critical so that further plastic deformation and strain hardening must proceed before the tensile stress level becomes sufficient to cause crack propagation. With further increase in temperature, micro-cracks no longer form and fracture mode changes from cleavage to ductile.

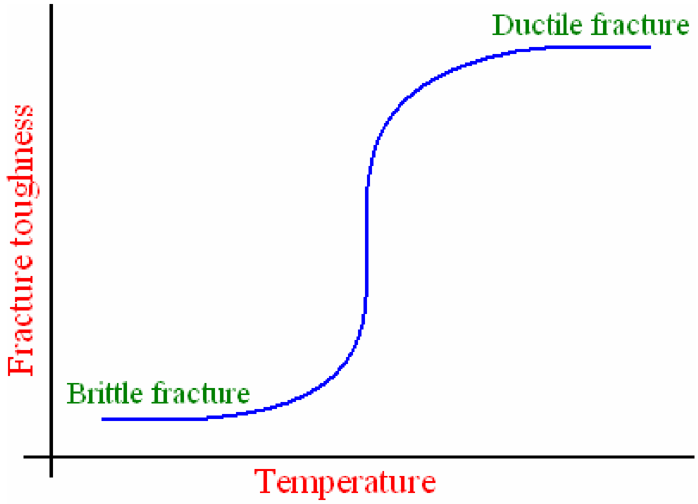


Fig 4.10: Typical variation of fracture toughness as a function of temperature.

As shown in the above figure, BCC metals possess a distinct DBTT compared with other metals. Common BCC metals are to become brittle at low temperatures or at extremely high rates of strain. Many FCC metals, on the other hand, remain ductile even at very low temperatures. In metals DBTT is around 0.1-0.2 T_m while in ceramics it is about 0.5-0.7 T_m, where T_m represents absolute melting temperature. The crack propagation stress usually is relatively insensitive to temperature. Strain rate which increases the yield strength but not the crack propagation stress increases the DBTT. As mentioned earlier, DBTT does not have a unique value for a given material, and is a function of several other variables such as flaw size, strain rate, triaxiality of stress, etc. Sharp notches in the specimen provide stress concentration centers and thus increase the DBTT. Fine grained materials have a lower transition temperature as compared to coarse grained materials.

There are other factors which affect the DBTT for a material, for example metallurgical factors. One of the most important is microstructure, which in turn can depend on heat treatment practice and temperature, for example, for steels. The composition also has a very pronounced effect on DBTT. In steels, it is found that impurities like P, Si, Mo, Cr along with C increase the DBTT, while Mn and Ni have reverse effect.

4.13. Fatigue

Failures occurring under conditions of dynamic or alternating loading are called fatigue failures, presumably because it is generally observed that these failures occur only after a considerable period of service. Fatigue failure usually occurs at stresses well below those required for yielding, or in some cases above the yield strength but below the tensile strength of the material. These failures are dangerous because they occur without any warning. Typical machine components subjected to fatigue are automobile crank-shaft, bridges, aircraft landing gear, etc. Fatigue failures occur in both metallic and non-metallic materials, and are responsible for a large number fraction of identifiable service failures of metals.

A typical fatigue-fracture surface looks like the one shown in figure. The fatigue crack nucleates at the stress concentration. Generally, the fatigue fracture surface is perpendicular to the direction of an applied stress. A fatigue failure can be recognized from the appearance of the fracture surface, which shows a smooth and polished surface that corresponds to the slow growth of crack, when the crack faces smoothen out by constant rubbing against each other and a rough/granular region corresponds to the stage of fast growth, after critical conditions is attained where member has failed in a ductile manner when cross section was no longer able to carry the applied load. The region of a fracture surface that formed during the crack propagation step may be results in characteristic pattern of concentric rings spread over the smooth region of the fracture surface, known as beach marks or striations, radiating outward from the point of initiation of the failure, as shown in figure. Beach marks (also known as clamshell pattern) are macroscopic dimensions and may be observed with the unaided eye. These markings are found for components that experienced interruptions during the crack propagation stage. Each beach mark band represents a period of time over which crack growth occurred. On the other hand fatigue striations are microscopic in size and subject to observation with the electron microscope (either TEM or SEM). The relatively widely spaced striations are caused by variations in the stress amplitude during the life of the component. On a much finer level, a large number of striations may be sometimes being seen. The width of each striation here is equal to the distance by which the crack grows during one cycle. Any point with stress concentration such as sharp corner or notch or metallurgical inclusion can act as point of initiation of fatigue crack.

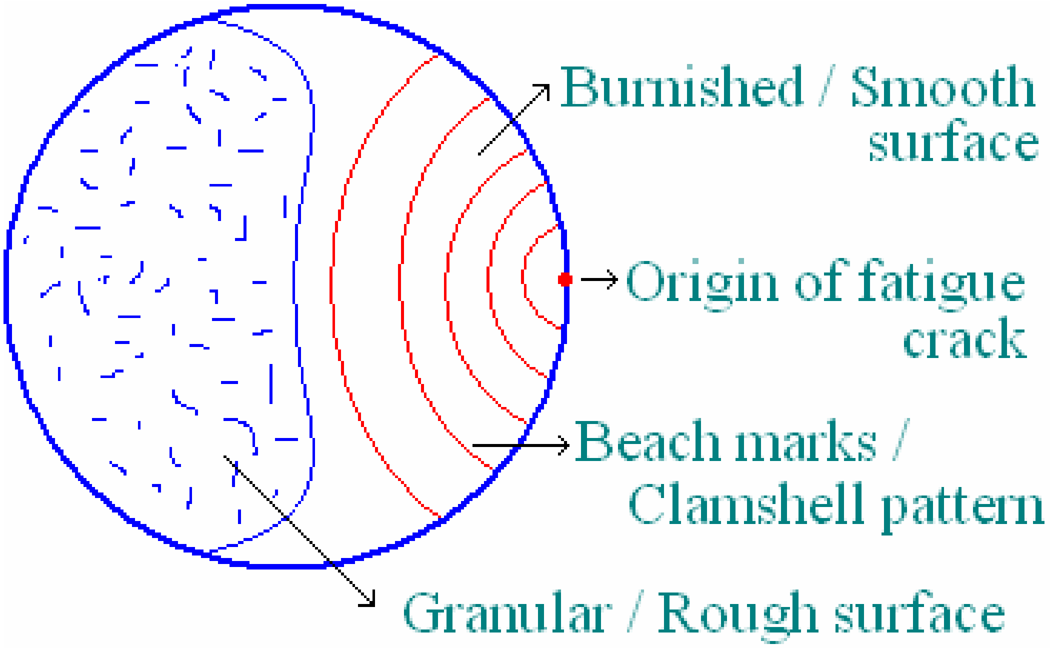


Fig 4.11: Schematic of fatigue fracture surface.

Three basic requisites for occurrence of fatigue fracture are: (a) a maximum tensile stress of sufficiently high value (b) a large enough variation or fluctuation in the applied stress and (c) a sufficiently large number of cycles of applied stress. The stress cycles that are evident in fatigue studies are characterized using many parameters, such as mean stress, alternating stress, stress ratio and amplitude ratio. If the applied stress varies between σ_{max} and σ_{min},

Range of stress, $\sigma_r = \sigma_{max} - \sigma_{min}$
Alternating stress, $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min})/2$ Mean stress, $\sigma_m = (\sigma_{max} + \sigma_{min})/2$
Stress ratio, $R = \sigma_{min} / \sigma_{max}$
Amplitude ratio, $A = \sigma_a / \sigma_m = (1-R) / (1+R)$

There are as many ways of conducting a test to measure fatigue as there are ways of applying repeated stresses to a metal. A specimen of rotating beam type is often used because of its simplicity. In a fatigue test, the premium output is number of cycles required to fracture the specimen at a given stress. If the maximum tensile stress applied is only slightly less than the yield strength (or tensile strength), test will run only a few cycles. Continues reduction of the stress greatly increases the life of the specimen, hence fatigue data is usually presented by plotting maximum stress (S) against number of cycles to fracture (N), using a logarithmic scale for the latter variable. This form of curve, S-N curve, shown in figure, is significant because there is a stress below which the specimens do not fracture. This limiting stress is called fatigue limit or endurance limit (σ_e), below which fatigue will never occur. Fatigue limit can be related to tensile strength of the material, and the ratio of fatigue limit to tensile strength is known as endurance ratio. Most steels have distinct fatigue limit, and is usually about 0.4-0.5 of tensile strength i.e. endurance ratio=0.4-0.5. Unlike steels, most nonferrous metals do not have a fatigue limit i.e. S-N curve continues to fall steadily with decreasing stress, though at a decreasing rate. Thus, fatigue will ultimately occur regardless of the magnitude of the applied stress. Fatigue response of these materials is specified for a number of stress cycles, normally 10^7, and is known as fatigue strength. Another important parameter that characterizes a material’s fatigue behavior is fatigue life, N_f, number of cycles to cause fatigue failure at a specified stress level.

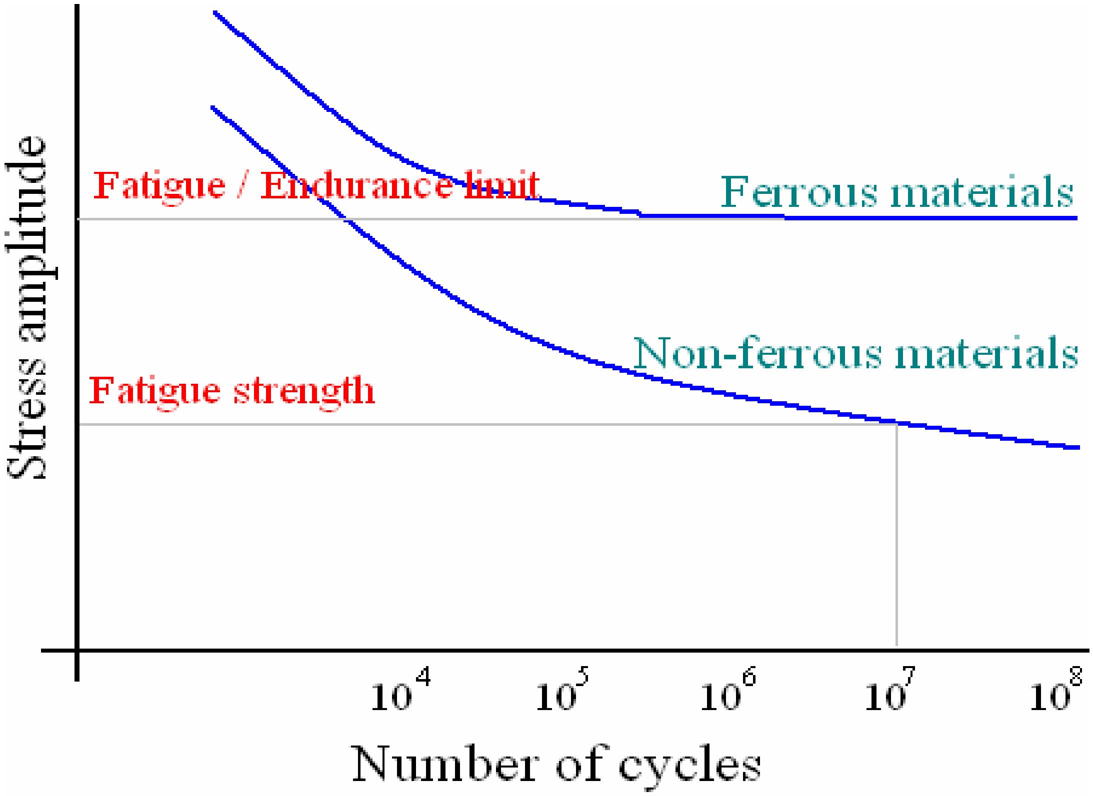


Fig 4.12: Typical S-N curves for ferrous and non-ferrous metals.

4.14. Creep

Creep is the gradual increase of plastic strain in a material with time at constant load. Particularly at elevated temperatures some materials are susceptible to this phenomena and even under the constant load, mentioned strains can increase continually until fractures. This form of facture is particularly relevant to the turbines blades, nuclear reactors, furnaces rocket motors etc. The general from of strain versus time graph or creep curve is shown below.

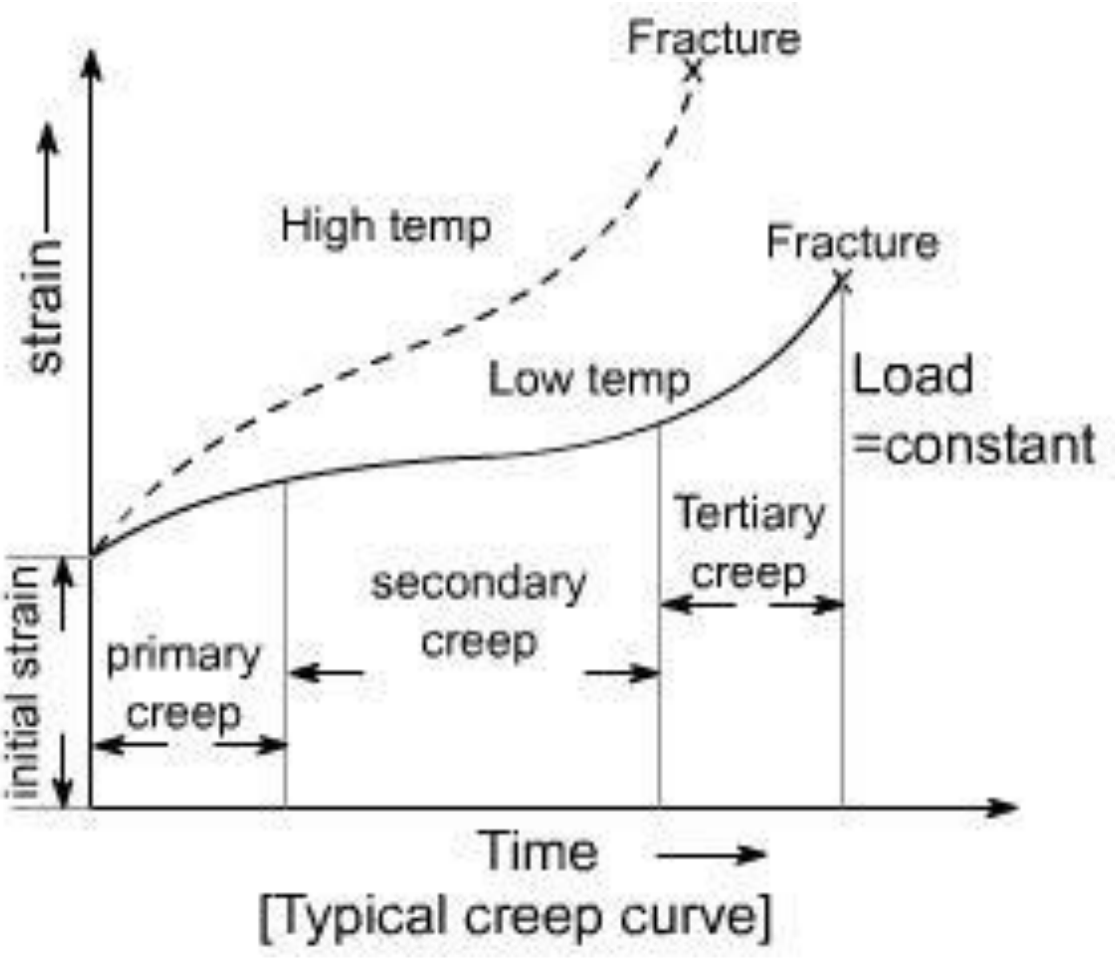


Fig 4.13: Typical creep curve

The general form of Î Vs t graph or creep curve is shown below for two typical operation conditions, In each case the curve can be considered to exhibit four principal features: An initial strain, due to the initial application of load. In most cases this would be an elastic strain. A primary creep region, during which he creep rate (slope of the graph) dimensions. A secondary creep region, when the creep rate is sensibly constant. A tertiary creep region, during which the creep rate accelerate to final fracture. It is obvious that a material which is susceptible to creep effects should only be subjected to stresses which keep it in secondary (st.line) region throughout its service life. This enables the amount of creep extension to be estimated and allowed for in design.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – V – Material Characterization and Selection – SMEA1201

5. Material Characterization and Selection

5.1. Crystal Structure Determination

The determination of an unknown structure proceeds in three major steps: 1. The shape and size of the unit cell are deduced from the angular positions of the diffraction lines. 2. The number of atoms per unit cell is then computed from the shape and size of the unit cell, the chemical composition of the specimen, and its measured density. 3. Finally, the position of the atoms within the unit cell are deduced from the relative intensities of the diffraction lines. The third step is generally the most difficult and there are many structures which are known only incompletely, in the sense that this final step has not yet been made. Size and Shape of the Unit Cell

Bragg's Law:

When x-rays are scattered from a crystal lattice, peaks of scattered intensity are observed which correspond to the following conditions:

1. The angle of incidence = angle of scattering.
2. The path length difference is equal to an integer number of wavelengths.

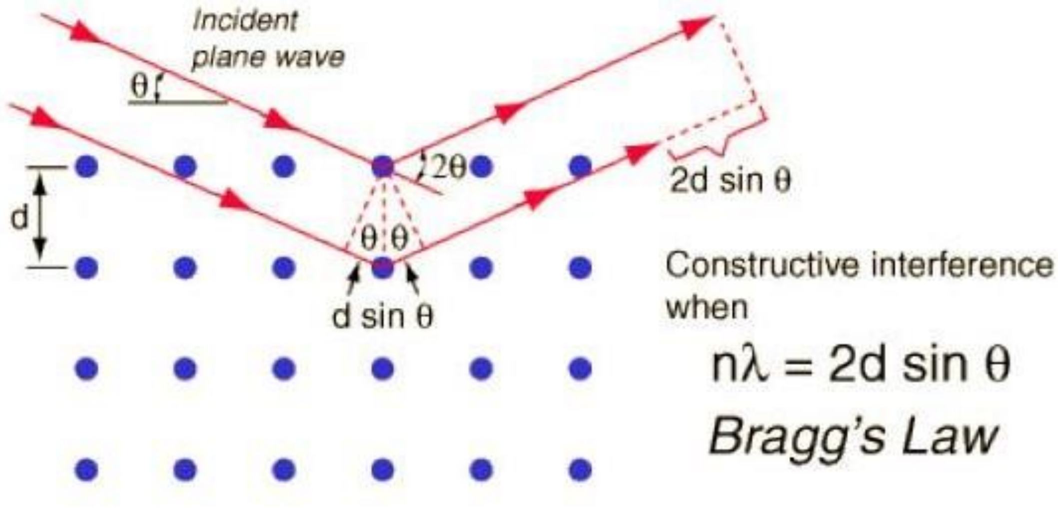

Fig 5.1: Bragg's diffraction

The condition for maximum intensity contained in Bragg's law above allow us to calculate details about the crystal structure, or if the crystal structure is known, to determine the wavelength of the x-rays incident upon the crystal.

5.2. X-ray diffraction:

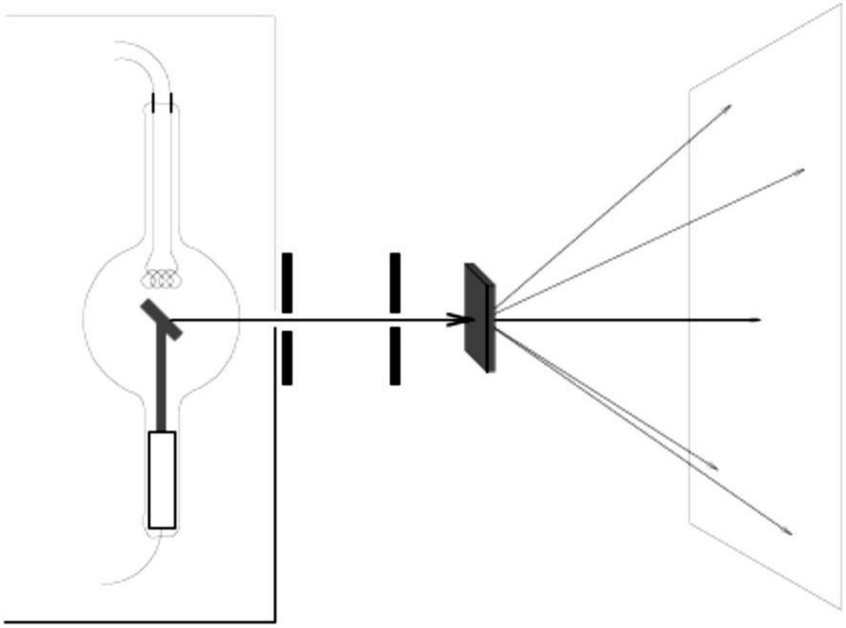

Fig 5.2: X-ray diffractometer

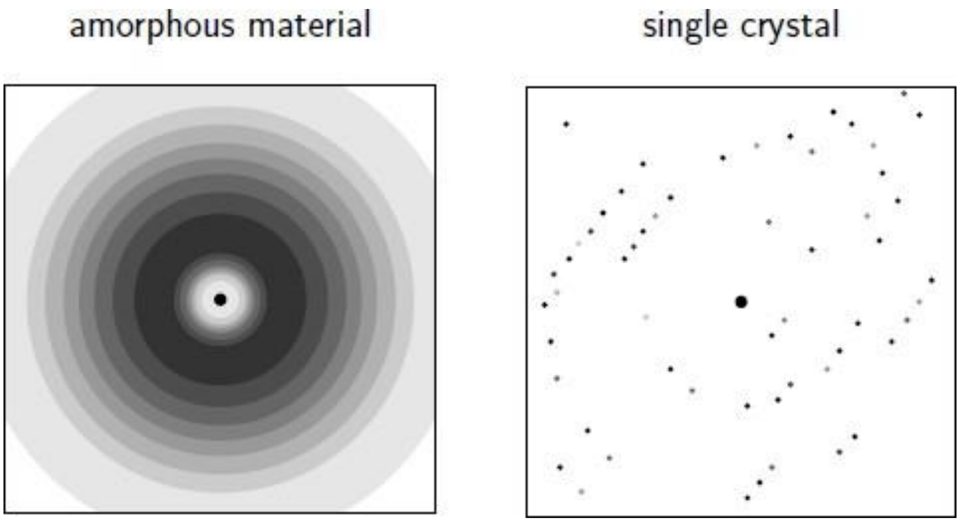

Fig 5.3: Diffracted images on the film

5.3. Powder diffraction method

A crystalline powder consists of small grains; each grain is a single crystal. In general the orientation of the grains in a powder sample is random. Grains with anisotropic shapes tend to show some ordering. The diffraction pattern consists of discrete cones, with top angle 4θ, dictated by Bragg's law. When projected on a plane perpendicular to the incident beam, a series of concentric circles is obtained. The diffraction pattern of a single crystal will change when the sample is rotated. The diffraction pattern of a powder will keep the same appearance when the sample is rotated, although other powder grains will contribute to the pattern.

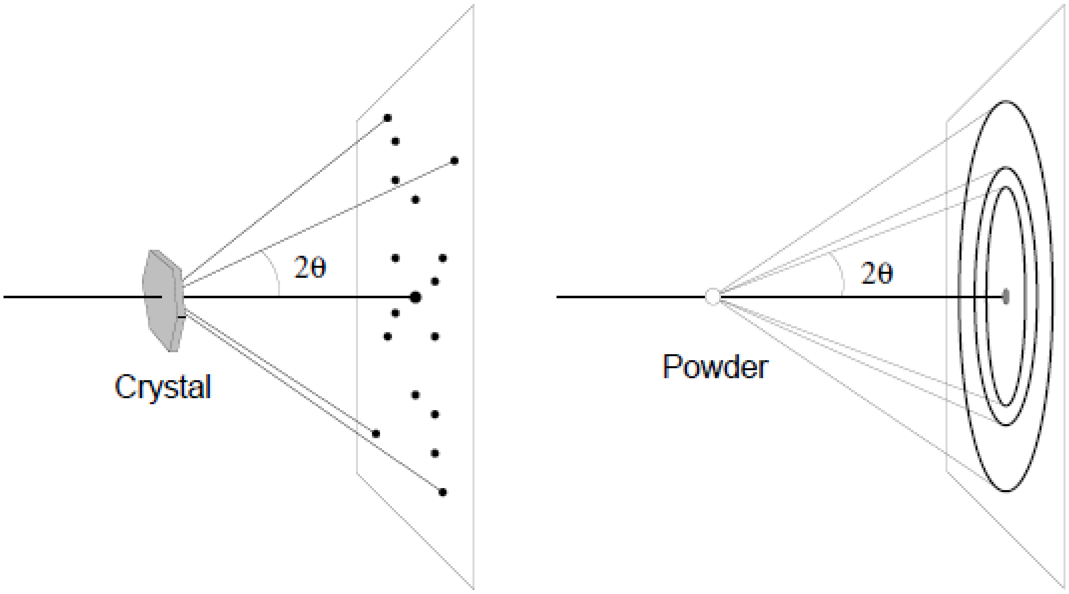

Fig 5.4: Diffraction in powder diffractometer

In a powder diffraction pattern large numbers of reflections will overlap, causing problems with indexing (determination of the unit cell) and intensity measurement. Powder diffraction can be used to identify materials without solving the structure.

- In the powder sample there are crystallites in different 'random' orientations (a polycrystalline sample too has grains in different orientations)
- The coherent x-ray beam is diffracted by these crystallites at various angles to the incident direction
- All the diffracted beams (called 'reflections') from a single plane, but from different crystallites lie on a cone.
- Depending on the angle there are forward and back reflection cones.
- A diffractometer can record the angle of these reflections along with the intensities of the reflection

- The X-ray source and diffractometer move in arcs of a circle- maintaining the Bragg ‘reflection’ geometry as in the figure.

5.4. Optical microscope

The optical microscope, also referred to as a light microscope, is a type of microscope that commonly uses visible light and a system of lenses to generate magnified images of small objects. Optical microscopes are the oldest design of microscope and were possibly invented in their present compound form in the 17th century. Basic optical microscopes can be very simple, although many complex designs aim to improve resolution and sample contrast. The object is placed on a stage and may be directly viewed through one or two eyepieces on the microscope. In high-power microscopes, both eyepieces typically show the same image, but with a stereo microscope, slightly different images are used to create a 3-D effect. A camera is typically used to capture the image (micrograph).

The sample can be lit in a variety of ways. Transparent objects can be lit from below and solid objects can be lit with light coming through (bright field) or around the objective lens (dark field). Polarised light may be used to determine crystal orientation of metallic objects. Phase-contrast imaging can be used to increase image contrast by highlighting small details of differing refractive index.

A range of objective lenses with different magnification are usually provided mounted on a turret, allowing them to be rotated into place and providing an ability to zoom-in. The maximum magnification power of optical microscopes is typically limited to around 1000x because of the limited resolving power of visible light. The magnification of a compound optical microscope is the product of the magnification of the eyepiece (say 10x) and the objective lens (say 100x), to give a total magnification of 1,000×. Modified environments such as the use of oil or ultraviolet light can increase the magnification.

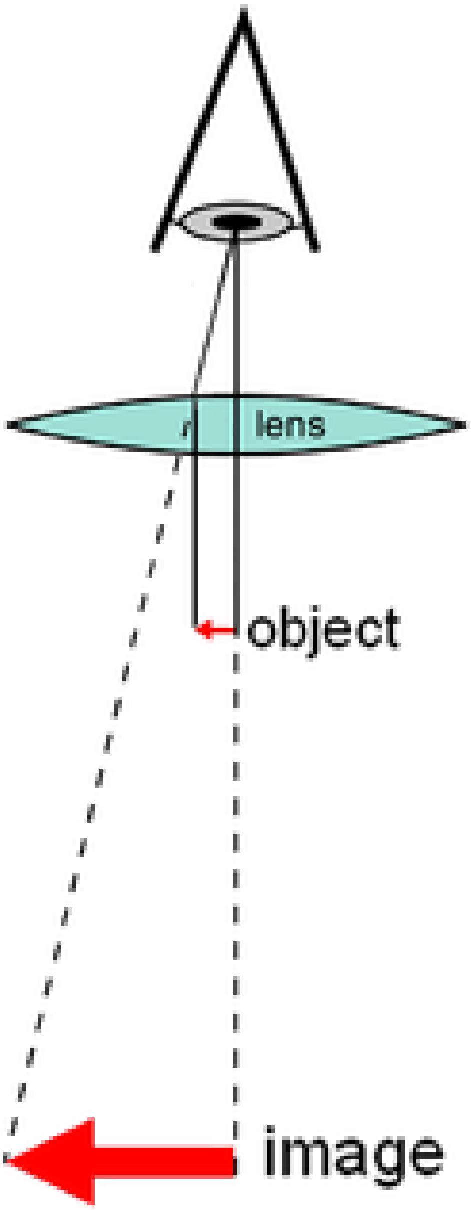

Fig 5.5: Image formation in optical microscope

A simple microscope uses a lens or set of lenses to enlarge an object through angular magnification alone, giving the viewer an erect enlarged virtual image. The use of a single convex lens or groups of lenses are found in simple magnification devices such as the magnifying glass, loupes, and eyepieces for telescopes and microscopes.

5.5. TEM and STEM

TEM, an abbreviation which can also stand for the instrument, a transmission electron microscope, is a microscopy technique in which a beam of electrons is transmitted through a specimen to form an image. The specimen is most often an ultrathin section less than 100 nm thick or a suspension on a grid. An image is formed from the interaction of the electrons with the sample as the beam is transmitted through the specimen. The image is then magnified and focused onto an imaging device, such as a fluorescent screen, a layer of photographic film, or a sensor such as a scintillator attached to a charge-coupled device. Transmission electron microscopes are capable of imaging at a significantly higher resolution than light microscopes, owing to the smaller de Broglie wavelength of electrons. This enables the instrument to capture fine detail—even as small as a single column of atoms, which is thousands of times smaller than a resolvable object seen in a light microscope. Transmission electron microscopy is a major analytical method in the physical, chemical and biological sciences. TEMs find application in cancer research, virology, and materials science as well as pollution, nanotechnology and semiconductor research, but also in other fields such as paleontology and palynology.

TEM instruments boast an enormous array of operating modes including conventional imaging, scanning TEM imaging (STEM), diffraction, spectroscopy, and combinations of these. Even within conventional imaging, there are many fundamentally different ways that contrast is produced, called "image contrast mechanisms." Contrast can arise from position-to-position differences in the thickness or density ("mass-thickness contrast"), atomic number ("Z contrast," referring to the common abbreviation Z for atomic number), crystal structure or orientation ("crystallographic contrast" or "diffraction contrast"), the slight quantum-mechanical phase shifts that individual atoms produce in electrons that pass through them ("phase contrast"), the energy lost by electrons on passing through the sample ("spectrum imaging") and more. Each mechanism tells the user a different kind of information, depending not only on the contrast mechanism but on how the microscope is used—the settings of lenses, apertures, and detectors. What this means is that a TEM is capable of returning an extraordinary variety of nanometer- and atomic-resolution information, in ideal cases revealing not only where all the atoms are but what kinds of atoms they are and how they are bonded to each other. For this reason TEM is regarded as an essential tool for nanoscience in both biological and materials fields.

A TEM can be modified into a scanning transmission electron microscope (STEM) by the addition of a system that rasters a convergent beam across the sample to form the image, when combined with suitable detectors. Scanning coils are used to deflect the beam, such as by an electrostatic shift of the beam, where the beam is then collected using a current detector such as a Faraday cup, which acts as a direct electron counter. By correlating the electron count to the position of the scanning beam (known as the "probe"), the transmitted component of the beam may be measured. The non-transmitted components may be obtained either by beam tilting or by the use of annular dark field detectors.

Fundamentally, TEM and STEM are linked via Helmholtz reciprocity. A STEM is a TEM in which the electron source and observation point have been switched relative to the direction of travel of the electron beam. See the ray diagrams in the figure on the right. The STEM instrument effectively relies on the same optical set-up as a TEM, but operates by flipping the direction of travel of the electrons (or reversing time) during operation of a TEM. Rather than using an aperture to control detected electrons, as in TEM, a STEM uses various detectors with collection angles that may be adjusted depending on which electrons the user wants to capture.

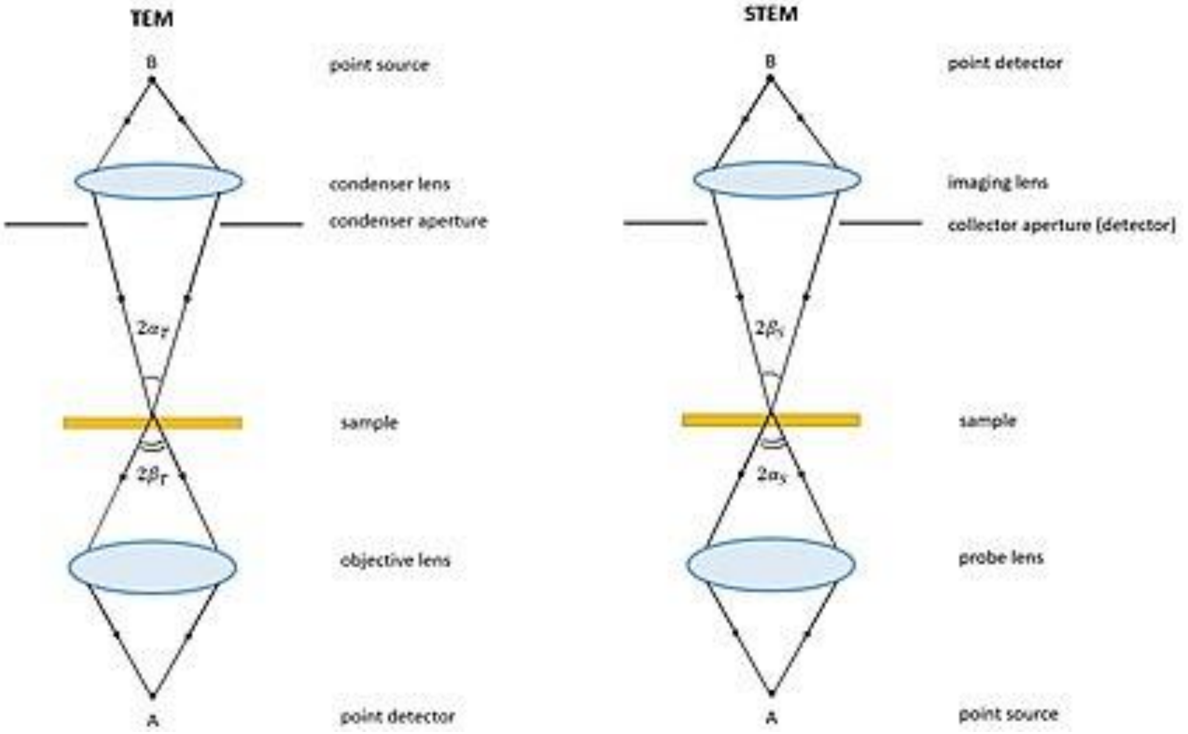

Fig 5.6: Image formation in TEM and STEM

5.6. Material selection

In an engine many parts work together and achieve the goal of converting chemical energy of fuel into mechanical energy. These parts are bolted together and the combination of all these parts is known as engine. Today I am going to tell you about these parts and how they work so you can know the basic of automobile engine.

1. Cylinder Block:-

- It is a container fitted with piston, where the fuel is burnt and power is produced.

- Cylinder is the main body of IC engine. Cylinder is a part in which the intake of fuel, compression of fuel and burning of fuel take place. The main function of cylinder is to guide the piston.
- For cooling of cylinder a water jacket (for liquid cooling used in most of cars) or fin (for air cooling used in most of bikes) are situated at the outer side of cylinder.
- At the upper end of cylinder, cylinder head and at the bottom end crank case is bolted.
- Material : Ductile (Nodular) Cast Iron ,30C8 (Low Carbon Steel)
- Manufacturing method : Casting, Forging and after that heat transfer , Machining

2. Cylinder Head/Cylinder Cover:-

- One end of the cylinder is closed by means of cylinder head. This consists of inlet valve for admitting air fuel mixture and exhaust valve for removing the products of combustion.
- The inlet valve, exhaust valve, spark plug, injector etc. are bolted on the cylinder head. The main function of cylinder head is to seal the cylinder block and not to permit entry and exit of gases on cover head valve engine.
- Material: Aluminium alloys
- Manufacturing Method: Casting

3. Piston:-

- Piston is used to reciprocate inside the cylinder.
- It transmits the energy to crankshaft through connecting rod.
- Material : Aluminum Alloy 4652 because of its Low Specific Gravity.
- Manufactuirng Method: Casting

4. Piston Rings:-

- These are used to maintain a pressure tight seal between the piston and cylinder walls and also it transfer the heat from the piston head to cylinder walls.
- These rings are fitted in grooves which have been cut in the piston. They are split at one end so they can expand or slipped over the end of piston.
- Material: cast iron of fine grain and high elastic material
- Manufacturing Method: Pot casting method

5. Connecting Rod:-

- One end of the connecting rod is connected to piston through piston pin while the other is connected to crank through crank pin.
- It transmits the reciprocatory motion of piston to rotary crank.
- There are two end of connecting rod one is known as big end and other as small end. Big end is connected to the crankshaft and the small end is connected to the piston by use of piston pin.
- Material: Low Carbon steel 30C8
- Manufacturing Methods : Forging and after that heat heat treatment.

6. Crank:-

- It is a lever between connecting rod and crank shaft.

7. Crank Shaft:-

- The function of crank shaft is to transform reciprocating motion in to a rotary motion.
- The crankshaft of an internal combustion engine receives the efforts or thrust supplied by piston to the connecting rod and converts the reciprocating motion of piston into rotary motion of crankshaft.
- The crankshaft mounts in bearing so it can rotate freely.
- The shape and size of crankshaft depends on the number and arrangement of cylinders.
- Material: 37C15 Alloy Steel.
- Manufacturing Method: Casting