RRB - JE
MECHANICAL

Railway Recruitment Board

Volume - 2

Production Engineering

MATERIAL SCIENCE

1.1 INTRODUCTION

Two materials will combine together and form alloy when the conditions of Hune-Rothary Rules are satisfied.

Conditions:

(i)   The difference in atomic radius should be less then 15%.

(ii) Valency of both the materials should be same.

(iii) Electronegativity and Electron affinity of both materials should be comparable.

(iv) Crystal Structures of both materials will be same.

1.2 PHASE DIAGRAM

Phase diagram is a plot on temperature composition space showing stability of various phases. In other words, it tells us what will be the melting point of alloy.

$$(P) = \text{Number of Phase}$$
$$(C) = \text{Number of Components}$$
$$(F) = \text{Number of Degree of Freedom}$$
$$C + 2 = F + P$$

If $\qquad\qquad C = 1$; Unitary phase diagram

Example: Carbon phase diagram

1.2.1 Binary Phase Diagram (C = 2)

(a) *Cu-Ni Phase Diagram:*

Materials which are completely soluble in the liquid state as well as solid state.

The line which separates the Mushy zone with the liquid phase is called liquids and the line which separates the Mushy zone with the solid phase is called Solidus.

Larger is the mushy zone of material, lesser will be its fluidity and hence large variation will be there in the properties of alloys. Fluidity also increases by increasing the temperature but there is a limit in casting practice beyond which we cannot increase the temperature.

Higher the temperature rise, design becomes very complex, also at high temperature moisture disintegrate in H_2 and O_2 and as hydrogen gas is coming out, it creates large. Number of pin holes on the surface of casted part. These defect is called Pin Hole Porosity.
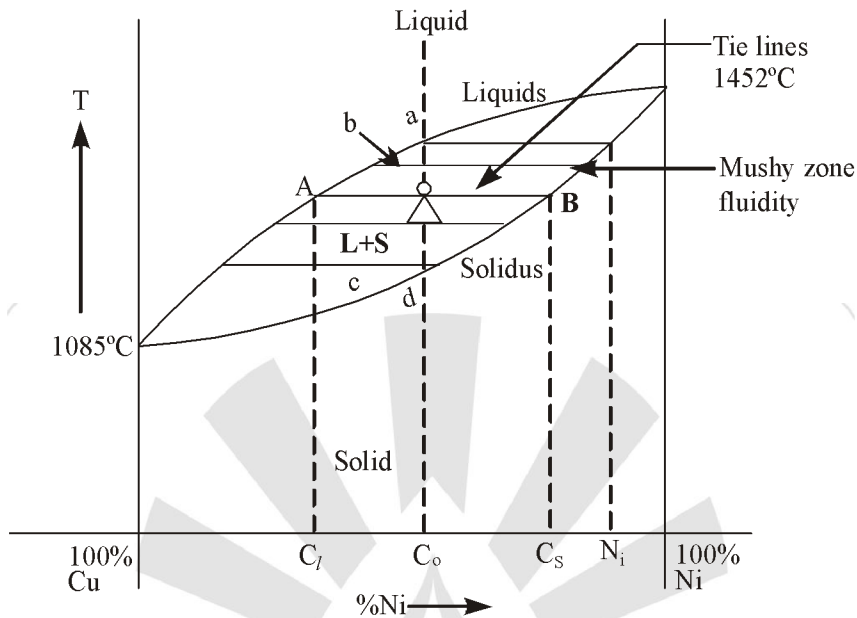
Cu-Ni Phase Diagram

$$m_l = \text{liquid}$$

$$m_s = \text{solid}$$

$$m_s + m_l = 1$$

$$m_s c_s + m_l c_l = c_0$$

$$(1 - m_l)c_s + m_l \cdot c_l = c_0$$

$$\therefore \quad c_s - c_s m_l + c_l \cdot m_l = c_0$$

$$\therefore \quad m_l (c_l - c_s) = c_0 - c_s$$

$$\because \quad m_l = \frac{c_0 - c_s}{c_l - c_s} \text{ (lever Rule)}$$

$$m_s = 1 - \frac{c_0 + c_s}{c_l - c_s} = \frac{c_l - c_s - c_0 + c_s}{c_l - c_s}$$

$$\because \quad m_l = \frac{c_l - c_0}{c_l - c_s} \text{ (lever Rule)}$$

Upon slowly cooling the sample of copper and nickel along line "a-d", following microstructures changes will be occurred.

At point "a" entire microstructure will be in the liquid phase. As soon as the temperature decreases slightly below the liquids line, solid particle at the liquid region upon decreasing nucleate.

For the temperature from point b to c, following conclusions can be drawn by drawing a no. of tie lines

(i) Mass fractions of solid phase increases.

(ii)   The moment solid nucleates, percentage of nickel in solid phase is very high and by decreasing the temperature, percentage of Nickel in solid phase is decreasing and approaching towards over all composition c_0.

At high temperature, phenomenon called diffusion appears in the material in which the atoms diffuses from higher to lower concentrations. It is solid so that at every 20°C increase in temperature, diffusion get doubles.

So nickel diffuses from centre to outward direction, making the entire composition homogeneous.

The moment temperature decreases slightly below the solidus line, entire sample converts into the solid phase. Each solidification front will have a particular arrangement of atoms and the region where two solidification front meets, there will be orientation mismatch of atoms called Grain Boundaries.

Bond length at the grain boundaries will be higher, larger the bond length, easily bond can break. That is why it is said that grain boundaries are at the high energy level. So atmospheric oxygen first attacks the grain boundaries atom and corrodes the materials. Finer is the grain structure, lesser will be the corrosion resistance of materials.

Generally to improve the corrosion resistance, chromium is added in the material, which after reacting with oxygen produces Chromium oxide which gets settle down at the grain boundaries, protecting the atoms from further oxidation.

(i)   Generally in iron nickel is called austenite phase stabilizer.

(ii)   Chromium is called ferrite phase stabilizer.

For Rapidly cooling
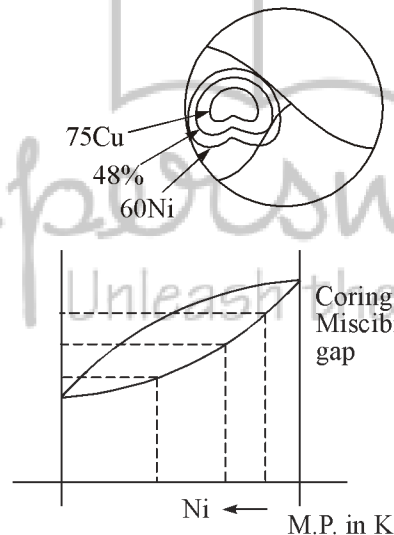
Cold working < 0.4 T_m

Warm working – 0.4 to 0.6 T_m

Hot working > 0.6 T_m

If the sample of copper and nickel is cooled rapidly. Since there is no sufficient time for diffusion to take place. There will be concentration gradient within the grain. At the grain boundaries, percentage of Nickel will be very low.

It can be observed in the phase diagram that lower is the percentage of Nickel, lower will be melting point of material. So upon hot working, the grain boundary material will melt out producing cracks, these leads to Brittle Fractures and the phenomenon is called Coring or Miscibility Gaps.

Note: All the binary phase diagram are plotted at a particular pressure which is one of the degree's of freedom. So the modified gibb's phase rule can be written as:
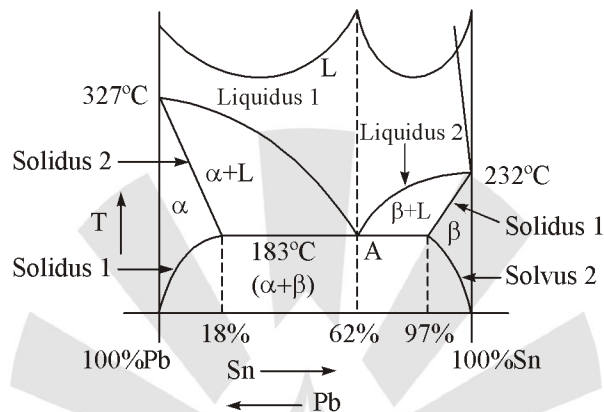
$$C + 2 - 1 = F - 1 + P$$

$$\Rightarrow \qquad C + 1 = F + P$$

(b) *Pb-Sn Phase Diagram:*

Materials which are completely soluble in the liquid state but partially soluble in the solid state.

Phase Diagram of Pb–Sn (Lead Tin) (Soldering Alloy)

Pb-Sn Phase Diagram

$$0.5 \; T_m = 0.5 \; (327 + 273) - 273$$

$$= 27°C \text{ (Melting point of lead)}$$

$$\alpha = \text{Phase is solid solubility of Sn (Tin) in Pb (lead) and}$$

$$\beta = \text{Phase is solid solubility of Pb in Sn.}$$

Maximum solid solubility appears at 183°C and it decreases by decreasing the temperature. Any line on the phase diagram which separates a single solid phase with a mixture of solid phases. is called solidus

At point-A　　　　　　　$L \underset{183°C}{\overset{62\% \; Sn}{\rightleftharpoons}} \alpha + \beta$ 　　Eutectic Reaction

$$C + 1 = F + P$$

$$2 + 1 = 0 + P$$

$$\therefore \qquad\qquad P = 3$$

On such phase diagrams, there appears a point at which there is no Mushy zone and liquid directly converts into two different solids. It is called Eutectic Reaction. At Eutectic point three phases exist in equilibrium simultaneously.
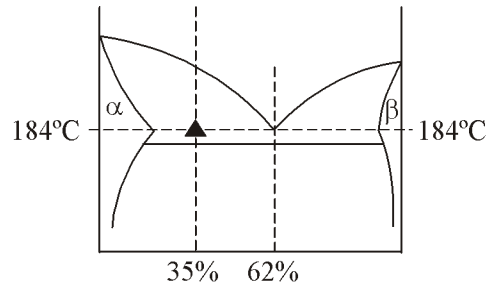
Example: Calculate the mass-fractions of phases present in an alloy of lead-Tin with 35% Sn and 62% Pb and at 184°C.

Solution: We know, 　　　　　$m_\alpha = \dfrac{62 - 35}{62 - 18} = \dfrac{27}{44} = 0.613$

And 　　　　　　　　　　$m_\beta = \dfrac{35 - 18}{62 - 18} = \dfrac{17}{44} = 0.386$

184°C α   β 184°C

35% 62%

Example: Calculate the mass and volume fraction of lead and Sn alloy with 35% Sn and 100°C. At this temperature. 10% Sn can be dissolved in Pb and 2% Pb can dissolve in Sn. Take density of Pb and Sn to be 10.25 g/cc. and 13.38 g/cc

Solution: 35% Sn at 100°C

$$m_\alpha = \frac{98.35}{98-10} = 0.715$$

And

$$m_\beta = \frac{35-10}{98-10} = 0.285$$

$$\alpha = 10\% \text{ Sn} + 90\% \text{ Pb}$$

And

$$\beta = 98\% \text{ Sn} + 2\% \text{ Pb}$$

∴

$$\frac{1}{\rho_\alpha} = \frac{0.1}{\rho_{Sn}} + \frac{0.9}{\rho_{Pb}}$$

And

$$\frac{1}{\rho_\beta} = \frac{0.98}{\rho_{Sn}} + \frac{0.02}{\rho_{Pb}}$$

$$\rho_\alpha = 10.49 \text{ gm/cc}$$

And

$$\rho_\beta = 13.29 \text{ gm/cc}$$

∴ Volume fraction
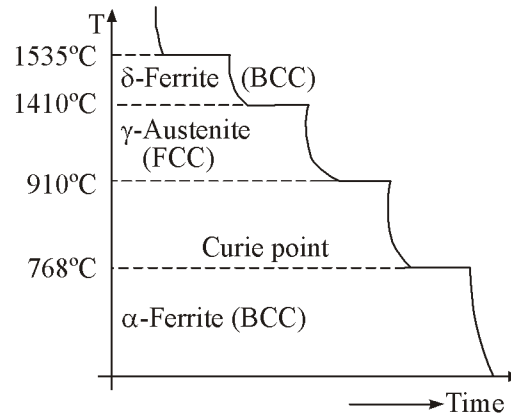
$$V_\alpha = \frac{\dfrac{m_\alpha}{\rho_\alpha}}{\dfrac{m_\alpha}{\rho_\alpha} + \dfrac{m_\beta}{\rho_\beta}} = 0.76$$

And

$$V_\beta = 1 - V_\alpha = 0.24$$
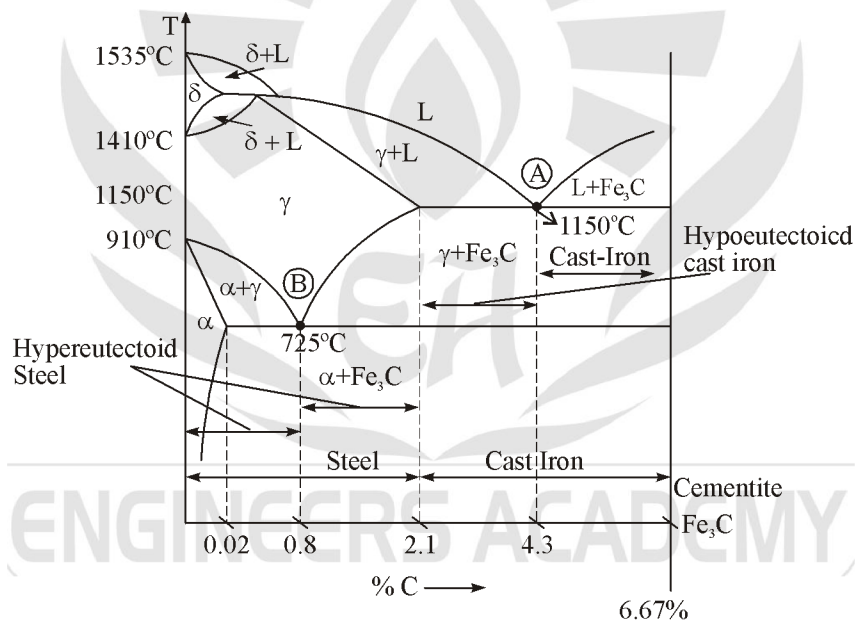
1.3 IRON CARBON PHASE DIAGRAM

Generally latent heat transactions indicates the change of phase and it can be represented by a horizontal line on temperature time graph. But in case of iron at 768°C, there is no change of phase and only magnetic properties are disappearing. These temperature is called *Curie Point.*
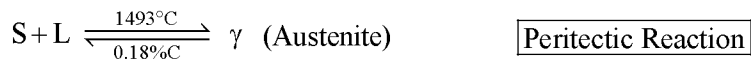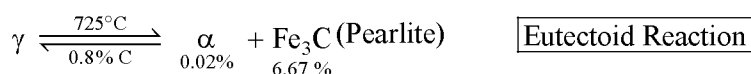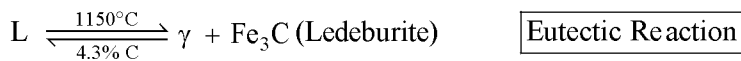
These characteristic of Iron due to which it exist in different phases at different temperature is called Allotropy.
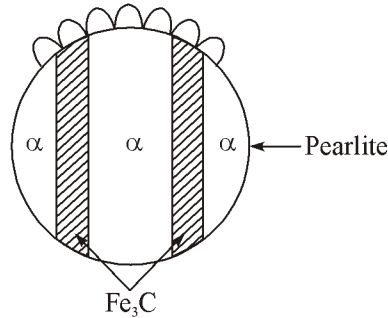
1.3.1 Paramagnetic Materials

Are those in which electron are unpaired and such materials exhibit colour like alloys of copper. Di-Magnetic materials are those in which electrons are paired and such materials are colourless. But some materials such as iron which sometimes behave as paramagnetic and sometimes as Di-Magnetic, depending upon temperature, due to its unique characteristic are called as *Ferro-Magnetic.*

Fe-C Phase Diagram

$$L \underset{4.3\% C}{\overset{1150°C}{\rightleftharpoons}} \gamma + Fe_3C \text{ (Ledeburite)}$$ | Eutectic Reaction |

$$\gamma \underset{0.8\% C}{\overset{725°C}{\rightleftharpoons}} \underset{0.02\%}{\alpha} + \underset{6.67\%}{Fe_3C} \text{(Pearlite)}$$ | Eutectoid Reaction |

$$S + L \underset{0.18\%C}{\overset{1493°C}{\rightleftharpoons}} \gamma \text{ (Austenite)}$$ | Peritectic Reaction |

Both are not phase of iron these are phase mixture of iron.

When one solid upon cooling converts into two different solids, these reaction is called Eutectoid reaction. Austenite is not stable below 725°C. So carbon diffuses from one interstitial side to another and forms alternate plate like structure of α and Fe_3C called pearlite. It all takes place by diffusion process.

Similarly eutectoid decomposition produces alternate plates of austenite and cementite and there microstructure ledeburite. Pearlite and Ledeburite are not phases, these are phase mixtures.

Note: *Five phases of Iron:*

α– Ferrite, γ– Austenite, δ– Ferrite, Cementite, Martensite

*When there is a large difference in the melting point of two materials, peritectic reactions appears on such phase diagrams and there diagrams, are called "**Peritectic Phase Diagrams**".*

__Peritectoid Reaction :__ When two solid combine together to form a single solid (one component) is called peritectoid reaction

$$S_1 + S_2 \underset{\longleftarrow}{\overset{Cooling}{\longrightarrow}} S_3$$
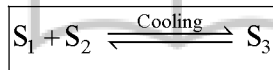
1.3.2 Classification of Steel

(a) *Low Carbon Steel/Mild Steel :*

Percentage of Carbon : 0 – 0.3%

(b) *Medium Carbon Steel :*

Percentage of Carbon : 0.3 – 0.7%

(c) *High Carbon Steel :*

Percentage of Carbon : > 0.7%

(d) *Gray Cast Iron :*

Cast iron of such composition in which carbon appears in free or flake form is called Gray Cast Iron. These materials is used in making machine beds, piston rings etc.

(e) *White Cast Irons :*

Cast iron of such composition in which entire carbon appears in the combined form is called white cast iron.

(f) *Chilled Cast Iron :*

Cast iron of such composition in which it will normally freezed as Gray but forced to appears as white are called chilled cast Iron (Sudden cooling). White and chilled cast irons are extremely brittle, and these materials are used to produce *Ductile Cast Iron.*

(g) Ductile Cast Iron :

Chilled Cast Iron is heated to a temperature below 1150°C and then cooled slowly in the present of Magnesium or Cerium (Ce). Carbon diffuses towards the centre and produce spheroidal structure which are Ductile. Slightly higher cooling rates produces Nodular structure.

Spheroids

SG Iron

Nodular Iron

Nodular structure
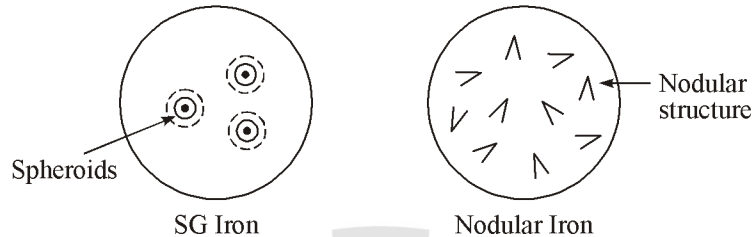
Note: We cannot avoid sulphur in Iron, it is from nature.

1.3.3 Effect of Sulphur and Mangnese in Iron

Whatever liquid and solid present in the nature impurity of sulphur cannot be avoided.

Sulphur in iron is a very dangerous impurity because after reacting with iron, it produces iron sulphide (FeS) which is having very low melting point.

So upon heating FeS melts out producing cracks at grain boundaries which leads to Brittle fracture. These phenomenon is called Hot shortness. To eliminate the ill effect of sulphur, Mangnese is added in the material. Mangnese capture sulphur, before sulphur captures iron and produces MnS (Mangnese Sulphide).

MnS is not only having high melting point but also it is having low shear strength, which increases the machinability of material. Further addition of mangnese, increases the strength of materials and with 12% Mn materials becomes exceptionally strong called Hadfield steel, used in haeavy duty applications like Bulldozers etc.

1.3.4 Effect of Silicon on Steel

Steels are very difficult to cast because it undergoes excessive shrinkages during solidification. So steel is having a tendency to capture oxygen from surroundings. Addition of silicon and, absorbs these Oxygen and produces SiO_2 which settles down as sludge.

Note: When deoxidization process of steel is complete it is called Killed Steel, but when the deoxydization is partial, it is called semi-killed steel.

Effect of Silicon in Cast Iron

$$C\text{-equivalent} = \%C + \frac{1}{3}C \% Si + \%P = 4.3 \%$$

3.3 % C + 3% Si

1.3.5 Effect of Silicon and Phosphorous

Addition of silicon and phosphorus in iron, shifts the iron-carbon diagram towards left. So, graphite flakes in cast-iron appears at much lower percentage of carbon. Addition of silicon in liquid iron, discharges graphite in red hot condition, & since graphite is having lower density, it jumps over the surface of liquid iron and sparkles. These phenomenon is called KISH.

Elements	Gray C.I.	White C.I.
C	2.5 – 4	1.8 – 3.6
Si	1 – 3	0.5 – 1.9
Mn	0.4 – 1.0	0.25 – 0.8
S	0.05 – 0.25	0.06 – 0.2
P	0.05 – 1.0	0.06 – 0.18

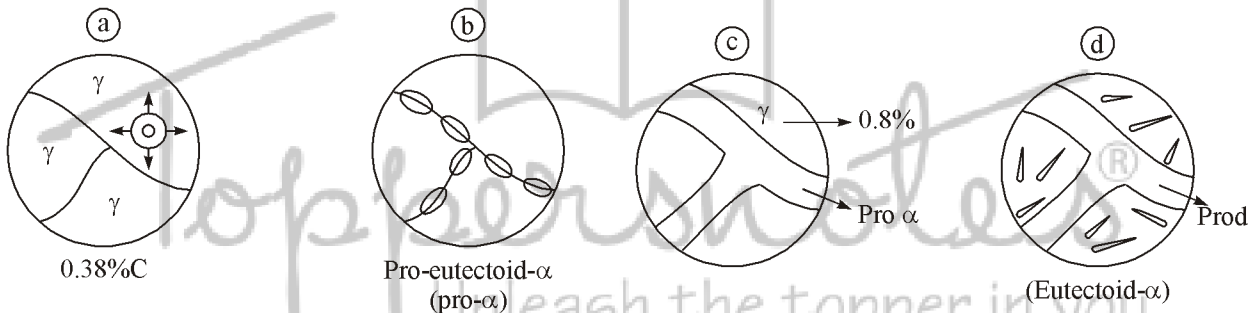### 1.3.6 Development of Micro-structure In Fe-C System

Upon cooling the sample of hypoeutectoid steel, with 0.35% C along line "a–d", following microstructural changes can be observed. At point "a", it is all austenite within the grain with 0.35% C. When the temperature decreases slightly below to point "b", Ferrite phase starts appearing in microstructure.

These ferrite which appears before eutectoid temperature is called hypereutectoid ferrite. Upon decreasing the temperature slowly from point "b–c" following conclusions can be made using lever rule.
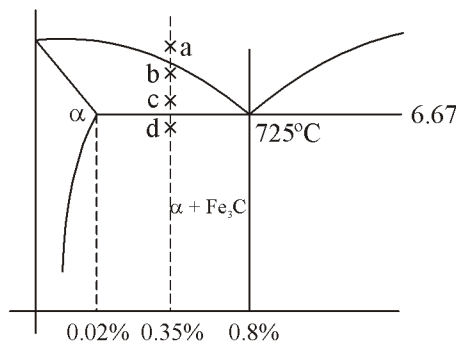
Mass fraction of pro-eutectoid ferrite increases.

Percentage of carbon in austenite within the grain increases and approaches towards the eutectoid composition.

Upon decreasing the temperature slightly below the eutectoid temperature, austenite within the grain converts into pearlite. Ferrite within the microstructure of pearlite is called Eutectoid Ferrite.

Development Of Micro-Structure

$$M_\alpha = \frac{6.67 - 0.8}{6.67 - 0.02} = 0.88$$

Example: Determine the mass fraction of pro-eutectoid ferrite, Eutectoid ferrite, total ferrite in steel sample having 0.35% C.

Solution: "b" Pro-eutectoid,

$$\Rightarrow \qquad m_{Pro\text{-}\alpha} = 0.576$$

$$H_{Fe_3C} = 0.423$$

$$m_{Pro\text{-}\alpha} = \frac{0.8 - 0.35}{0.8 - 0.02} = 0.576$$

"d"
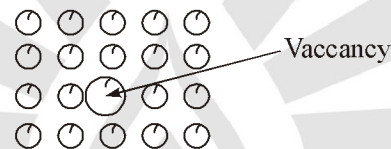$$m_{Total\text{-}\alpha} = \frac{6.67 - 0.35}{6.67 - 0.02} = 0.95$$

"c"
$$m_{eutectoid\text{-}\alpha} = 0.95 - 0.57 = 0.38$$

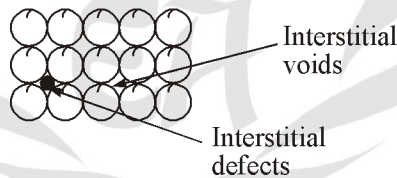# 1.4 TYPES OF DEFECTS

1.4.1 Point Defect

(a) *Vaccancy Defects*

When one atom from the crystal structure is escaped this type of defect is called as vaccancy defect.
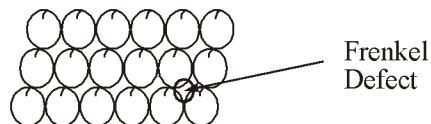

(b) *Interstitial Defects*

When one extra atom occupied the interstitial voides in crystal structure this type of defect is called as interstitial defect.
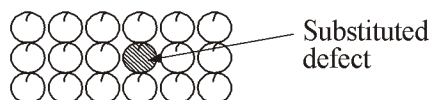

(c) *Frenkel Defects*

When one cation or anion is found extra in crystal structure this type of defect is called as frenkel defect.
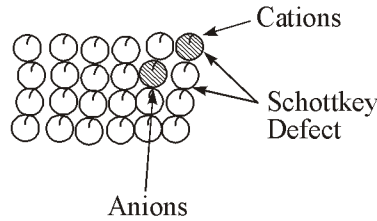

(d) *Substituted Defects*

When one extra atom replaced the previous crystal structures atom this type of defect is called as substituted defect.

(e) Schottkey Defects

When one cation and anion pair is found extra in crystal structure this type of defect is called as schottkey defect.

1.4.2 Surface Defect

(a) Grain Boundary Defect
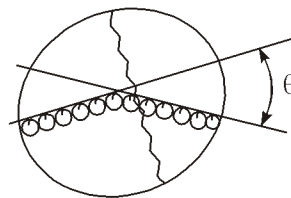
(b) Tilt Boundary Defect

If $\theta = \dfrac{1}{2}$ to $2°$

Then it is called as tilt boundary defect.

(c) Twin Boundary Defect

When the orientations across the grains boundaries are such, that it is the mirror image of each other it is called twin boundary defect.

(d) Staking Faults

1.4.3 Line Defects

(a) Edge Dislocation

AB (Edge) Dislocation

Edge dislocation cannot be removed from material.
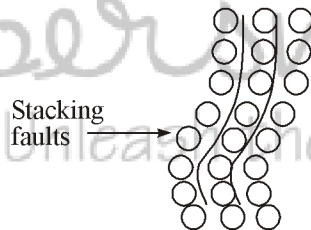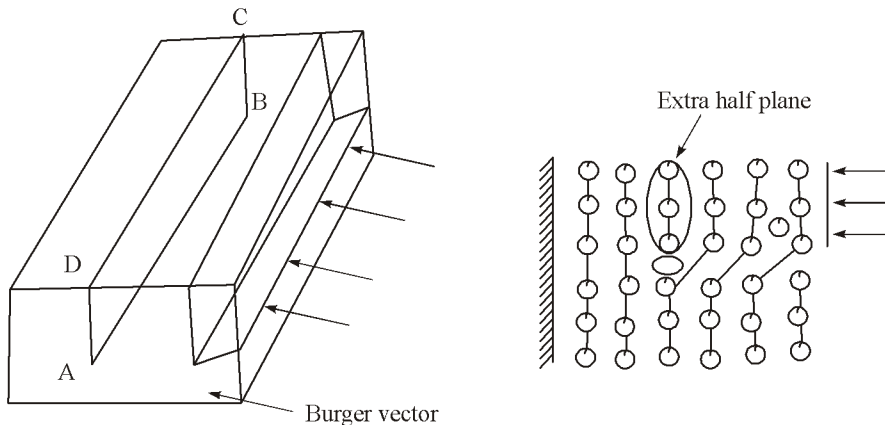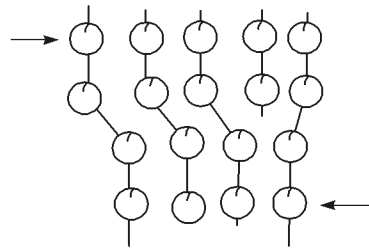
Although millions of edge dislocations are already there in the real material, but to understand the concept let us take an ideal material free from any defect. Once surface of these materials is restricted to deform and on the opposite face's 50% area a uniform pressure is applied, once this pressure exceeds beyond certain value, there will be slipping of atoms.

Slip is unit plastic deformation and it always appears in direction of applied load.

The direction of the slip is called Burger vector.

It can be observed in the diagram, that there will be a boundary AB between slipped and unslipped regions called Edge Dislocation.

It can be observed that at the edge dislocation line :

(i)   There appears an extra half plane.

(ii)   Interstitial void at the dislocation site will be slightly larger in size.

(b) *Screw Dislocation :*

In case of Edge dislocation, dislocation line is perpendicular to Burger vector. In screw dislocation, dislocation line is parallel to Burger vector.

Since millions of dislocations are already there within the grain, oriented in all the possible directions, when a load is applied on the materials, dislocations in that direction, starts moving within the materials. When the dislocation comes out it is said that plastic deformation has begin.

Any obstacle created in the movement dislocation, increase the strength of material.

1.5 YIELD POINT PHENOMENON

Cottrel area or region
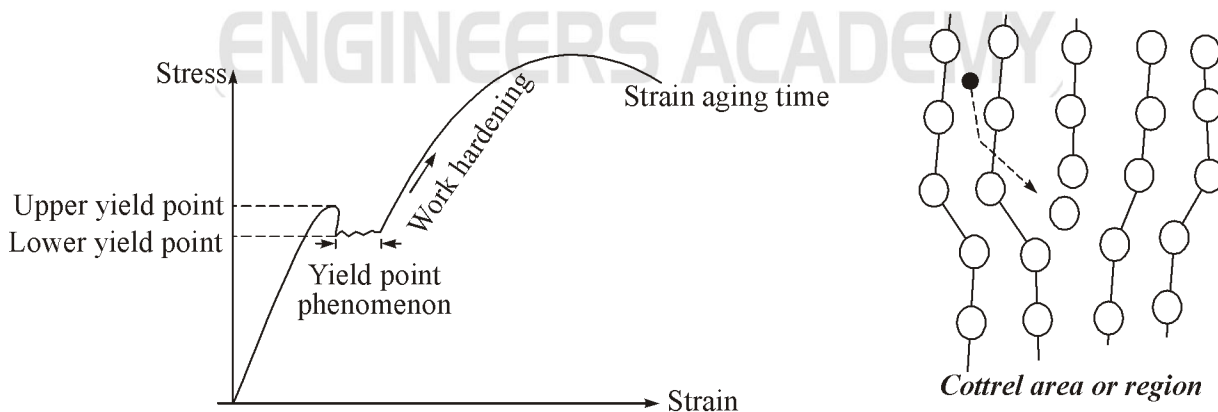
Carbon and nitrogen are interstitial impurity in iron. But the size of interstitial void is much smaller than size of carbon atom. So carbon diffuses through atomic structure and get accumulated to dislocation site and produces a carbon rich atmosphere called cottrel atmosphere.

These cottrel atmosphere produces atomic strains in the host iron atoms, so when external load is applied on the material, slightly larger stresses are required to break the cottrel atmosphere and jump the dislocation to new site. That is why upper yield point appears in materials.

Once the dislocation jumps the new site, relatively lower stresses are required to keep the dislocation moving. That is why lower yield point and yield point phenomenon appears in the material.

Upon unloading the material from the region of work hardening and unloading again, yield point phenomenon will not appear. But after waiting for some time (Around 2 years) carbon Nitrogen will again diffuse to dislocation site and again Cottrel Atmosphere will be produce. Hence yield point phenomenon will reappear in material.

The period after which yield point phenomenon reappears in material is called strain Aging Time.

These phenomenon doesn't appear in medium and high carbon steels because carbon is not only present at dislocation site but on the other interstitial sites as well. So once dislocation jump into new position, carbon is already there to diffuse.

1.6 STRENGTHENING MECHANISM

1.6.1 Alloying
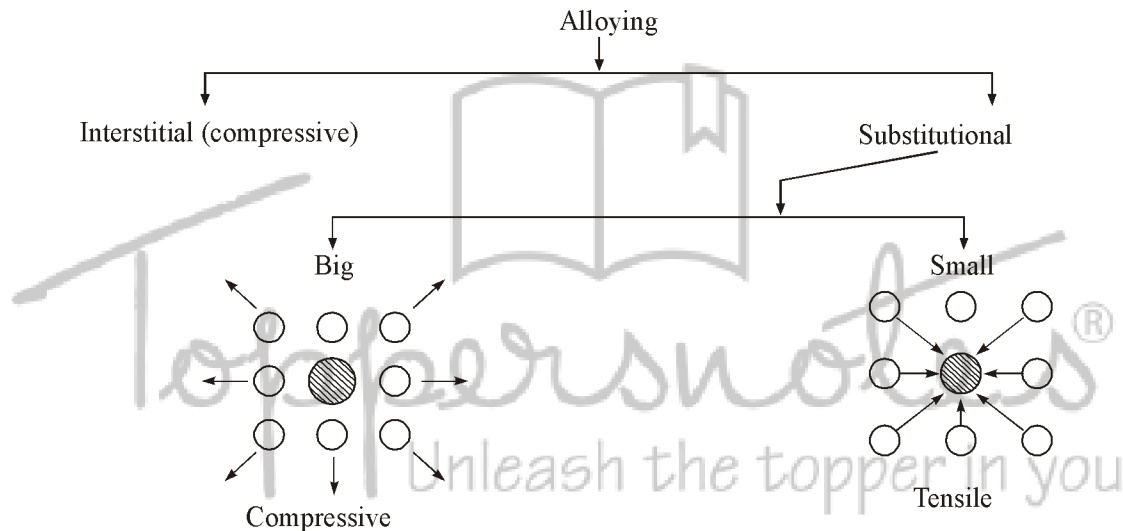
If impurity atoms occupies the interstitial site, it produces compressive Strain field. A smaller size substitutional impurity produces tensile strain field and large size substitutional impurity produces compressive strain field. These strain field creates as obstacle in movement of dislocation, which increases the strength of material. Larger the strain field created by impurity atom, more increase in strength will takes place.

1.6.2 Grain Refinement

As soon as dislocation reaches the grain boundaries, it has to change its direction and also due to larger bond length larger stresses are required by dislocation to cross through grain boundaries. Hence finer is the grain structure, more stronger the material will

1.6.3 Work Hardening or Strain Hardening

Upon cold working any material no. of dislocation increases. How much dislocation multiplication, material will undergo is the property and cannot be changed. These new dislocations which have been formed accumulates at the grain boundaries and produces a dislocation forest. The interaction between two dislocations are repulsive in nature.

Bauschinger Effect

$\sigma_c = 700$ MPa

$700 - 300 = 400$MPa

Ⓐ = Power
Hallomon equation or Flow curve equation
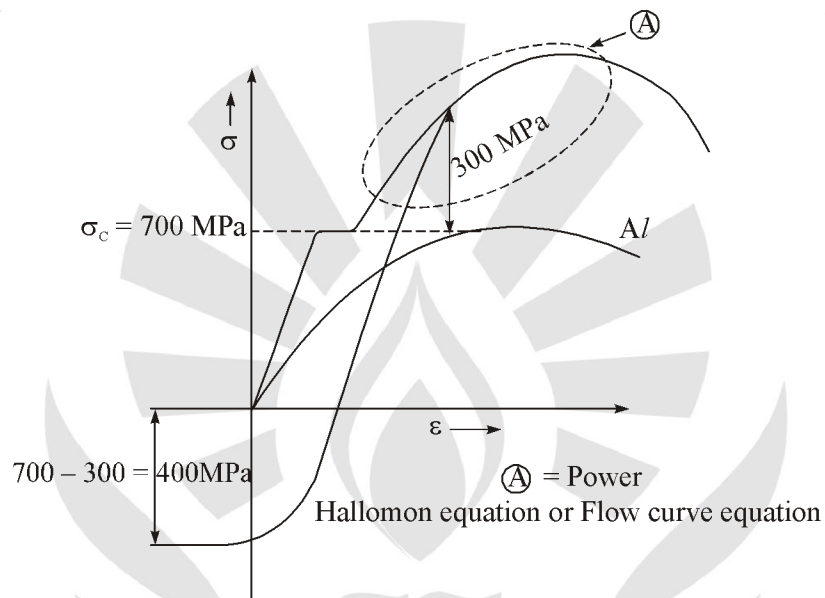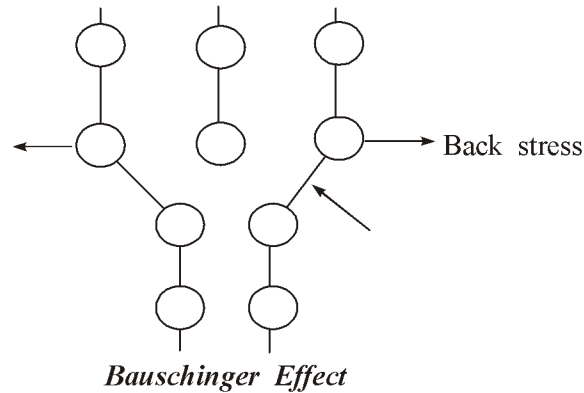
So these dislocation forest creates a back stress in the movement of dislocation within the grain. These increases the strength of material.

Upon unloading the material from the region of work hardening and the reloading in the opposite direction, back stresses now support the movement of dislocation and as a result of that yield point in compression appears prematurely. These phenomenon is called Bauschinger Effect.

Note: *Power law or Hollomen equation = Flow curve Equation"*

$$\sigma_f = K\varepsilon^n$$

σ_f = True stress

K = Strength coefficient

ε = True strain

n = 0.3 → Standard working exponent

Engineering Stress (Nominal Stress) $\sigma_0 = \dfrac{P}{A_0}$

True stress, $\sigma_f = \dfrac{P}{A} \times \dfrac{A_0}{A_0} = \sigma_0 \left(\dfrac{A_0}{A} \right)$

Now, $V = A_0 l_0 = A.l.$

$\Rightarrow$ $\qquad \dfrac{A_0}{A} = \dfrac{l}{l_0} = \dfrac{l}{l_0} - 1 + 1 = \dfrac{l - l_0}{l_0} + 1$

$\Rightarrow$ $\qquad \dfrac{A_0}{A} = \varepsilon + 1$

$\therefore$ $\qquad \sigma_f = \sigma_0 \,(\varepsilon + 1)$

True Strain :

$$\int_0^\varepsilon d\varepsilon = \int_{l_0}^l \dfrac{dl}{l}$$

$\Rightarrow$ $\qquad \varepsilon = ln\left(\dfrac{l}{l_0}\right) = ln(\varepsilon + 1)$

True Stress: $\qquad \sigma_f = \dfrac{P}{A}$

$\therefore$ $\qquad \dfrac{d}{d\varepsilon}[P = \sigma_f \cdot A]$

$\Rightarrow$ $\qquad \dfrac{dP}{d\varepsilon} = \sigma_f \cdot \dfrac{dA}{d\varepsilon} + A \cdot \dfrac{d\,\sigma_f}{d\varepsilon}$ $\qquad$ ..(1)

And $\qquad V = Al$

$\therefore$ $\qquad \dfrac{dV}{d\varepsilon} = A \cdot \dfrac{dl}{de} + l \cdot \dfrac{dA}{d\varepsilon}$ $\quad$ (V = constant) $\qquad$ ...(2)

$\Rightarrow$ $\qquad 0 = \dfrac{A}{l}\dfrac{dl}{d\varepsilon} + \dfrac{dA}{d\varepsilon}$

$\Rightarrow$ $\qquad \dfrac{dA}{d\varepsilon} = -A$ $\qquad$ ...(3)

$\therefore$ $\qquad \dfrac{dP}{d\varepsilon} = -\sigma_f A + A \cdot \dfrac{d\sigma_f}{dt}$

At UTS (Ultimate Tensile Stress)

$$\dfrac{dP}{d\varepsilon} = 0$$

$\therefore$ $\qquad \dfrac{d\sigma_f}{d\varepsilon} = \sigma_f$ $\qquad$ ...(4)

$\therefore$ $\qquad \dfrac{d}{d\varepsilon}\left[\sigma_f = K \cdot \varepsilon^n\right]$

$\Rightarrow$ $\qquad \dfrac{d\sigma_f}{d\varepsilon} = Kn.\varepsilon^{n-1} \cdot \dfrac{\varepsilon}{\varepsilon}$

$\therefore$ $\qquad \dfrac{d\sigma_f}{d\varepsilon} = \dfrac{n}{\varepsilon} \cdot \sigma_f$ $\qquad$ ...(5)
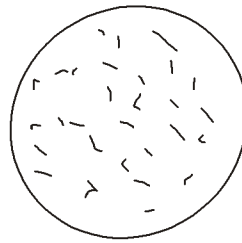
At UTS by, (4) and (5) $\qquad n = \varepsilon$

Example: The UTS of material is 400 MPa, Elongation is 35% and $\sigma_f = K.\varepsilon^n$.

       What is K and n ?

Solution:

$$Al_2Cu$$

$$\varepsilon = 0.35$$

$$\therefore \qquad \varepsilon = ln(1+\varepsilon)$$

$$= ln(1+0.35) = 0.3$$

At UTS $\qquad \varepsilon = n$

$$\sigma_f = K.\varepsilon^n = K.\varepsilon^n$$

$$400 = K(0.3)^{0.3}$$

$$K = 574.71 \text{ MPa}$$

1.6.4 Age (Precipitation) Hardening

An alloy of aluminum and copper with less than 5.5% Cu in it, is heated to a temperature at which uniform phase α appears in microstructure.

The sample is quenched from these temperature and as a result of that, copper gets locked in the structure of aluminium. Slowly copper starts coming out of the microstructure and forms precipitates of Al_2Cu. These precipitates creates and obstacle in the movement of dislocation. These increases the strength of material.
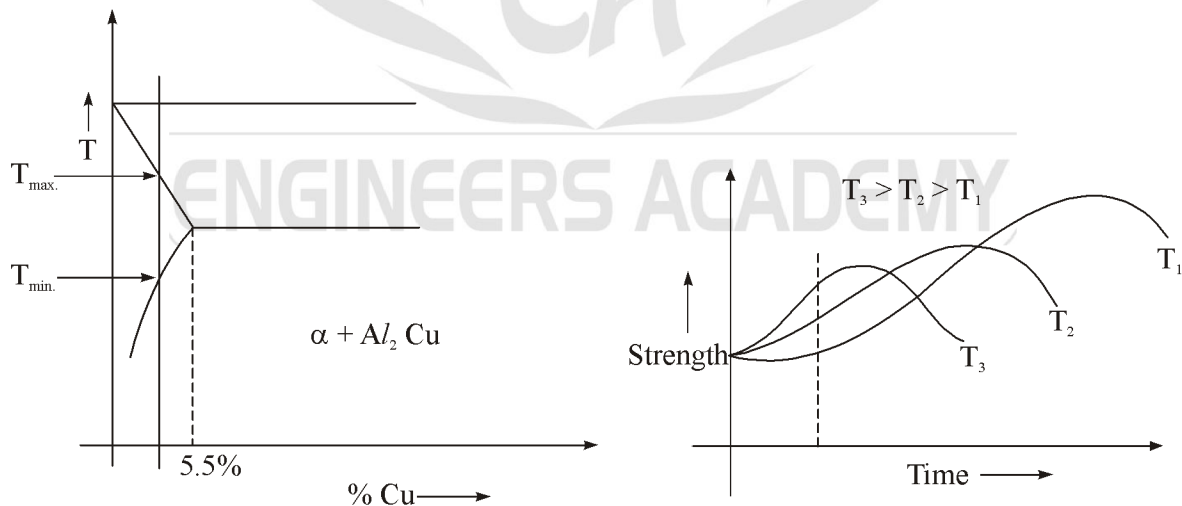

As the time passes more and more precipitate nucleates, this decreases the average distance between the precipitates and hence dislocation find more number of obstacle in its movements. These increases the strength further. Since the copper in the limited quantity, after sometime nucleation stops. These corresponds to peak strength of the material.

After sometime smaller precipitates are combining together and forming bigger precipitates. These increases average distance between precipitates and hence dislocation finds less number of obstacles in its movements. These decreases the strength of the sample and these phenomenon is called over aging.

When aging is observed at elevated temperature, it is called Artificial Aging. Higher the temperature of artificial aging, due to higher diffusion, rate of nucleation will increase so material will become stronger in lesser time period. But also at elevated temperatures, the rate at which smaller precipitates combining together, also increases, these decreases the peak strength.

1.7 CREEP

Creep is slow and progressive deformation of material over a period of time at constant load and at a temperature higher than recrystallization temperature. As soon as the material is loaded instantaneous creep will appear in it which is similar to the elastic strength. In the primary creep region, since work hardening phenomenon is predominating, so the strain rate decreases.
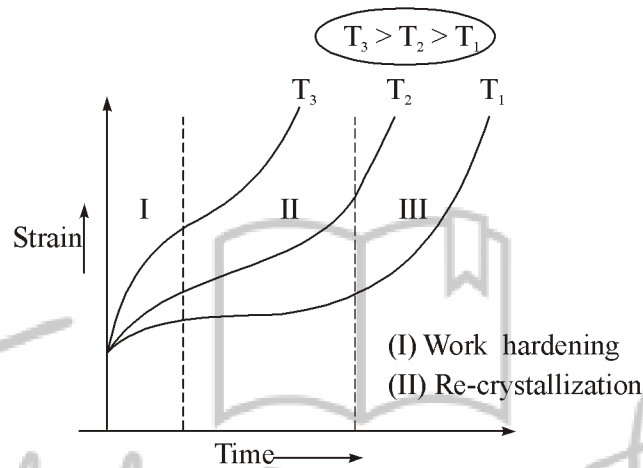
In the secondary creep region a balance will be achieved between work hardening and recrystallization, so almost constant strain rates will be observed. But there will be a limit upto which work hardening can take place and slowly recrystallization phenomena takes over and strain rate suddenly increases and finally material fractures.

Higher is the temperature more predominating the recrystallization phenomenon will be and hence creep curve will keep on shifting left. There is a tendency of grain boundary material to flow at elevated temperature, so finer is the grain structure, lower will be the creep resistance.

1.8 TENSILE TEST

ASTM : American standard for testing materials.

The middle portion of tensile test specimen where cross-section area is uniform is called parallel length. Gauge length is the length marked over parallel length for observation purpose.
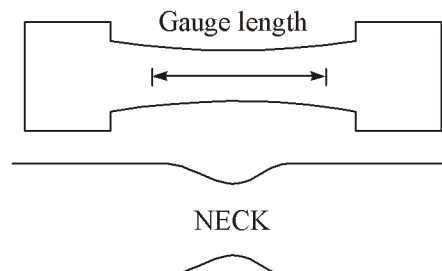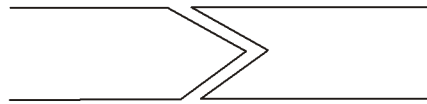
Cup & Cone

Once the stress exceeds the yield strength, cross section are of sample decreases and stress increases, but still sample is not failing because due to work hardening, material is developing sufficient strength to compensate the increase in stress.

At UTS point, there will be a point of minimum weakness anywhere in parallel length where sufficient work hardening has not been done to increase the strength. That is the point at which a unique neck will appear in material and finally material will fracture like cup and cone.

1.9 HARDNESS TEST

1.9.1 Rockwell Hardness Test
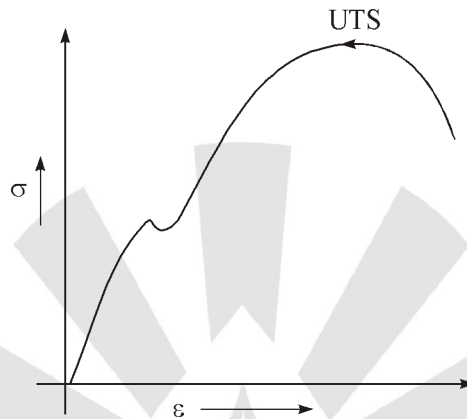
The rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter. The indenter is forced into the test material under a preliminary minor load F_0 usually 10 kgf.

When equilibrium has been reached, an indicating device, which following the movements of the indenter and so responds to changes in depth of penetration of the indenter is set to a datum position. While the preliminary minor load is still applied an additional major load is applied with resulting increase in penetration.
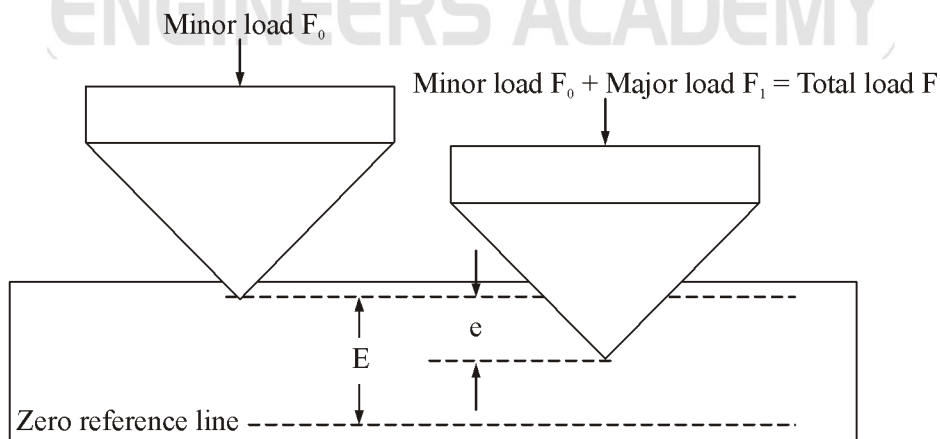
Rockwell Hardness Testing

When equilibrium has again been reach, the additional major load is removed but the preliminary minor load is still maintained. Removal of the additional major load allows a partial recovery, so reducing the depth of penetration.

The permanent increase in depth of penetration, resulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.

$$F_0 = \text{Preliminary minor load in kgf}$$

$$F_1 = \text{Additional major load in kgf}$$

$$F = \text{Total load in kgf}$$

$$e = \text{Permanent increase in depth of penetration due to}$$
$$\text{major load } F_1 \text{ measured in units of } 0.002 \text{ mm}$$

$$E = \text{A constant depending on from indenter}$$
$$100 \text{ units for diamond indenter}$$
$$130 \text{ units for steel ball indenter}$$

$$HR = \text{Rockwell hardness number}$$

$$D = \text{Diameter of steel ball}$$

$$HR = E - e$$

1.9.2 Brinell Hardness Test

The Brinell hardness test method consists of indenting the test material with a 10 mm diameter hardened steel or carbide ball subjected to a load of 3000 kg. For softer materials the load can be reduced to 1500 kg or 500 kg to avoid excessive indentation.

The full load is normally applied for 10 to 15 seconds in the case of iron and steel and for at least 30 second in the case of other metals.

The diameter of the indentation left in the test material is measured with a low powered micropscope. The brinell harness number is calculated by dividing the load applied by the surface area of the indentation.
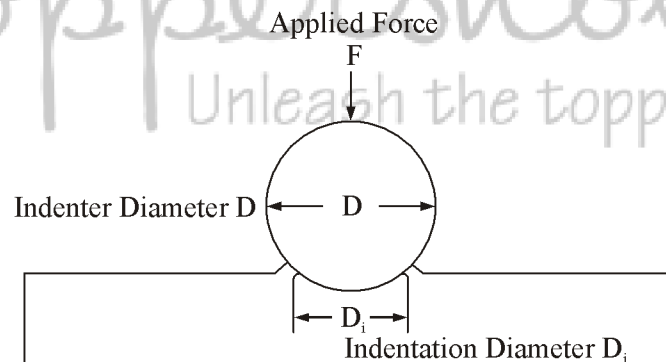
$$BHN = \frac{F}{\frac{\pi}{2} D \left(D - \sqrt{D^2 - D_i^2} \right)}$$

The diameter of the impression is the average of two readings at right angles and the use of a brinell hardness number table can simplify the determination of the brinell hardness. A well structured brinell hardness number reveals the test conditions, and looks like this, "75 HB/10/500/30" which means that a brinell hardness of 75 was obtained using a 10 mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds.

On tests of extremely hard metals a tungsten carbide ball is substituted for the steel ball. Compared to the other hardness test methods, the brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures and any irregularities in the uniformity of the material.

This method is the best for achieving the bulk or macro-hardness of a material, particularly those materials with heterogeneous structures.

1.9.3 Vickers Hardness Test

The vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite face subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds.

The two diagonals of the indentation left in the surface of material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

$$F = \text{Load in kgf}$$

$$d = \text{Arithmetic mean of the two diagonals}$$

$$d_1 \text{ and } d_2 \text{ in mm}$$

$$HV = \text{Vickers hardness}$$

$$HV = \frac{F}{d}$$

When the mean diagonal of the indentation has been determined the vickers hardness may be calculated from the formula, but is more convenient to use conversion tables. The vickers hardness should be reported like 800 HV/10, which means a Vickers hardness of 800, was obtained using a 10 kgf force. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary change of scale with the other hardness testing methods.

The advantages of the vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of material, under varying loads, the vickers machine is a floor standing unit that is more expensive than the brinell or rockwell machines.

1.10 IMPACT TEST

The Charpy impact test, also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture.

Impact Test
(Simply supported)
Charpy (Cantilever)
55
2mm
10x
45°
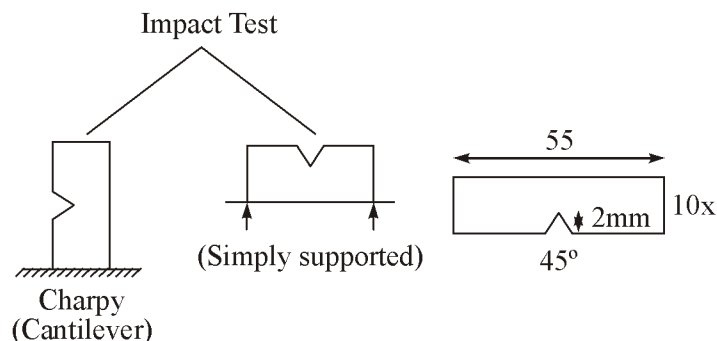
This absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature dependent ductile brittle transition. It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. A disadvantage is that some result are only comparative.

1.11 TTT CURVE

If can observed from Fe-C phase diagram that Austenite cannot be stable below 725°C. But upon quenching austenite to different temperature, it was observed that for a substantial period of time, there is no change in microstructure.
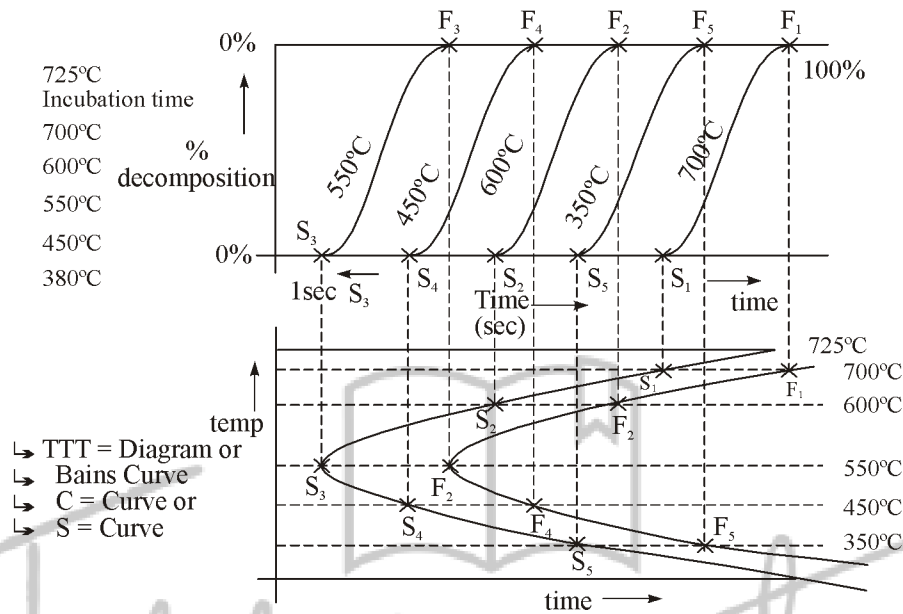
This period is call incubation time. Upon decreasing the temperature incubation period decreases and at 550°C it was only 1 sec. Upon decreasing the quenching temp. Further, incubation period started increasing again.

1.11.1 Driving Force

$$\Delta G = G_{initial} - G_{initial}$$

$$= +ve \ stable$$

$$= 0 \ neutral$$

$$= -ve \ unstable$$

1.11.2 Atomic Mobility (Diffusion)

Near 725°C, incubation period is high due to lower driving force. At 550°C both driving force and diffusion are optimum. So the incubation time is only 1 second. Below 550°C, all the driving force is high but due to lower diffusion carbon atoms doesn't have enthusiasm to jump from one interstitial site to another, these increases incubation time.
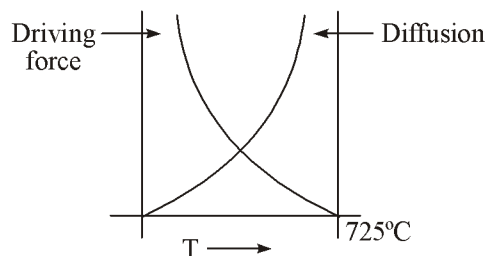
Under these circumstances, iron atom will slip and carbon will be forced to dislodge. That is why mechanics of formation of bainite is due to combine effect of diffusion and shear.

1.12 HEAT TREATMENT

1.12.1 Introduction

It may be defined as an operation of heating and cooling of metals in the solid state to induce certain desired properties into them. Heat treatment can alter the mechanical properties of steel by changing the size and shape of the grains of which it is composed, or by changing its micro-constituents.

It is generally employed for the following purposes :

(i)   To improve machinability

(ii) To change or refine grain size.

(iii) To relieve the stresses of the metal induced during cold or hot working.

(iv) To improve mechanical properties, e.g., tensile strength, hardness, ductility, shock resistance to corrosion etc.

(v)   To improve magnetic and electrical properties.

(vi) To increase resistance to wear, heat and corrosion.

(vii) To produce a hard surface on a ductile interior.

The various improvements from heat treatment are a result of the development of certain micro-constituents which have desired qualities. These micro-constituents are obtained by different rates of heating and cooling which have been discussed under various processes of heat treatment.

1.12.2 Annealing

It is one of the most widely used operations in heat treatment of iron and steel and is defined (according to American Society of Material Testing) as the softening process in which iron base alloys are heated above the transformation range, held there for a proper time and then cooled slowly (at the rate of 30 to 150°C per hour) below the transformation-range in the furnace itself. Alternately, the steel may be transferred to another furnace at about 650°C, and held there until the austenite has transferred into pearlite (final cooling can be done in still air).

Temperature Ranges used in Heat-treatment
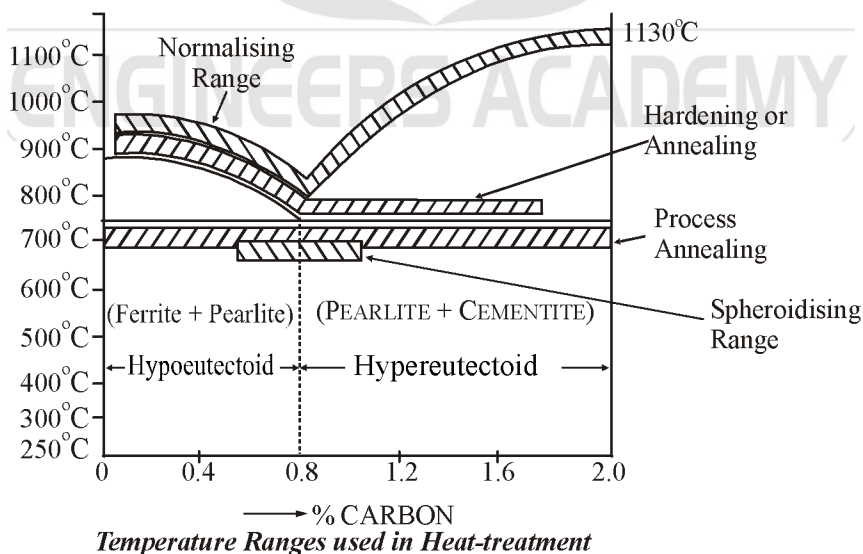
The success of annealing depends on controlling the formation of austenite, and the subsequent transformation of the austenite at high sub-critical temperature.

The heating and cooling of steel is carried about as follows.

Heating is carried out (20°C) above the upper critical temperature of steel in case of hypo-eutectoid steel and the same degree above the lower critical point in case of hyper-eutectoid steel.

Since prolonged heating of steel can cause scaling due to carbon coming out, steel workpieces are packed into refractory-lined and sealed boxes to overcome this problem, or heated in a controlled atmosphere furnace to exclude air during the annealing operation.

The steel on cooling changes into ferrite and pearlite for hypo-eutectoid steel, pearlite for eutectoid steel, and pearlite and cementite for hyper-eutectoid steel.

The time for which an article is held in the furnace is recommended as 1 to 2 hours.

The following important observations regarding annealing operating should be borne in mind.

The objects of annealing are :

(i) To soften the metal so that it can be cold worked.

(ii) To reduce hardness and improve machinability.

(iii) To refine grain size due to phase recrystallization and produce uniformity.

(iv) To increase ductility of metal.

(v) To prepare steel for subsequent heat-treatment.

(vi) To obtain desired mechanical, physical, electrical and magnetic properties.

(vii) To relieve internal stresses.

(viii) To produce a desired microstructure.

(a) *Process Annealing* :

It is a process that provides the recrystallization of ferrite at subcritical temperature. But in this process hardness of steel is decreased as the ductility is increased. When the effects of cold working become so pronounced as to make further cold working impracticable, the process of sub-or process-annealing is carried out as an intermediate operation and steel thus becomes soft for further cold working. So it is generally used on rolled products such as flats, sheets, etc. The steel is heated to about 650°C soaked, and cooled freely in still air.

The free cooling can be employed because the heating and soaking do not produce any changes in the micro-constituents.

(b) *Full Annealing* :

It is described in the definition of annealing, i.e. annealing ferrous alloy by austenites and then cooling slowly through the transformation range.

(c) *Spheroidising* :

It is another process of annealing in which high carbon steels, tool steels containing a large amount of free cementite, which makes them brittle, are heated 20 to 40°C below the lower critical temperature, hold there for a considerable period of time e.g. for 2.5cm diameter piece the time recommended is four hours. It is then allowed to cool very slowly at room temperature in the furnace itself.

The objects of spheroidising are :

(a) To reduce tensile strength and to increase ductility.

(b) To ease machining (minimum-hardness and maximum ductility). Spheroidising is seldom used on low-carbon steels because it becomes extremely soft. On low carbon steels, it is used to permit severe deformation.

(c) To give a basic tool structure for subsequent hardening process.
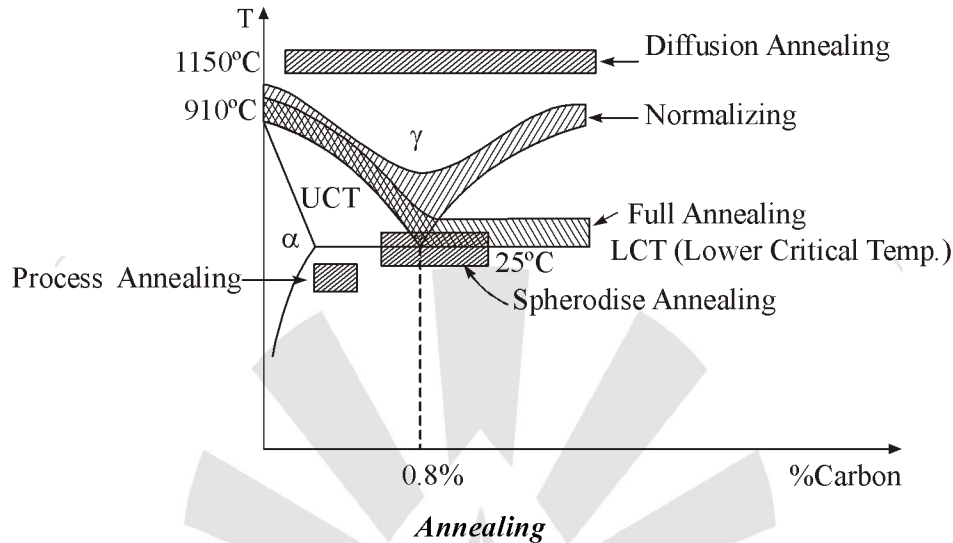
Annealing

(d) Isothermal Annealing :

This process is used for plain and alloy high carbon steels. The time required to produce the desired microstructure is much less in this process than in conventional annealing. In this process a ferrous alloy is austenitised, and then cooled and held at transformation temperature at which austenite transforms to a relatively soft ferrite carbide aggregate.

For lamellarly micro structure higher austenites temperature is used, and for spheroidal structure lower austenitising temperature is employed. For softest structure, minimum austenitising temperatures and maximum transformation temperature are used.

Furnace time is saved by cooling rapidly from the austenitising temperature to transformation temperature and cooling rapidly by removing part from the furnace after the steel has completely transformed. For high-carbon high chromium bearing steels, 100% spheroidised microstructure (ideal for machining) is obtained by austenitising at 775°C and transforming at 727°C for 4 hours and at 705°C for 1 hour and then cooling rapidly.

1.12.3 Normalizing

According to American Society of Material Testing, it is defined as the process in which iron base alloys are heated 40 to 50°C above the upper transformation range and held there for a specified period (to ensure that a fully austenitic structure is produced) and followed by cooling in still air at room temperature.

The heating of hypo-eutectoid as well as hyper-eutectoid steel is done above the upper critical temperature. The normalized steel consists of ferrite and pearlite for hypoeutectoid, and pearlite and cementite for hypereutectoid steel.

Normalizing operation of steel is carried out to improve the machining characteristics, refining grain size and homogenize microstructure, modify and refine cast dendritic structures, and provide desired mechanical properties.

The parts on which normalizing treatment is carried out are :

(i) Normalising is generally carried out on large castings and forgings to put steel in the best condition for machining or hardening. It is also applied to low and medium carbon steel parts.

(ii) It is frequently applied as the final heat-treatment process on items which are subjected to relatively high stresses.

The objects of normalising are :

(i) To eliminate coarse grain structure obtained during forging, rolling and stamping and produce fine grains.

(ii) To increase the strength of medium carbon steel.

(iii) To improve the machinability of low carbon steel.

(iv) To improve the structure of welds (uniformity of structure).

(v) To reduce internal stresses.

(vi) To achieve desired results in mechanical and electrical properties.

The parts subjected to normalising treatment have higher yield strength, ultimate tensile strength and impact strength but ductility is somewhat reduced.

1.12.4 Hardening

According to American Society of Material Testing, it is defined as the heat-treatment process in which steel is heated at 20°C above the transformation range, soaking at this temperature for a considerable period to ensure through penetration of the temperature inside the component, followed by continuous cooling to room temperature by quenching in water, oil or brine solution.

Heating and cooling of steel is carried out as follows :

Heating is carried out (20°C) above the upper critical temperature of steel in case of hypo-eutectoid steel and same degree above the lower critical point of steel in case of hyper-eutectoid steel. The former consists of ferrite and pearlite while the latter consists of pearlite and cementite. On heating above the critical temperature, these get changed into a single structure known as austenite structure containing a considerable part of cementite.

Upon cooling which in this case is a critical cooling (200°C/minute), the austenite is changed into a fine, needle-like microstructure known as martensite. Martensite is a super-saturated solution of carbon in α-iron. Hardness in steel is due to this microstructure.

The parts on which hardening process is applied :

(i) As the hardness in steel is due to carbon content only, the hardening process is carried out only on high carbon steels.

(ii) It is also applied on tool and structural steels.

Purpose of Hardening :

(i) To harden the steel to resist wear.

(ii) To enable steel to cut other metals.

1.12.5 Quenching

(a) *Hardening by Quenching :*

Quenching can be described as an operation that provides for the rapid cooling of steel from a high temperature, at which the steel is all austenite, to some lower temperature, such as room temperature.

Such cooling, if rapid enough, will usually result in the steels becoming much harder and stronger than if it had been allowed to cool more slowly. Rapid cooling is obtained by immersing the austenised steel in quenching baths.

These baths may contain air, water various kinds of oils, brines, molten salts and molten metals such as lead and tin.
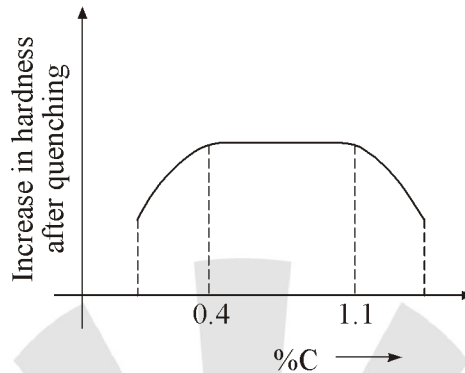
(b) *Purpose of Quenching :*

Tools must be hard and capable of assuming sharp cutting edges and maintaining the sharp cutting edges under severe operating conditions. Tools and dies must be able to resist wear; and must be strong enough to resist fracture. Proper quenching with subsequent heat treatment will develop desirable properties in steels for tools and dies.

Also in selecting the desirable properties, it is always necessary to make a compromise. Maximum hardness is usually accompanied by excessive brittleness. If a plain carbon steel is heat treated so as to obtain maximum hardness and strength, it may be so brittle that will prove useless for a particular service. Increasing the rate of cooling during the full annealing or steel results in increasing fineness of the iron carbide and ferrite plates in the pearlite and then changes in structures result in somewhat higher hardness and strength values.

Increased rate of cooling results in still greater magnitudes of hardness and strength in the steel. Under such conditions the iron carbide or cementite particles become increasingly fine and are most uniformly distributed throughout the ferrite matrix.

(c) *Quenching Media :*

There are about thirty-two classified quenching media whose cooling rates are known, not all of them different in substance, but all different in their effect on the cooling rate. The most commonly used, cheapest and simplest quenching medium is water, and after it, though not the best in all instances is brine. The advantage of these processes is a high cooling rate for the hot steel.

The speed with which these cool the steel (182° Per sec) is extremely close to the minimum cooling rate essential for unalloyed carbon steels, and as the hardenable carbon steel demands this, these are the media most suitable for their quenching. Next to water and aqueous solutions, the most widely used quenching medium is oil.

Here an entirely new set of conditions exists. Oil cools hot steel less rapidly than water, and the larger the piece quenched, the slower is the cooling rate. One advantage of the slower cooling is reduced danger of wrapping. In the oil quenched part the stress distribution is generally more uniform than in a water quenched steel.

The quenching media can be classified into five groups :

(i)   Brine

(ii)   Water

(iii) Solution of special compounds (sodium hydroxide and sulphuric acid in water)

(iv) Oil

(v) Air

The sequence in which these follow indicate their relative cooling powers; brine having highest and air the lowest.

(b) *Hardening Defects :*

When steel particles are hardened, defects may be caused in a number of ways.

(i) Oxidation and decarburisation

(ii) Quenching cracks

(iii) Distortion and wrapage

(iv) Change in dimensions

(v) Mechanical properties not conforming to specifications.

(vi) Soft spots.

The broken hardening operation consists of following three steps :

(i) Cooling the part in a fused salt bath.

(ii) Holding it in the fused salt.

(iii) Subsequently cooling it in the open air.

1.12.6 Tempering

According to American Society of Material Testing, it is defined as the reheat process, reheating being carried out under sub-critical temperature. Such a reheating permits the trapped martensite to transform into troosite or sorbite depending on the tempering temperature and relieve the internal stresses. Toughness and ductility are improved at the expense of hardness and strength.

It is an operation used to modify the properties of steel hardened by quenching for the purpose of increasing its usefulness.

The mechanical properties produced by hardening and tempering depend upon the carbon content of the steel, the rate at which it is cooled during the hardening process, and the tempering temperature. The troosite or sorbite structure consists of ferrite and finely divided cementite, and is different from that produced by mild quenching which is of a laminated form.

Tempering is divided into three classes according to the usefulness of steel required.

(a) Low Temperature Tempering :

This process is used in order to retain hard microstructure of martensite, but to give up brittleness. The temperature upto which hardened steel is reheated is nearly 200°C.

This type of tempering operation is applied on cutting and measuring tools of carbon and low alloy steel, and parts which are surface hardened and case-carburised.

(b) Medium Temperature Tempering :

It is employed for coil and laminated spring as it provides the highest attainable elastic limit in conjunction with ample toughness.

The temperature upto which the steel is heated varies from 250 to 350°C. The steel on tempering develops troosite structure.

(c) High Temperature Tempering :

This process is employed for structural steel as it provides the most favourable ratio of strength to toughness. It also eliminates completely internal stresses which are produced by quenching.

The temperature up to which the steel is heated varies from 350 to 550°C. The steel on tempering develops sorbite structure.
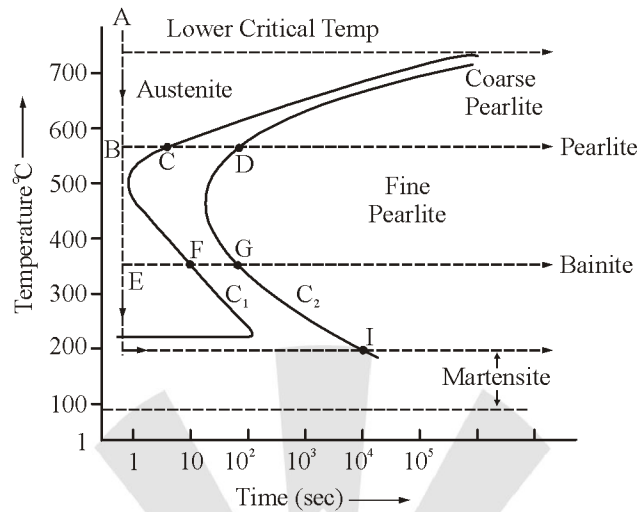
(d) Austempering of Steel :

Austempering is a kind of tempering process which consists of holding the steel in a molten salt bath having temperature of 250 to 500°C above the critical temperature when the structure consists purely of Austenite. The part is then quenched at sufficient rate to avoid transformation to ferrite and pearlite and is held at the quenching temperature for a time sufficient to give complete transformation to an intermediate structure referred to as bainite. It is then cooled to room temperature.

It works best on work pieces of small and delicate cross-section and appears to be most beneficial in steels with carbon content ranging from 0.5 to 1% carbon.

(i) Advantages :

> Quenching cracks are avoided.

> Distortion and wraping are avoided.

> A more uniform micro-structure are superior to conventional hardening micro-structure.

(ii) Limitations :

The process is very costly and time-consuming and it is mainly used for aircraft engine parts.
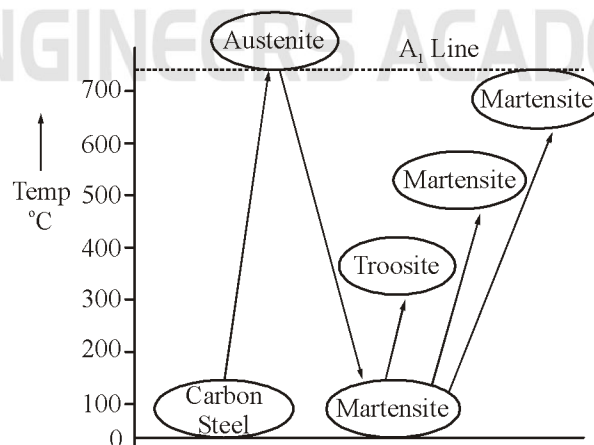
Tempering of Martensite to produce different structures
depending on temperature of reheating martensite

(e) Martempering :

It is a type of the tempering process in which iron and its base alloys are heated above the transformation range and then suddenly quenched in a molten salt bath a temperature of 180 to 300°C. The piece is held at that temperature until the core and outside temperature are equalised. The part is then removed and cooled at moderate rate. Martempering produces martensite in steel but with minimum distortion and residual stresses.

(f) Spheroidising :

When hardened steel is tempered at a temperature (just below lower critical or A_1 line), the cementite converts to small spheroids surrounded by ferrite when heated at this temperature for about 16 to 70 hours. The process can be accelerated by alternatively heating and cooling slightly above and below A_1 line.

Spheroidising results in greater ductility, which improves the forming qualities and machinability.

1.12.7 Case Hardening

This process is used to produce a high surface hardness for wear-resistance supported by a tough, shock-resisting core.

It is the process of carburisation, i.e. saturating the surface layer of steel with carbon to about 0.9%, or some other process by which, case is hardened and core remains soft. The carburised steel is then heated and quenched, so that only the surface layers will respond, and the core remaining soft and tough since, its carbon content is low.

The parts to which it is applied are :

(i)   Low carbon steel containing 0.1 to 0.18% carbon, which otherwise will not respond to direct hardening.

(ii) Steel with 0.2 to 0.3% carbon for large components.

(iii) Recently it has become the tendency to case harden steel with higher carbon content for medium and small machine parts.

(iv) Alloy steel such as chromium steel, Cr-Ni-steel, Cr-Mn-Ti-steel.

(v)   It is possible to keep some areas soft by insulating them during carburisation.

The Objects of case hardening are :

(i)   To obtain a hard and wear resistant surface on machine parts with enrichment of the surface layer with carbon to a concentration of 0.75 to 1.2%.

(ii) To obtain a tough core.

(iii) To obtain close tolerances in machining parts.

(iv) To obtain a higher fatigue limit and high mechanical properties in the core.
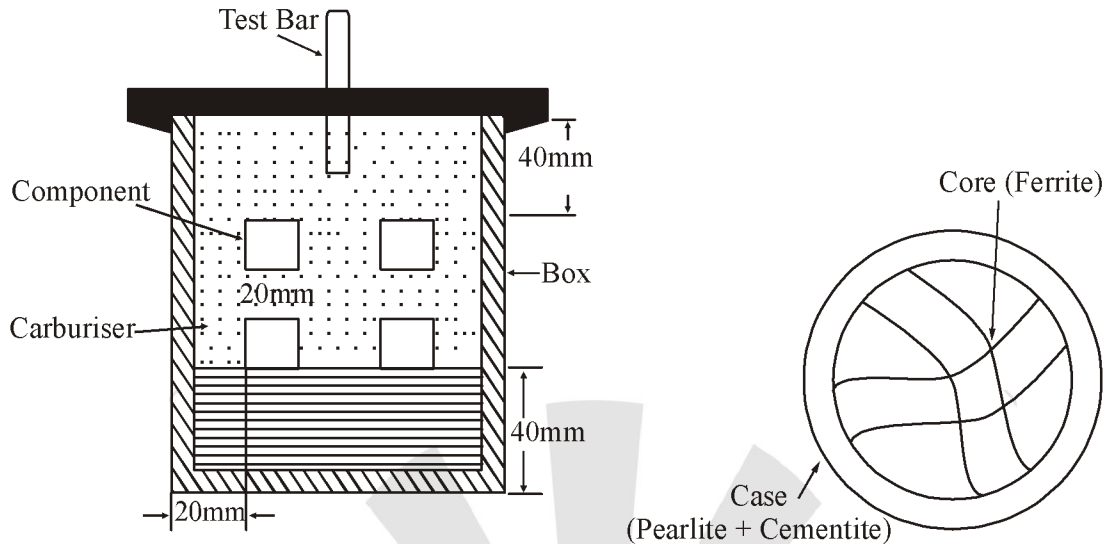
(a) Carburisation :

In this process, the carbonaceous medium is solid carburiser. The chief carburisers for pack carburising are activated charcoal with grain size varying from 3.5 to 10 mm in diameter, semi-coke and peat coke. Carbonates are added to the charcoal to accelerate the carburising process.

Usually barium carbonate ($BaCO_3$) and soda-ash (Na_2CO_3) are added in an amount varying from 10 to 40% of the total weight of charcoal.

A specific composition of a carburising medium is given below :

(i)   80 — 85% of charcoal with grain size varying from 3.5 to 10 mm diameter.

(ii) 10 — 12% of $BaCO_3$

(iii) 1— 3% of $CaCO_3$

(iv) 1 % of Na_2CO_3

A working mixture consists of 25 to 35% of fresh carburiser and 65 to 75% of used material.

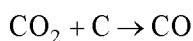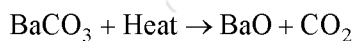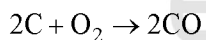*Backing of work for carburization*   *Structure of Case Carburized Product*

The components which are to be pack carburised are first cleaned from dirt, scale and rust. These are then packed into the box. Welded steel boxes usually of rectangular or cylindrical form are employed.

Packing of work is accomplished by first covering the bottom of the box with 40 to 45 mm layer of carburiser, then the component is placed with 20 to 25 mm space between the component and box walls. The remaining space is then covered with dense layer of carburiser 20 to 25 mm thick and rammed.

After this the top is covered with a cover and the edges are fluted with fire clay. This is done so that carbon gas may not escape and air may not enter the box to cause decarburisation. The packed box is placed in the furnace and is heated to temperature of 900 to 950°C and held at that temperature for a sufficient length of period depending upon the hard surface depth required.

Normal practice shows that for obtaining hardness upto a depth of 0.1 mm, about 1 hour heating is necessary. Initially the rate of carburising is about 0.3 mm per hour and subsequently it takes four hours to produce depth of about 1.3 mm of high carbon steel at the surface.

The carburising of steel is due to atomic carbon and in pack carburising the atomic carbon is liberated by the decomposition of CO.

Air as always present in the carburising box, even when filled with carburiser. At higher temperatures oxygen in the air reacts with carbon in the carburiser to produce CO.

$2C + O_2 \rightarrow 2CO$

$BaCO_3 + Heat \rightarrow BaO + CO_2$

$CO_2 + C \rightarrow CO$

$2CO + Heat \rightarrow CO_2 + C$ (atomic)

$2CO$ + Low carbon austenite $\rightarrow$ CO_2 + High carbon austenite which makes the case hard.

The portion of the surface to be kept soft is insulated against carburising by coating it with a suitable paste, or by plating it with about 0.1 mm of copper.

Carburising may also be carried out in a heated sodium carbonate and sodium cyanide salt-bath. Cases upto 0.3mm depth can be produced, and at very fast rate. It is however observed that case is likely to flake because of abrupt change in carbon from surface to core. Gas-carburising is also used to carburise to a depth of about 1 mm in 4 hours, the carbon content being controlled by the composition of gas fired in a furnace.

The prolonged heating during carburisation makes the core coarse. It needs to be refined in order to make it tough. The core is refined by reheating to about 870°C and holding at that temperature long enough to produce uniformity of structure and then cooling rapidly.

Since outer surface contains lot of carbon, it gets transformed into extremely brittle martensite. The case is then refined by reheating steel to about 760°C and then quenching. Finally the case is tempered at about 200°C, to relieve the quenching stresses. Core refining operation is carried out when it is required to resist shock load.

(b) Nitriding :

It is the process of saturating the surface of steel with N_2 by holding it for a prolonged period (upto 100 hours) at a temperature ranging from 480 to 650°C in an atmosphere of NH_3. A case of 0.7mm takes about 100 hours.

For a steel specimen to respond to nitriding treatment, it must contain a small amount of chromium, or both chromium and aluminium. Steel with 3% Cr develops about 850 HV hardness and steel with 1.5% Cr and 1.5% aluminium about 1100 HV.
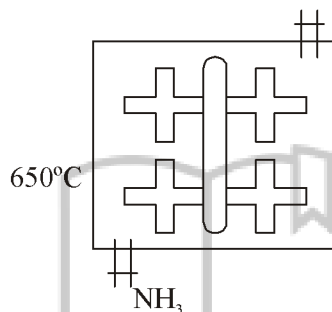
Carbon content is between 0.2 to 0.5%, according to the core strength required. The required core properties are attained prior to nitriding treatment. Since no quenching is done after nitriding, finish machining operation is done before hand.

The parts on which nitriding process is applied are :

(i) Alloy steels containing Cr, Ni, A*l* Mo, V. These elements may be present one at a time or all of them be present in the steel.

(ii) Best steel to be nitrated is Nitre-alloy. (A trade name given to nickel steel)

(iii) Plain carbon steels are seldom nitrided.

Objects of nitriding are :

(i) To increase the hardness of surface to a very high degree.

(ii) To increase the wear-resistance of surface.

(iii) To increase the fatigue limit

(iv) To increase resistance to corrosion in media (atmosphere, water, steam).

Process :

It consists of heating the steel in atmosphere of NH_3 at temperature ranging from 600 to 650°C without any further treatment. Anhydrous ammonia is dissociated into nascent nitrogen. The atomic nitrogen thus formed diffuses into iron nitrides of chromium, molybdenum and vanadium.

These nitrides give extreme hardness to surface. The hardness is of the order of 1000 to 1100 V.P.N. The grain growth is very less in this process. Local surface areas can be kept soft by insulating.

(i) *Advantages :*

➤ No heat treatment is required after nitriding operation

➤ No possibility of any damage to the job such as scale on surface, crack and distortion.

➤ Very high hardness is obtained (1000 to 1100 V.P.N) which cannot be obtained by any other process

➤ No machining is required.

(ii) *Disadvantages :*

➤ Only a few alloys respond to this treatment.

➤ It takes a very long time to case harden the job and at the same time it is a costly process.

(c) *Cyaniding :*

It is a process in which both carbon and nitrogen in the form of cyaniding salt are added to the surface of, low and medium carbon steel to increase its hardness and wear resistance. This method is also effective for increasing the fatigue limit of medium and small sized parts such as gears, shafts, wrist-pins etc.
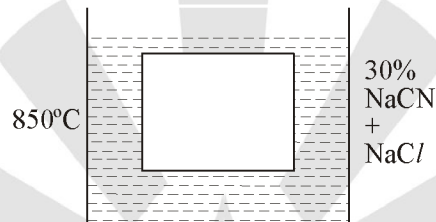
It involves the heating of parts in the molten cyanide salt bath maintained at temperature of 800 to 850°C and then quenching the steel in oil or water bath. The salt bath contains sodium cyanide (NaCN), soda ash (Na_2CO_3) and the sodium chloride (NaCl) in the proportion varying from 25 to 40%.

Cyaniding time is determined by the depth of the hardened case required and varies from 5 to 20 minutes. The resulting case contains 0.6 to 0.8 per cent C and 0.4 to 0.5 per cent N, The hardness obtained on the case by this process varies from 56 to 60 RC and the depth varies from 0.0745 to 2.5 mm.

(d) *Induction Hardening :*

The purpose of induction or flame hardening is to obtain hard and wear resistant surface whilst the core remains soft. The processes of induction hardening and flame hardening differ from each other in the way of heating.

In process of induction hardening a high frequency current of about 1000 to 10,000 cycles per second is passes through a copper inductor block which acts as primary coil of the transformer. Heating by high frequency current is accomplished by the thermal effect of the current induced in the article being heated.

The latter is placed in an alternating magnetic field set by the high frequency current. The part to be heated is placed in inductor coil which compresses of one or several turns of copper tube or busbar. When alternating current is passed through the inductor, it sets up a magnetic field, the intensity of which varies periodically in magnitude and direction.
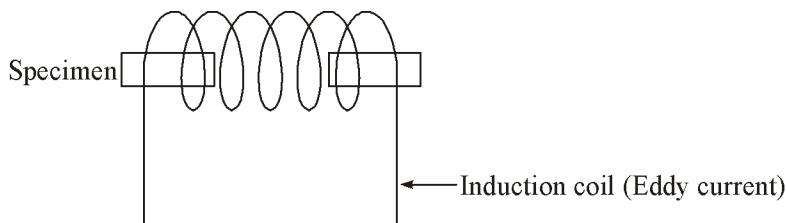
The alternating magnetic lines pass through the surface of the articles being heated in the inductor and induce in the surface an alternating current of the same frequency but reversed in direction. This alternating current produces heating effect on the surface and temperature produced of the order of 750 to 800°C for plain carbon and alloy steel.

The heating areas are then quenched immediately by sprays of water delivered through numerous small holes in the inductor block. The depth of hardness obtained varies from 0.1 to 0.8 mm. The part should have carbon content of about 0.45% for this method.

The induction hardening is at present extensively used for producing hard-surfaces on crankshafts, cam shafts, axles and gears.

The principle advantages are listed below:

(i) The time required for this heat-treatment operation is less thereby increasing the labour productivity.

(ii) Deformation due to heat-treatment is considerably reduced.

(iii) The articles which are induction heated have no scale effect.

(iv) The hardening of the surface can be easily controlled by controlling the current.

(v) The depth of hardness can be easily controlled by varying the frequency of supply voltage.

(e) Flame Hardening :

This process is just like induction hardening with the difference that the heating of the specimen is carried out by flame instead of by induction effect. It is also based on rapid heating and quenching. The rapid quenching is achieved by sprays of water, connections of which are intergral with the heating device.

The heating is generally accomplished by means of oxyacetylene flame. Heating is carried out for sufficient time so as to raise the temperature of the surface of the specimen above the critical temperature. As soon as this temperature is reached, spraying is started.
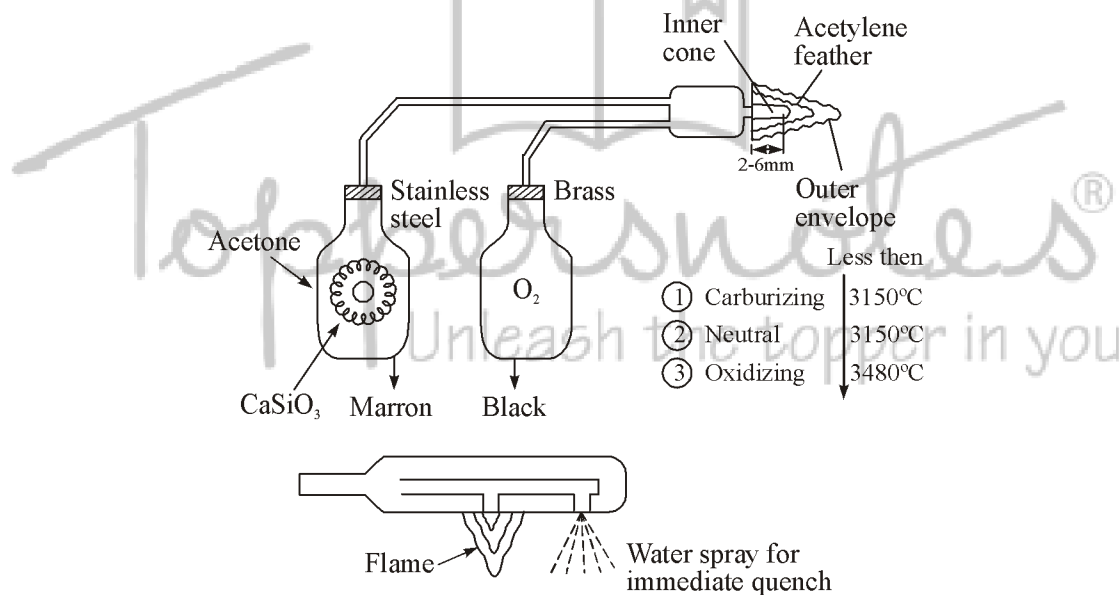
Generally in mass production work, progressive surface hardening is carried out in which the flame and spraying equipment arranged suitably move together with respect to the work piece. As the flame progresses it keeps on heating the surface to critical temperature and simultaneously the surface is quenched behind the flame. Thus the operation becomes continuous one.

The jets of water and flame remain fixed in position and the work keeps on moving at the calculated rate. In such cases, there are usually more than one flame arranged radially.

This is best suited to small works where heating time is short. The method is suitable for cases of upto 0.1 mm depth. Other method is stationary type in which both the heating torch and work are stationary and it is suitable for large works.

In flame hardening, by proper control the interior surface is not at all affected and the depth of hardened case can be easily controlled by controlling heating time and flame temperature. Also the surface treated by this process is free of scale and the equipment used is portable. In comparison to induction hardening, it is cheaper method as initial investment is less.

Same equipment can be used for all the sizes of specimen unlike induction hardening process. But by induction hardening process the hardness depth can be controlled very accurately by using different frequencies and also the method is very clean and quick. After flame hardening, steel is usually tempered.
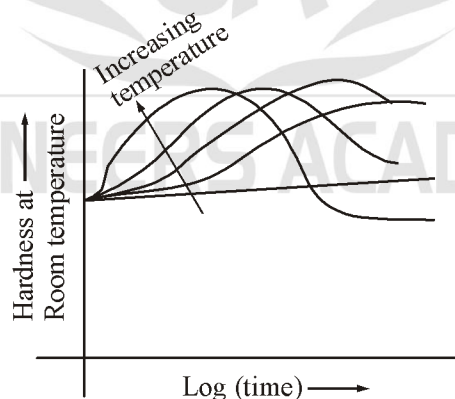
(f) *Age Hardening and Precipitation Hardening :*

This process of hardening is applicable to alloys that can exist as a two-phase material at room temperature and can be heated up to single phase. For example, alloy containing 97% Al and 3% Cu exhibits such a phenomenon.
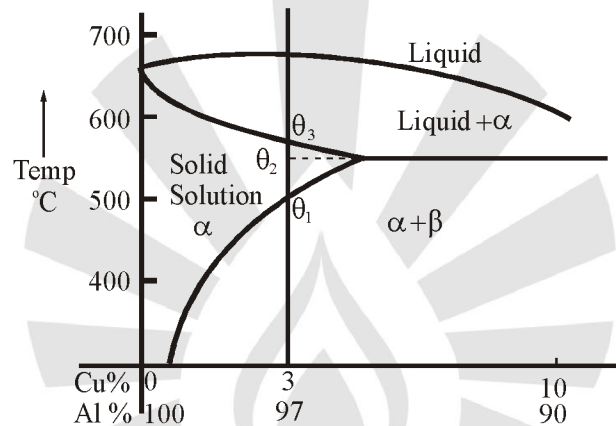
When this alloy is heated between temperature θ_1 and θ_3, it exists as solid solution α. For homogenization, it is essential that it be retained at such temperature for sufficient time. A rapid quenching from this state does allow all the β-Phase to separate out, resulting in supersaturation of the solution.

This supersaturated β-phase precipitates slowly proportional to the temperature after quenching. The precipitation takes place at the grain boundaries and crystallographic planes, making the slippage of atomic layers more difficult, and the alloy thus becomes harder and stronger.

In age hardening, precipitation takes place at room temperature and it require longer time for completion of precipitation. The rate of precipitation can be increased by quenching at a higher temperature (than room temperature) and such a process is called precipitation hardening.

The hardness at room temperature is not a direct function of precipitation temperature. In some cases, it first increases and then starts decreasing. Fig. shows the variation of hardness with the precipitation temperature and the time elapsed after quenching.

1.13 CRYSTALLOGRAPHY

1.13.1 Crystal Structure

In crystallography, crystal structure is a description of the ordered arrangement of atoms, ions or molecules in a crystalline material.

Ordered structures occur from the intrinsic nature of the constituent particles to form symmetric patterns that repeat along the principal directions of three-dimensional space in matter.

1.13.2 Unit Cell

The smallest group of particles in the material that constitutes the repeating pattern is the unit cell of the structure. The unit cell completely defines the symmetry and structure of the entire crystal lattice, which is built up by repetitive translation of the unit cell along its principal axes.

The repeating patterns are said to be located at the points of the Bravais lattice.

1.13.3 Bravais Lattices

The bravais lattices concept is used to formally define a crycstalline arrangement and its (finite) forntiers.

1.13.4 Lattice Constants

The lengths of the principal axes, or edges, of the unit cell and the angles between them are the lattice constants, also called lattice parameters.

1.13.5 Type of Unit Cells

Units cell is obtained by joining the lattice points. The choice of lattice points to draw a unit cell is made on the basis of the external geometry of the crystal, and symmerty of the lattice. There are four different types of unit cells.

(a) Simple Cubic:

Atoms are arranged only at the corners of the unit cell.

$$n = \frac{1}{8} \times 8 = 1$$

$$APF = \frac{n \times \frac{4}{3} \times \pi \left(\frac{9}{2}\right)^3}{a^3} = 0.52$$

Co-ordination No. = 6 (No. of atoms in neighborhood)

(b) Body Centered Cubic (BCC):

Atoms are arranged at the corners and at the centre of the unit cell.

$$n = \frac{1}{8} \times 8 + 1 = 2$$

Atomic packing factor

$$APF = \frac{2 \times \frac{4}{3} \pi \, r^3}{a^3} = 0.68$$

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

Co-ordination number = 8

Example: Mo, V, Cr, α–iron

(c) Face Centred Cubic (FCC) :

Atoms are arranged at the corners and at the centre of each faces of the unit cell.

$$n = \frac{1}{8} \times 8 + \frac{1}{2} \times 6$$

$$n = 1 + 3 = 4$$

Atomic packing factor   = 0.74

Example: Ag, Cu, Pb, P, Au, Al, Co

(d) Hexagonal Closed Packing (HCP)

Atoms are arranged at the centre of only one set of faces in addition to the atoms at the corner of the unit cell.

$$n = \frac{1}{6} \times 12 + \frac{1}{2} \times 2 + 3 = 6$$

Atomic packing factor   = 0.74
Co-ordination number   = 12

Example: Ti, Zn, Be, Mg

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