

# Chapter-1 Solid state phase transformation

## Introduction:

The knowledge about the nature of austenite and its transformation behaviour is very important before proceeding for a heat treatment process. In fact this is essential in order to learn the theory of heat treatment practice.

## Formation of Austenite

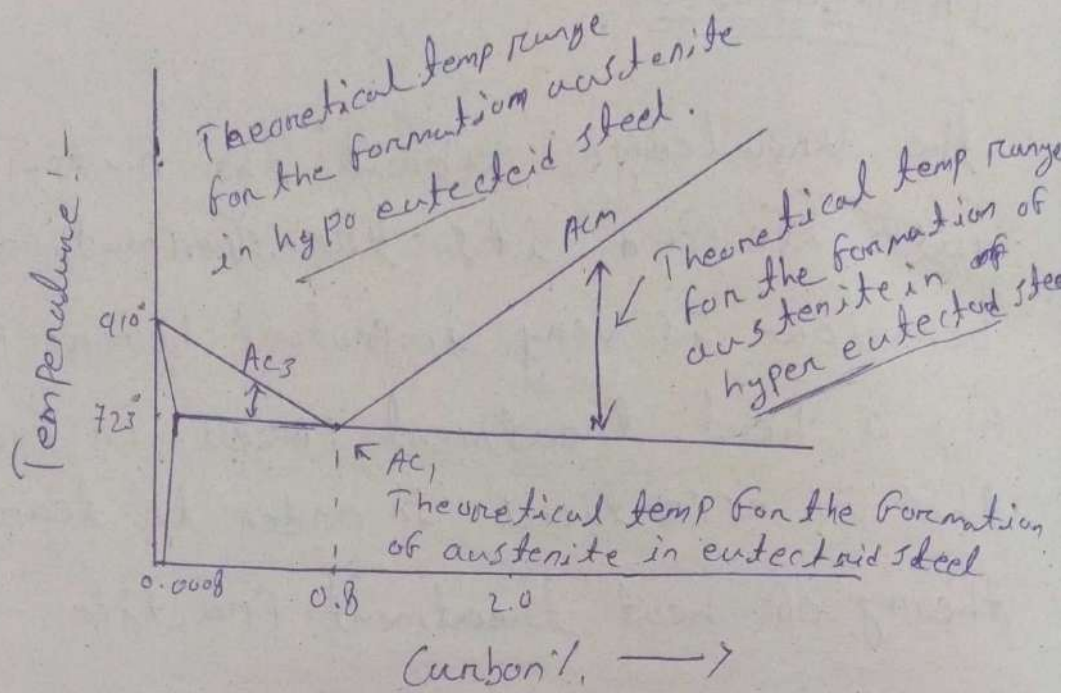
=> Formation of austenite is a preliminary step for any heat treatment process.

=> Austenitization may be defined as the process of heating the steel into the austenitic range.

=> Austenite starts to form when when the steel is heated above  $A_{c1}$  ( $723^{\circ}\text{C}$ )

=> Austenite is a solid solution of carbon in gamma iron (FCC)

# Mechanism of Formation of Austenite



## Temp Range for the formation of austenite on heating of steel

- ⇒ The formation of austenite on heating always occurs at a temp higher than predicted by Fe-C equilibrium diagrams.
- ⇒ Formation of austenite depends upon temperature and time.
- ⇒ For eutectoid steel, the formation of austenite begins at a particular temp ( $Ac_1$ ).
- ⇒ For hypoeutectoid and hyper eutectoid steel, the formation of austenite occurs over a range of temp.
- ⇒ In order to get homogeneous austenite, it becomes essential to heat the different types of steel as:-



- \* eutectoid steel above  $A_{c1}$
- \* hypoeutectoid steel above  $A_{c3}$
- \* hyper eutectoid steel above  $A_{cm}$

## Austenitic Grain Size

⇒ Generally the grain size of steel refers to the austenitic grain size,

It is the size of grains before the steel is cooled to room temperature.

⇒ Grain size is a very important factor for the physical properties and usefulness of steel.

⇒ The actual austenitic grain size depends on the temperature to which steel has been heated up and holding time at that temperature.

∴ - So by varying the grain size of steel the following properties can be altered

- (i) Tensile strength
- (ii) Yield strength
- (iii) Toughness
- (iv) Hardenability
- (v) Machinability
- (vi) Ductility
- (vii) Creep strength
- (viii) Fatigue strength

## Importance of Grain Size

→ The austenite grain size is important because it affects the fabrication properties of steel.

⇒ The austenite grain size is important in determining the hardening response of steel.

⇒ The austenite grain size of steel is important in controlling the properties as :-

<u>Property</u>	<u>Fine Grain Size</u>	<u>Coarse Grain Size</u>
Yield strength	Better	inferior
Tensile strength	Better	inferior
Ductility	Better	inferior
Fatigue strength	Better	inferior
Toughness	Better	inferior
Hardenability	inferior	Better
Machinability	inferior	Better
Creep strength	inferior	Better



# Determination of Austenitic Grain Size

⇒ The most popular method for designating the austenitic grain size been developed by the American Society of Testing Materials (ASTM).

⇒ In this designation system, the grain size is expressed by "Grain Size Number"  $N$

⇒ The ASTM Grain Size number ( $N$ ) is obtained by the relation :-  $n = 2^{N-1}$

where  $N$  = Grain size number

$n$  = Average number of grain per square inch viewed at 100x

⇒ usually the grain size of steel are graded in to eight classifications.

	<u>ASTM GRAIN SIZE NUMBER ('N')</u>	<u>AVERAGE NUMBER OF GRAINS SQUARE Inch at 100x (n)</u>
Coarse Grained steel	1.	1.
	2.	2.
	3.	4.
	4.	8.
	5.	16.
Fine Grained steel	6.	32.
	7.	64.
	8.	128.

## Method of Measurement of Grain size

- ASTM has recommended 3 basic methods for grain size measurement these are:-

- (a) Comparison method
- (b) Intercept method
- (c) planimetric method

- Brief description :-

(a) Comparison method:-

Metal Specimen is prepared, etched and photo micrographed at 100x and compared with a series of ASTM grain size charts. By trial and error a match by a number according to chart.

(b) Intercept method

=> Take a photomicrograph. Draw a straight line on it and count the number of grains intersected by it. The length of the line in mm divided by the average number of grains intersected by it given the grain diameter i.e. size.



## (c) planimetric method:-

=> Take a photomicrograph draw a circle or rectangle on it. Count the number of grains within this drawn area and ultimately calculate the number of Grain per Square mm.

## Grain size control

The important factors governing the grain size of steel are:-

- (a) Nature and extent of deoxidizers.
- (b) Chemical composition of steel.
- (c) The method of manufacture of steel.
- (d) Alloying elements like vanadium & Aluminium.
- (e) Metallic and Non metallic inclusions.
- (f) Heat treatment process, Furnace and their atmosphere.
- (g) Mechanical working like forging and Rolling.

# DECOMPOSITION OF AUSTENITE

=> we know that, single phase austenite is stable.

=> above  $A_{c1}$  ( $723^{\circ}\text{C}$ ) for eutectoid steel.

=> above  $A_{c3}$  Temp for hypoeutectoid steel.

=> above  $A_{cm}$  Temp for hypereutectoid steel.

- So when we cool steel below  $A_{c1}$ ,  $A_{c3}$  and  $A_{cm}$  Temp. austenite will decompose to different products.

- The transformation of austenite on cooling is a complex process.

- when eutectoid steel is cooled from  $723^{\circ}\text{C}$  to  $0^{\circ}\text{C}$  the decomposition of austenite takes place in to three different products. These are:-

(i) Pearlitic transformation ✓

Temp. range:  $723^{\circ}\text{C} - 550^{\circ}\text{C}$

(ii) Bainitic transformation ✓

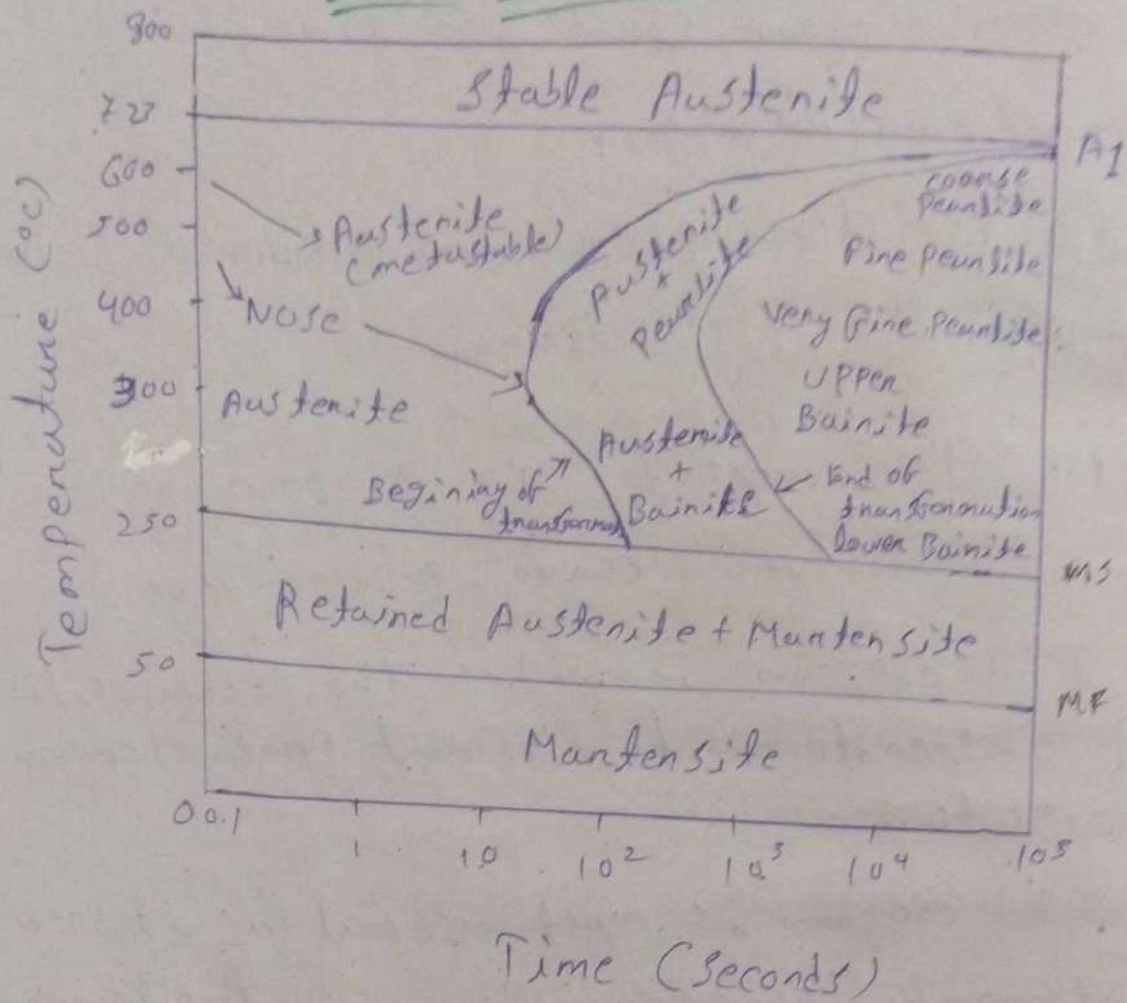
Temp. range:  $550^{\circ}\text{C} - 250^{\circ}\text{C}$

(iii) Martensitic transformation ✓

Temp. range:  $250^{\circ}\text{C} - 50^{\circ}\text{C}$



# TTT Diagram for eutectoid steel



- A1 = Lower critical Temp on Austenitizing Temp (727°C)
- MS = Temp of martensite formation start (250°C)
- MF = Temp of martensite finish (50°C)

## Method of constructing TTT diagram

We know that austenite is stable above A<sub>1</sub> temp and below this austenite is unstable.

⇒ The kinetics of austenite transformation at a constant temp. can be studied by the following method.

⇒ A number of small samples are taken from the steel under consideration.

⇒ These samples are heated to predetermined austenitizing temp. and held at that temp for a ~~long~~ long period so as to obtain homogeneous austenite.

⇒ These austenitized samples are transferred quickly to another bath maintained at a constant temp. below A<sub>1</sub> temp.

⇒ These samples are taken out one by one from the subcritical temp. bath after different time intervals and are quenched immediately.

⇒ Quenching of sample results in the formation of martensite from the untransformed austenite.

⇒ The amount of transformed austenite can be determined as a function of time at constant temp.

⇒ The amount of transformed austenite will increase when sample are held in constant temp. both for longer time.



⇒ So after a particular time, all the austenite will transform to ferrite and cementite at a given temp.

⇒ The transformation of austenite does not start immediately by keeping in constant temp. but transformation of austenite to ferrite-cementite mixture (i.e. pearlite) occurs after a definite time

⇒ So the time during which transformation of austenite doesn't proceed is known as

"incubation period" smaller incubation

corresponds to lesser stability of austenite

⇒ Finally the amount of transformed austenite at various time periods for different transform temp can be known and plotted in the TTT diagram.

### Pearlitic Transformation

⇒ pearlite is a mixture of two phases namely ferrite and cementite. So pearlite microstructure consists of alternate layers of ferrite and cementite.

⇒ Pearlite is formed when eutectoid steel is cooled just below the lower critical temperature  $A_1$  ( $723^\circ\text{C}$ )

⇒ when austenite is cooled from  $723^{\circ}\text{C}$  to  $550^{\circ}\text{C}$ , pearlite is produced.

⇒ The pearlitic transformation takes place by nucleation and growth of ferrite and cementite plates respectively.

⇒ This transformation is a diffusion controlled phenomenon.

### Bainitic transformation:-

⇒ Bainite is a mixture of ferrite and carbide. This ferrite and carbide mixture is not lamellar in nature.

⇒ The bainitic transformation takes place at a temperature range of  $550^{\circ}\text{C}$  to  $250^{\circ}\text{C}$ .

⇒ Two types of bainite formed during this transformation. Namely:-

⇒ upper Bainite

⇒ lower Bainite

⇒ Upper Bainite is formed by the process of nucleation and growth of ferrite and cementite plates respectively. The structure of upper Bainite is feathery.

⇒ Lower Bainite formation takes place by shear process. The structure of ~~upper~~ lower Bainite is acicular.

⇒ Bainite possess mechanical properties in between pearlite and martensite.



## Martensitic Transformation

- Martensite is the hardest and strongest constituent of steel. It is a super saturated solution of Carbon in  $\alpha$ -iron. It has a acicular or needle structure.
- when steel is cooled rapidly i.e. quenched below  $250^{\circ}\text{C}$  austenite begins to transform into martensite.

$\Rightarrow$  The martensitic transformation takes place at a temperature range of  $250^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ .

$\Rightarrow$  Basically, this transformation is diffusionless.

The mechanism of formation of martensitic structure is by a shearing process resembling to the process of mechanical twinning.

$\Rightarrow$  When austenite transforms into martensite, the FCC structure of austenite changes into body centered in a special way and doesn't involve diffusion. It occurs by a shearing action.

$\Rightarrow$  Due to shearing process, diffusion doesn't take place and carbon remains in the solid solution. Due to this retained carbon in the solid solution the structure of martensite becomes BCT (Body Centered Tetragonal) rather than BCC.

⇒ Due to presence of carbon, martensite is hard strong and brittle.

⇒ Martensite is a one phase structure.  
If temp increases it may decompose into Ferrite and Cementite.

### MS and MF temperature:-

⇒ Martensitic transformation starts at MS temperature and ends at MF temperature.

⇒ The amount of martensite formed depends upon temperature.

⇒ For a given steel, the temp. for beginning of martensitic transformation is known as 'ms temp' (approx  $250^{\circ}\text{C}$ )

⇒ The ~~ms~~ temp. for end of martensite formation is known as 'mf temp': (approx  $50^{\circ}\text{C}$ )

⇒ The MS and MF temperatures are different for different types of steel.

⇒ The MS temp is a definite temp. for a given steel. MS temp depends on the chemical composition of steel.

⇒ Alloying elements like C, Mn, Ni, Cr and Mo affects the MS temp of steel.

⇒ MF temp is dependent on the cooling rate of steel.



## CCT DIAGRAM :-

- CCT diagram stands for continuous cooling transformation diagram.
- In industrial practice, transformation during heat treatment occurs by continuous cooling and not isothermally. Thus TTT diagrams have limited application.
- ⇒ That's why CCT diagram, which can correlate time, temperature and transformation during continuous cooling will be of real value to heat treaters.
- Method for the construction of CCT diagram for a eutectoid steel :-
  - At first a large number of small samples are heated above the lower critical temperature ' $A_1$ ' to get a completely homogeneous austenitic structure.
  - From this temp, specimens are cooled at a constant cooling rate and points corresponding to start and finish of pearlite are determined. By repeating the same process at various cooling rates different sets of start and finish points of pearlitic transformation are obtained.

⇒ On joining start and finish points two curves are obtained similar as T-T-T diagram  
⇒ Thus, the CCT diagram is constructed

### The different observations from CCT diagram

- F/c Cooling** • A very slow cooling rate of crosses both the pearlite start and finish curves of CCT diagram at high temp. The <sup>micro</sup>structure obtained is coarse pearlite.
- Air Cooling** • A cooling rate of crosses both the curves and the microstructure is fine pearlite.
- Oil Quenching** • A higher cooling rate of crosses the pearlite finish curve at the nose and microstructure is very fine pearlite.
- CCR** • A cooling rate of just touches the pearlite start curve and doesn't enter the bainitic region and transforms to all martensite.
- Water Quenching** • A cooling rate of doesn't touch the pearlite start curve and austenite transforms to martensite only.
- In a eutectoid steel, continuous cooling doesn't yield bainite.



# Summary!

## Cooling Rate

## Transformation product

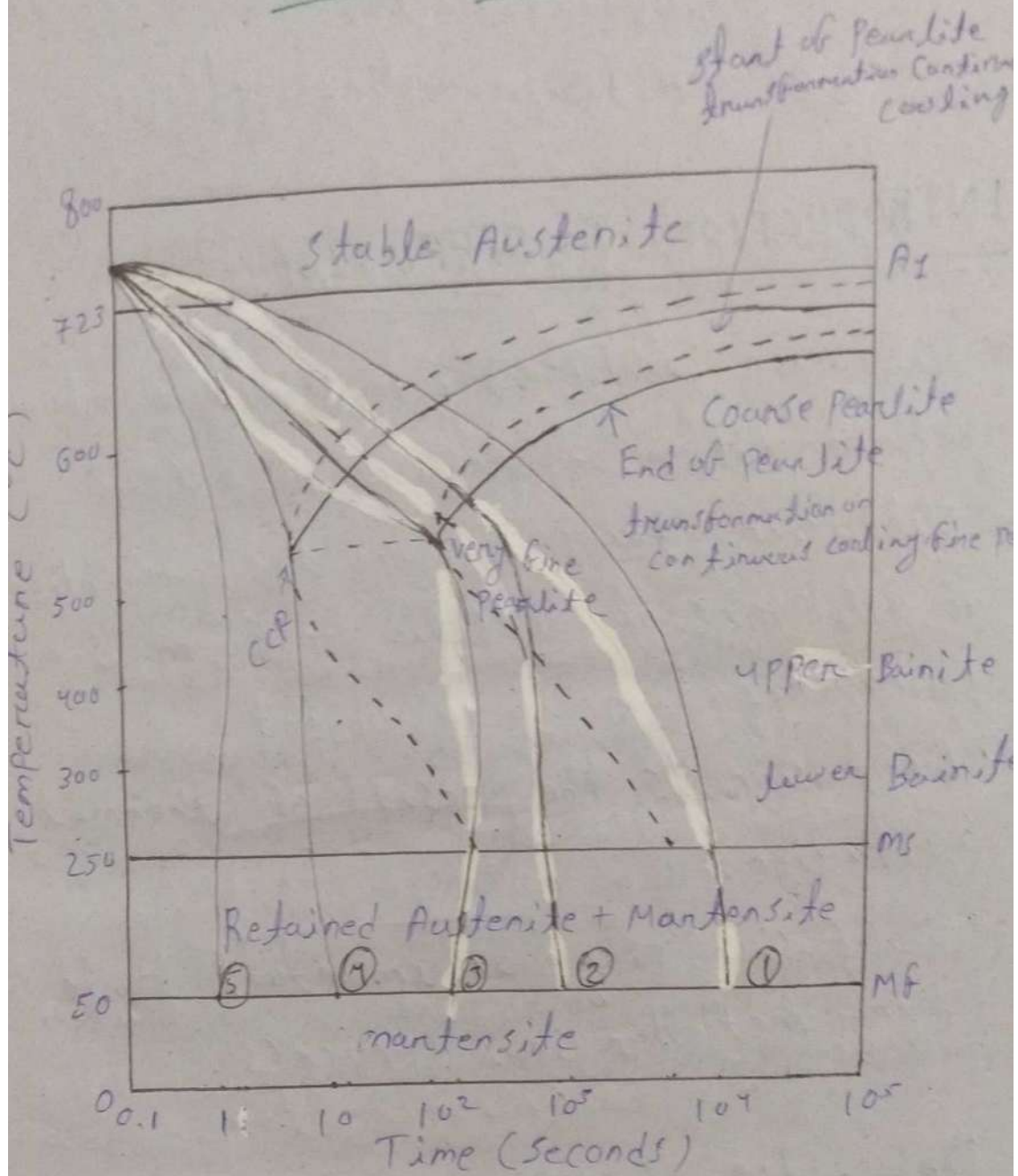
- ① Furnace cooling (Annealing) → Coarse Pearlite
- ② Air cooling (Normalising) Fine Pearlite
- ③ Oil Quenching (Hardening) → very fine Pearlite
- ④ CCR 1% Pearlite + 99% Martensite
- ⑤ Water Quenching (Hardening) Martensite.

The minimum cooling rate at which all austenite transforms to martensite is

Critical cooling rate (CCR):

- Critical cooling rate is the slowest rate of cooling at which all the austenite is transformed into 100% martensite.
- ⇒ Any cooling rate  $\geq$  CCR will form martensite.
- ⇒ Any cooling rate  $<$  CCR will form softer products like pearlite and bainite.
- CCR is important when hardening is done.
- The important factors affecting CCR are
  - Composition of steel.
  - Temperature of hardening.
  - Purity of steel.

# CCT Diagram for eutectoid ste



(In cooling rate 1: very slow cooling - course pear (furnace cooling) Annealing

(air cooling) Normalising 2: higher cooling - fine pear

(oil quenching) Hardening 3: higher cooling - very fine pear

CCR 4: CCR - touches the nose so very small amount of pearlite + 17. Pearlite + 83. Martensite

(water cooling) 5: Rapid cooling only martensite Hardening



The minimum cooling rate at which all austenite transformation to martensite is known as critical cooling rate.

## INTRODUCTION TO DIFFUSION:-

- ⇒ Diffusion implies the movement of atom between diffusion regions of a solid
- ⇒ Diffusion tends to make the composition of all parts of a solid uniform i.e. homogenization of a object.
- ⇒ Diffusion is the result of thermal agitation.
- ⇒ Diffusion plays an important role in many metallurgical process.

## Definition of Diffusion:-

∴ Diffusion may be defined as the mass flow process in which atoms change their positions relative to their neighbours in a phase under the influence of thermal energy and a concentration gradient.

## Types of Diffusion:-

- The diffusion types are diffusion one:

(a) self diffusion:-

- migration of atoms in pure materials.

(b) Inter diffusion:-

- Diffusion of one component through the other lattice.

- It occurs in binary metallic alloys, e.g. (Ni-Cu)

(c) volume diffusion

- It is the atomic migration through the bulk of the material.

(d) Grain Boundary Diffusion:-

- It is the atomic migration along the Grain Boundaries.

(e) Surface Diffusion:-

It is the atomic migration along the surface of the material.

## Application of Diffusion:-

Diffusion is very important for industrial metallurgical processes.

(a) Metal bonding (welding, brazing, soldering)

(b) phase changes.

(c) powder metallurgy.

(d) Recovery and recrystallization.

(e) Homogenising annealing.

(f) Surface treatment of steels.

(g) Precipitation hardening.



## Fick's law of diffusion:-

- the atomic movement in diffusion is generally in a direction from higher to lower concentration which leads to an equalization of concentration within a single phase.

### Fick's First law:-

Fick's first law describes steady state diffusion.

mathematically

$$J = -D \frac{dc}{dx}$$

Flux is independent of time  $t$  & position

where

$J$  = Diffusional flux in  $x$ -direction  
i.e. number of atoms transported per unit area per unit time.

$D$  = Diffusion coefficient

$\frac{dc}{dx}$  = Concentration gradient.

(-) symbol means diffusion takes place down the concentration gradient.

## Fick's Second law :-

Fick's second law is applicable to non steady state diffusion.

Mathematically

$$\frac{dc}{dt} = \frac{d}{dx} \left( D \cdot \frac{dc}{dx} \right)$$

Flux is changing as a function of time 't' & position 'x'.

where

$\frac{dc}{dt}$  = Rate of accumulation of the diffusing material.

D = Diffusion Co-efficient.

$\frac{dc}{dx}$  = Concentration gradient.