

LECTURE NOTES

ON

Heat Treatment Technology (5th Semester Metallurgy)

Compiled by

Mr. Pramod Kumar Sethi

(Sr. Lecture, Department of Metallurgical Engineering, KIIT Polytechnic BBSR)

CONTENTS

Sl.No	Chapter Name	Page No
1	Solid State Phase Transformation	
2	Heat Treatment Process for Steel.	
3	Hardenability	
4	Surface hardening Methods	
5	Heat Treatment of Non-Ferrous Alloys	
6	Alloy Steels and heat Treatment of Alloy Steels.	

SOLID STATE PHASE TRANSFORMATION

Ferrite stabilizer: - (CV, W, Ti, Mo)

Alloying elements tends to stabilize the ferrite phase inference to austenite. The substances as same as ferrite. They reduce the austenite area of the equilibrium diagram by forming a loop. Elements which tend to stabilize the ferrite. These are called ferrite stabilizer.

Austenite stabilizer: - (Mn, Ni & Ca)

Mn and Ni are the common austenite stabilizer element. They enlarge the area of γ phase on equilibrium diagram.

DIFFUSION

(Diffusion is the mass flow process in which atoms change their positions relative to their neighbors in a phase under the influence of thermal energy and a concentration gradient).

FICK'S Law: -

1st Law

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

Where J = Diffusional flux in the x-direction (no. of atoms transported per unit area per unit time)

dc/dx = concentration gradient

D = Diffusion coefficient

Under steady state conditions, the flux remains independent of time (t) and position (x)

2nd Law

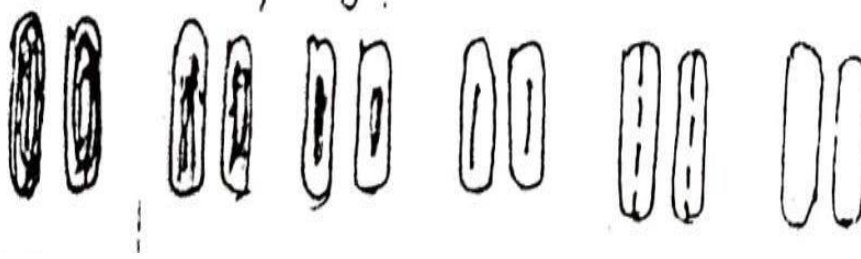
Fick's 2nd law is applicable to unsteady state diffusion. Here the flux is changing as a function of position and time. When the diffusion coefficient is not a function of concentration, the second law is of the form.

$$\frac{dc}{dt} = D \frac{d^2c}{dx^2}$$

Formation of Austenite: -

1. Austenite is formed by heating above type I eutectoid temperature of ferrite and pearlite, ferrite and cementite or pearlite and cementite reprecipitating.
2. If the temperature below the eutectoid temperature, carbon tends to diffuse into ferrite. But the rate of diffusion is very slow.
3. The maximum diffusion of carbon will take place from cementite at ferrite/cementite interface.
4. As sufficient no. of interfaces are available so austenite nuclei will form at the interface.

5. By gradual dissolution, carbon of cementite into gamma iron, primary austenite grains are formed. These primary austenite grains are dissolving the surrounding ferrite and austenite grains grow at the expense of ferrite.



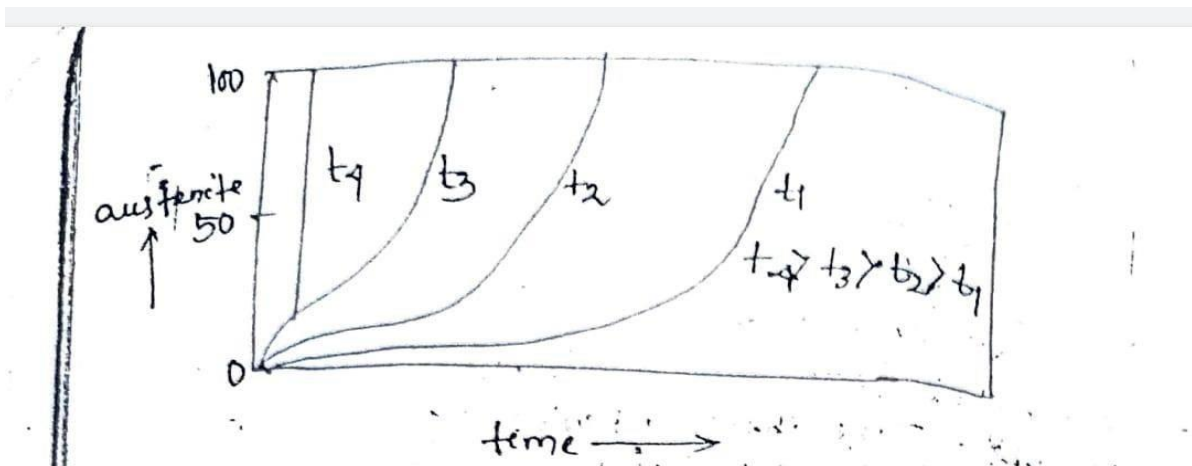
6. These process i.e., the formation of primary austenite grains and their growth by dissolving ferrite contain till all the ferrite and cementite dissolve to form austenite.

(The growth rate of austenite is higher than the rate of dissolution of the cementite into austenite because austenite grain growth takes place because of the transformation of alpha iron to gamma iron and diffusion of carbon atom from austenite to ferrite).

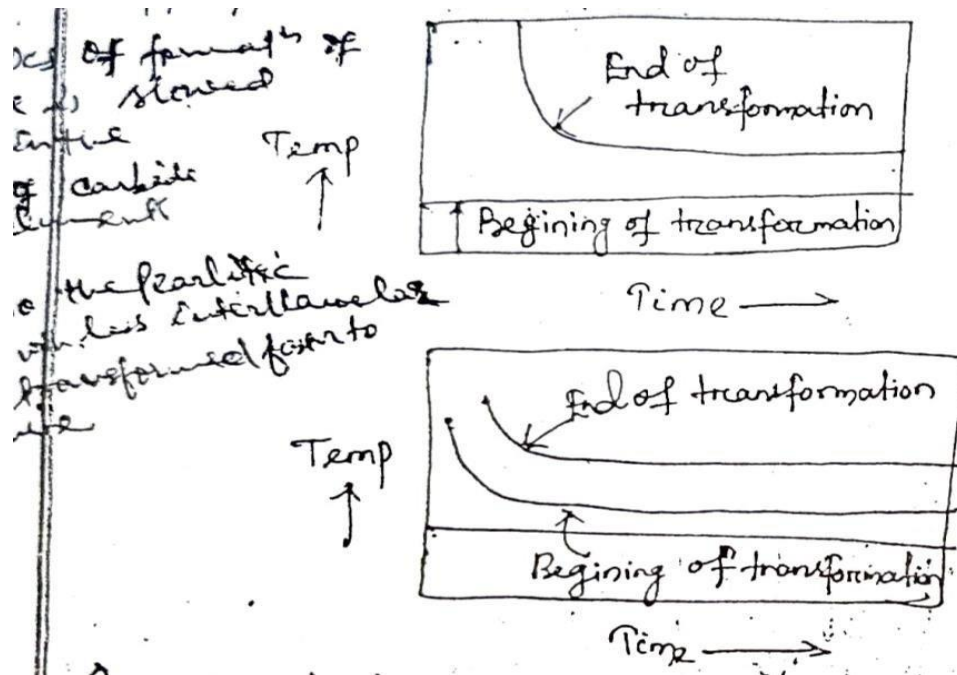
7. This explains experimentally observed that, dissolving of ferrite is completed before that of cementite. Thus, the austenite formed at eutectoid temperature not homogeneous.

Mechanism of Austenite: -

1. The formation of austenite on heating always occurs at a temperature higher than that critical.
2. Kinetic of austenite formation is to heat a number of steel samples to different temperature above the eutectoid temperature.
3. Heating is done by immersing samples in constant temperature bath and are taken out one by one after a definite interval of time, followed by immediately quenching which results the formation of martensite transformed austenite.
4. The amount of martensite formed will depend on the amount of transformed austenite which depends on the heating of steel and holding time at this temperature.
5. In this case, the temperature is higher than the eutectoid temperature. Thus, percentage of transformed austenite with time for a given temperature can be known.



6. Lower the temperature, more is the time required for complete transformation and higher the temp. Less is the time required for complete transformation.



7. Because Of form of austenite slowed down into presence of carbide forming element.
8. And also, the pearlitic structure with less inter angular space and transformed from to austenite.

Some important points for formation of austenite: -

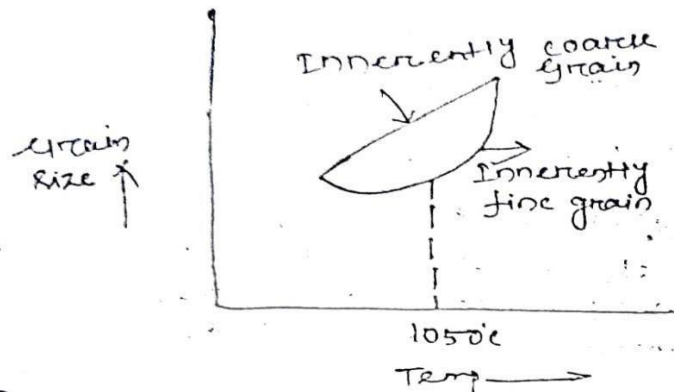
1. Transformation is completed in short period at higher transformation temperature.
2. For higher heating rates, transformation will start at higher temperature where as for slower heating rate, transformation will start at lower temperature.
3. Formation of austenite will occur above the eutectoid temp but not at a constant temperature for practical rate of heating.
4. For the formation of austenite, at a constant temperature the heating rate should be slow and two curved lines will converge to a single point located at eutectoid temp line.

Austenite Grain sizes: -

1. Nuclei of austenite is formed when steel is heated to eutectoid temperature. These nuclei give into primary austenite grains.
2. This process continues till all the ferrite and cementite transform to austenite.
3. At the end of transformation only austenite grain are present in the structure.
4. The size of these grains is referred to original grain size.
5. The grain size of austenite which is obtained is known as actual grain size of austenite. Actual grain size depends on

- a. Temperature
 - b. Holding time
6. Tensile strength, yield strength, toughness, harden ability and machinability can be changed altering the grain size of steel.
7. Depending upon the growth of grain, steel can be classified into two groups: -
- a. Inherently fine grain
 - b. Inherently coarse grain

- Ⓐ Inherently fine grain.
- Ⓑ Inherently coarse grain.



8. Inherently fine grain steel resists the growth of austenite grains with increasing the temperature.
9. In the other hand coarse grain steel grow abruptly with increasing temperature.

Determination of austenitic grain size: -

We have to calculate the austenitic grain size then we know

$$N = 2^{N-1}$$

Where n = Av. No. of grains per square inch.

N = Grain size Index

Carbonization: -

This method is applicable to only on this steel which can be case carbonized. This principle involved in this method is the production of hyper-eutectoid case and woling in such a way that excess cementite forms network around. The austenite grains (this method consists of heating the steel at 925°C for 8 hours followed by slow cooling in the furnace itself.

Oxidation: -

Oxidation method is employed for plain carbon and low alloy steel. The steel is oxidized under oxidizing atmosphere at an elevated temperature followed by quenching resulting in

oxidation of austenite grain boundary which is clearly revealed at room temperature by etching.

Importance of Grain size: -

The dependence of yield stress on grain size is expressed by the Hall-patch equation.

$$V_0 = V_1 + K_g D^{-1/2}$$

Where V_0 = yield stress

V_1 – frictional stress that opposes the motion of dislocation.

K_g = Constant to which dislocations are applied up the barrier.

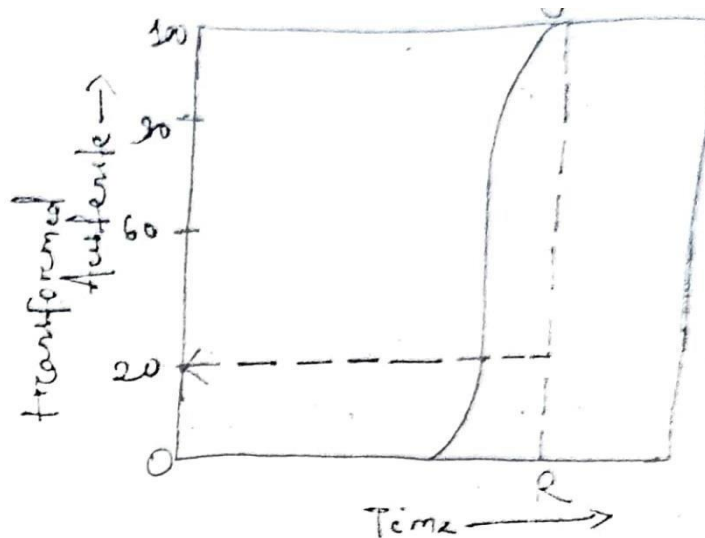
D = Av grain size

1. Finer the grain size, higher will be the yield stress.
2. A coarse grain has better creep strength above the equal-cohesive temperature. Below this temperature finer grained steels exhibit superior creep strength.
3. Finer grain steel has higher fatigue strength as compared to coarse grain steel.
4. Coarse grained steel has better machinability than the fine-grained steel and coarse-grained steel has reduces toughness.
5. An increase in grain size, rises the impact. Transition temperature and thus makes the steel more prone to fail by brittle fracture.

T-T-T Diagram: -

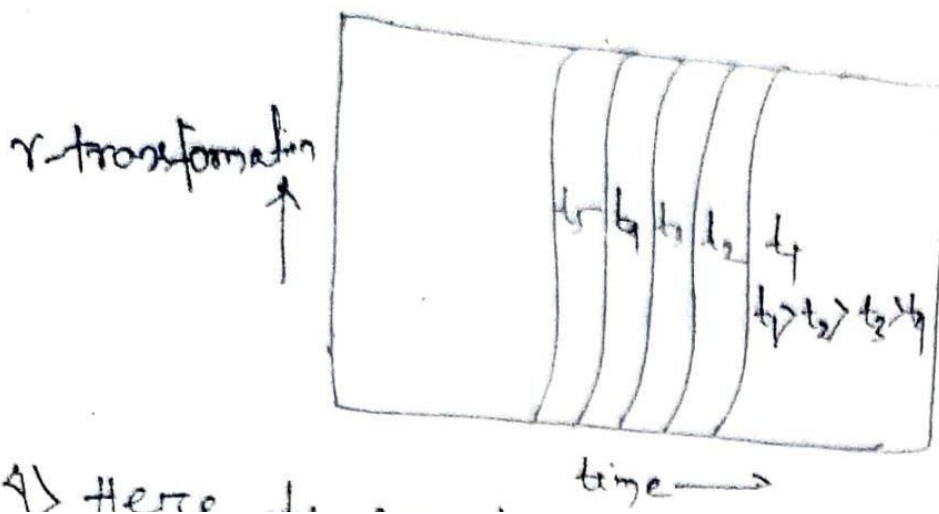
1. It is also known Time temperature transformation diagram.
2. A diagram which includes all the three parameters i.e., time, temperature and transformation will be great importance specially for the heat treating. Such a diagram is known as time temperature – transformation diagram or isothermal diagram or c-curve.
3. For the construction of T-T-T diagram, a no. of samples are taken. These samples are heated to predetermined austenizing temperature and hold at this temperature for a long time to obtain a homogeneous austenite. Then these austenizing samples are transferred quickly to another bath maintained at a constant temperature below the eutectoid temp selected for the study of kinetics of transformation. These samples are taken out one by one after different time intervals and are quenched immediately. These quenching samples results the formation of martensite from the untransformed austenite.
4. By this technique, the amount transformed austenite can be determined as a function of time at constant temperature.
5. The amount of transformed austenite will increase by allowing samples to remain in constant temperature both for longer time.

6. After particular time, all the austenite will transform to an aggregate to ferrite and cementite at given temperature.



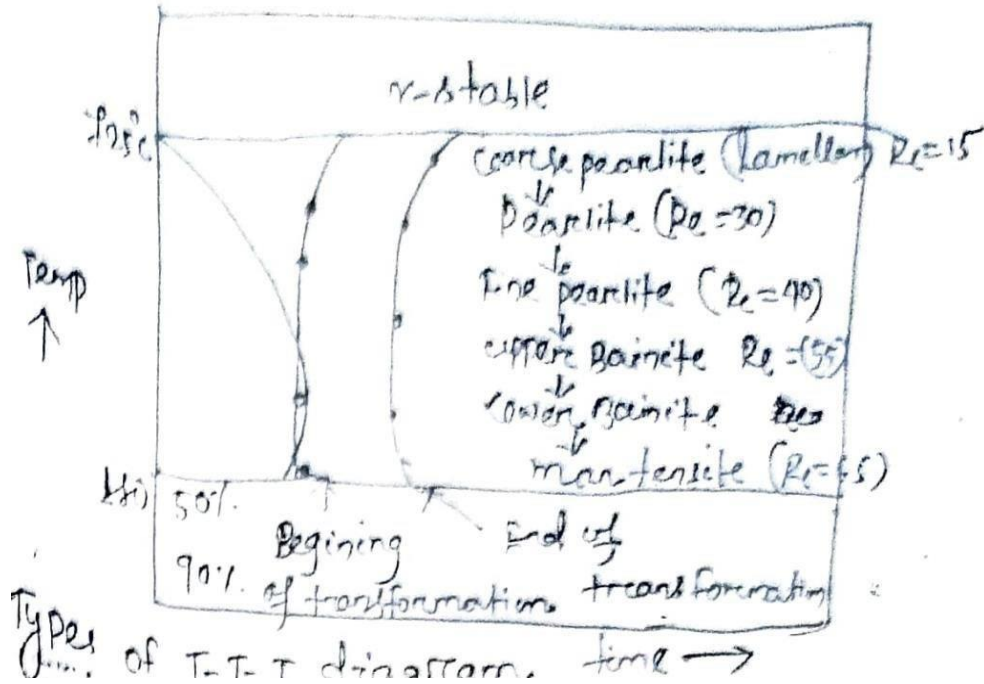
This diagram starts the effect of time in the amount of transformed austenite for a given transformation temperature.

1. It is clear from the fig. that transformation of austenite does not start immediately.
2. Incubation period in which transformation does not proceed because enough diffusion has not taken place in austenite for the transformation to start.
3. Smaller incubation period corresponds to lesser stability of austenite.



- 4) Here t_1 greater than t_2, t_3, t_4, t_5 and is really eutectoid temperature.
4. From the fig. it is observed that higher the transformation temperature, more is the incubation period and increase the time required to complete transformation.
 5. Incubation period and transformation time decrease by decreasing the transformation temp.
 6. After a particular temp decreasing tends to reversed and both incubation period and transformation time increase again with the lowering the transformation temperature.

8. Accordingly, the rate of nucleation increases.
9. Decreasing the transformation temp, the rate of diffusion decreases.
10. The transformation rate depends upon the rate of nucleation and rate of diffusion.
11. So, the incubation period and time increases further decreasing the transformation temperature.

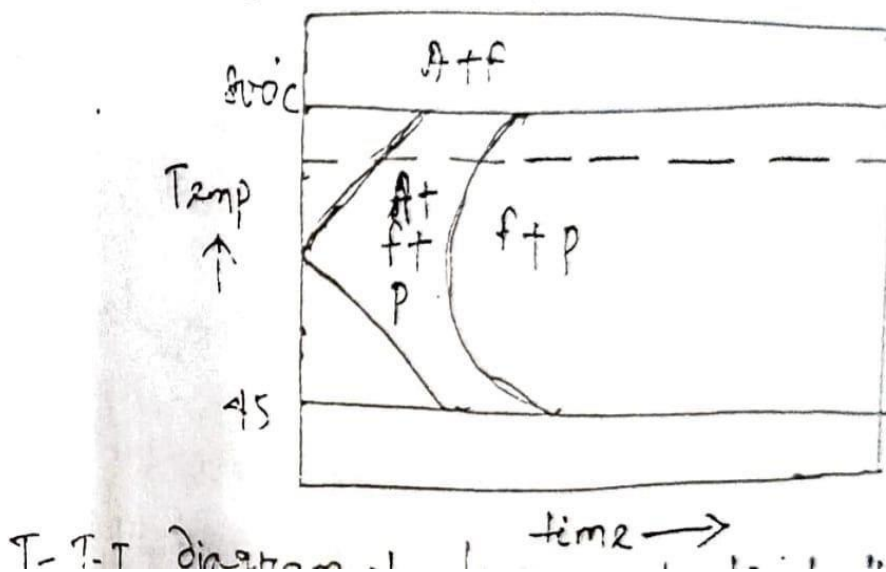


Types of T-T-T diagram

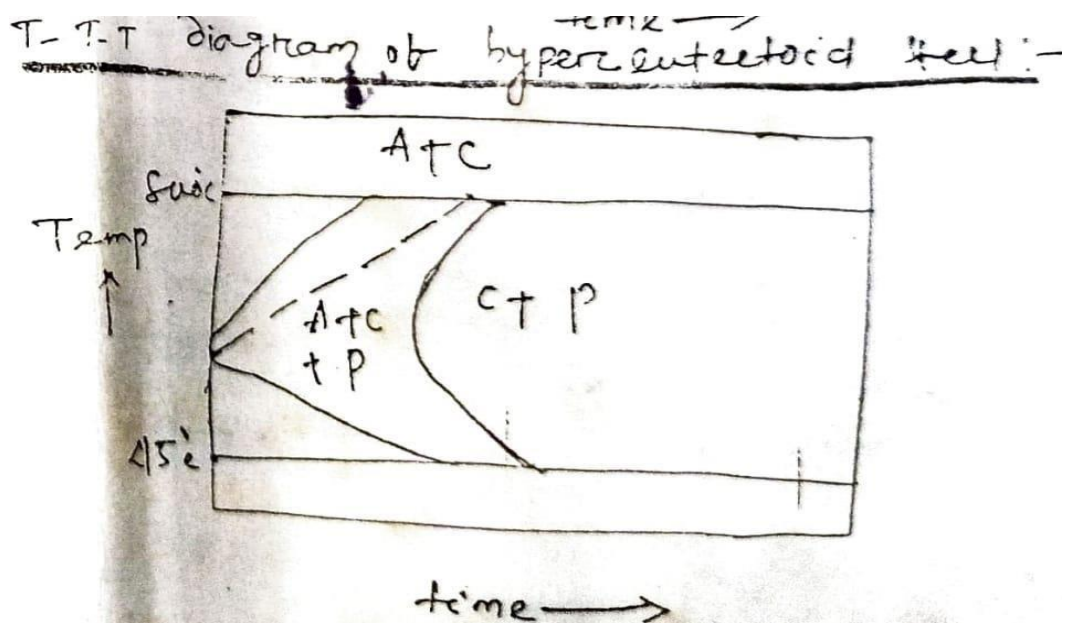
1. Hypo eutectoid
2. Eutectoid
3. Hyper eutectoid

T-T-T diagram of hypoeutectoid steel: -

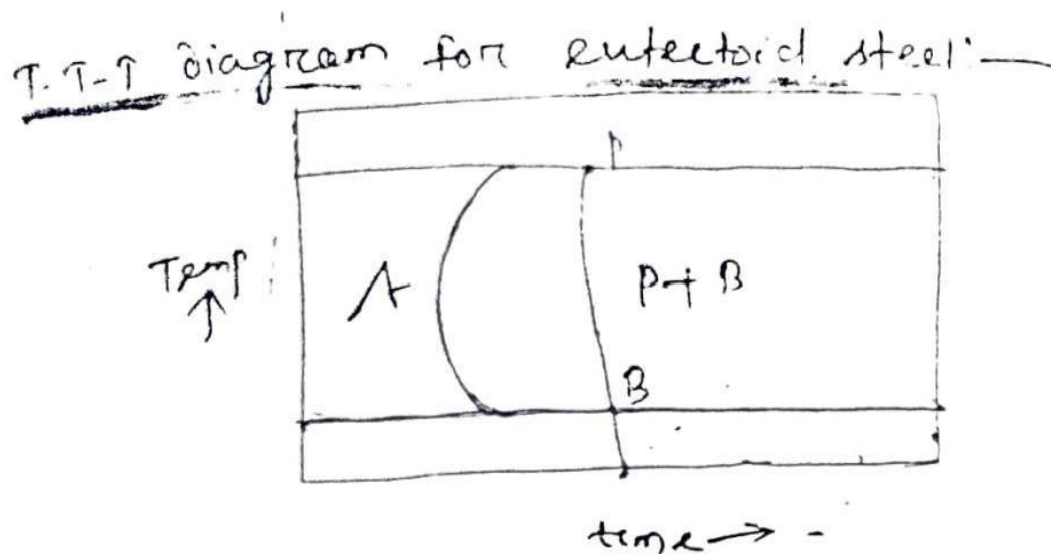
T-T-T diagram of hypoeutectoid steel:-



T-T-T diagram of hypereutectoid steel: -



T-T-T diagram for eutectoid steel: -

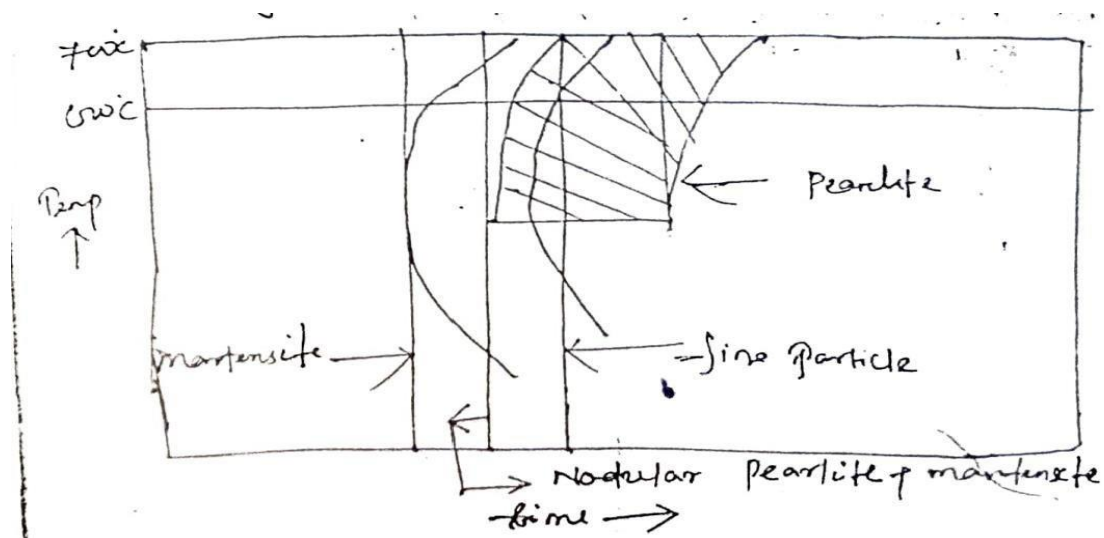


Limitation of Iron-cementite over T-T-T diagram: -

1. Actual treatment cycle used cooling rate much faster than equilibrium cooling rate by which iron cementite has been drawn.
2. Iron cementite diagram represents the behaviors of steel under equilibrium condition whereas actual treatment of steel is normally under non-equilibrium condition.
3. This diagram does not indicate the character of transformation of austenite such as bainite and martensite.
4. This diagram does not indicate the presence of metal stable phase like martensite and bainite.
5. Iron cementite diagram does not indicate the temperature of start of bainite and martensite.

C-C-T diagram

1. It is known as continuous cooling transformation diagram.
2. Most of industrial heat treatment of steel are carried out by continuous cooling rather than by isothermal transformation.
3. Information does not obtain directly in T-T-T diagram.
4. Thus, it becomes necessary to develop a diagram which represents the transformation of austenite or continuous cooling at various rate. This diagram is called continuous cooling diagram.
5. Continuous cooling shifts the beginning of austenite transformation of lower temperature and for longer time.
6. So, most of industrial heat treatment of steels are carried out by continuous cooling rather than by isothermal transformation.



Decomposition of austenite

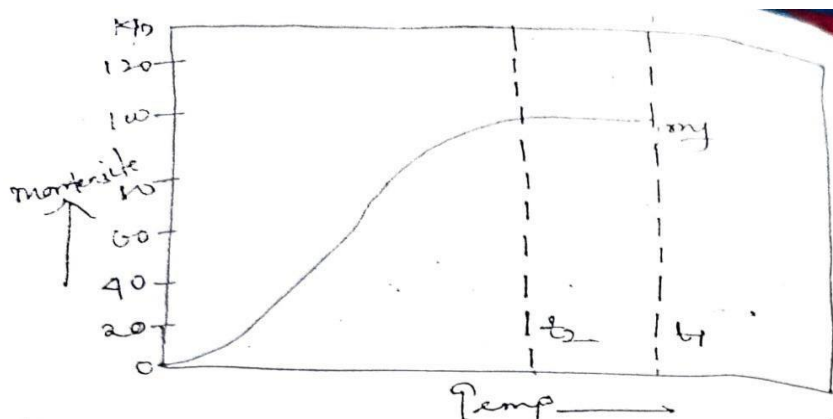
1. Austenite is a solid solution of carbon gamma (Fu) iron.
2. Single phase austenite is stable above the a_3 , A_1 and A_{cm} temperature for hypoeutectoid, eutectoid and hyper eutectoid steels respectively.
3. Below the A_1 temperature, the mixture of ferrite and cementite is thermodynamically stable.
4. On cooling the eutectoid steel below the eutectoid temp austenite will decomposes to an aggregate of ferrite and cementite.
5. The process of austenite decomposes becomes more and more complicated for hypo-eutectoid and hypereutectoid steel.
6. The decomposes of austenite to ferrite cementite is essentially diffusion control process and proceeds by nucleation and growth mechanism.
7. Diffusion is time and temperature-controlled process. Rate of diffusion decreases with decreasing the transformation temperature.

Bainitic Transformation: -

1. The term Bainitic refers to the mixture of ferrite and carbide.
2. For eutectoid steel, bainitic forms from the under-cooling austenite in the temperature range 200 – 500°C.
3. Transformation of austenite to bainitic occurs only below the definite temp. Known as 'B_s' temp.
4. Austenite and bainitic transformation complete at a definite temp called 'B_F'.
5. Two typical structures are formed of Bainitic: -
 - a. Upper Bainite
 - b. Lower Bainite
6. The structure of upper bainitic is feathery.
7. Formation of bainitic starts at a temp of which diffusion of iron atom is very slow but diffusion of carbon is very important.
8. The lower bainitic is acicular appearance.

Martensitic Transformation: -

1. The diffusion rate of carbon decreases with lowering of temperature and at about 200°C, the rate of diffusion of carbon becomes negligible.
2. Austenite when cooled below this temperature (200°C) transforms to a product known as martensite.
3. No. of carbon diffusion takes place during transformation.
4. During transformation from γ -iron to α -iron is same as no diffusion of carbon and other metallic atom takes place.
5. Martensite is defined a super saturated interstitial solid solution of carbon in α -Fe.
6. Martensite has BCT structure. (BCC \rightarrow body centered tetragonal)
7. Martensite is formed by quenching austenite.
8. Martensite transformation is diffusion less transformation.



9. The transformation of under cooled austenite to martensite starts at a definite temperature 'MS'
10. MF referred as the end temperature for martensite transformation.
11. The martensitic transformation is independent of holding time.

Athermal Martensite: -

Transformation stops and cooling is interrupted i.e., the steel is held at a constant temperature the transformation continuous for longer period. So, some of austenite transform to martensite at room temp. In this way the martensite formed is called isothermal martensite.

HEAT TREATMENT PROCESS FOR STEELS

The property of metal can be varied by several methods.

- Mechanical working
- Alloying
- Grain size control
- Heat treatment

Stress relieving: -

1. Generally, this process is employed to relieve internal stresses.
2. No. of micro structural changes will occur only structural improvement takes place.
3. Internal stresses are those stresses which are present in the body in the absence of external stresses.
4. This is also known as residual stress or locked in stresses.
5. These stresses are developed during solidification of casting, welding, machining and eliding.
6. This process of stress relieving consists of heating the steel uniformly to a temperature below the lower critical temperature.

Annealing: -

1. Annealing means heating the steel to a predetermined temperature, holding at this temperature and finally cooling at a very slow rate.
2. The temperature to which steel is heated and holding time are determined by various factors such a chemical composition, size and shape of steel.
3. Annealing may be used as final treatment or preparing step for other heat treatment.

Purpose of Annealing: -

1. It will relieve internal stresses & restore ducting toughness.

2. Enhance machinability.
3. Eliminate chemical non-uniformity.
4. Refine & rain size.
5. Reduce the gases content in steel.

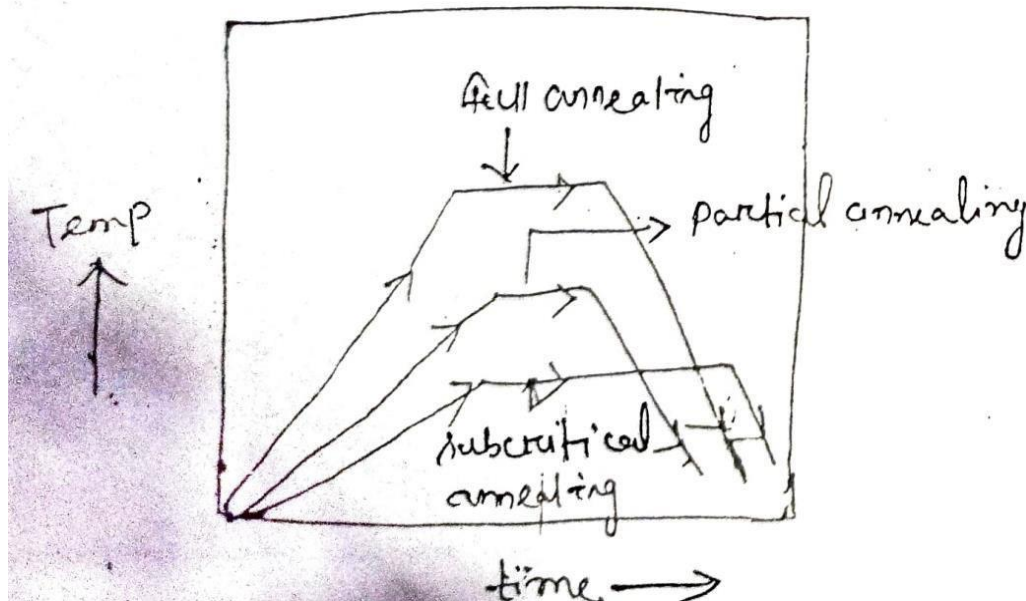
Types of Annealing: -

Annealing treatment can be classified accordingly into groups:

1. Temperature of treatment.
2. Phase transformation takes place during treatment.
3. Purpose of treatment.

Depending on temperature of treatment: -

1. Full annealing
2. Partial annealing
3. Subcritical annealing



Full annealing: -

For full annealing steel is heated above $30-50^{\circ}\text{C}$ the upper critical temperature (A_3) and cooled very slow rate.

Partial Annealing: -

1. It is also known as Inter-critical annealing or incomplete annealing.
2. It involves heating the steel to a temperature lying between the lower critical temperature (A_1) and upper critical temp (A_3 or A_{cm})
3. The steel may be cooled very slowly from annealing temp or it may be cooled in air from a temp at which all the austenite has been transformed into pearlite.

Sub-critical annealing: -

1. It is an annealing process in which the maximum temp to which steel is heated is always less than the lower critical temp (A_1)
2. In sub-critical annealing no phase transformation takes places.
3. Only thermally activated phenomena such as recovery, recrystallisation, grain growth and softening occurs.

According to phase transformation: -

According to phase transformation it is classified into two such as

- (1) 1st order Annealing
- (2) 2nd order Annealing

1st Order Annealing: -

1. In case of 1st order annealing, some properties will be achieved without giving importance to phase transformation.
2. Wide range of temperature is available for this type of annealing.

2nd Order Annealing: -

It is mainly essential for phase transformation only temperature above or below the lower critical temperature can be utilized for this type of annealing.

According to purpose of treatment: -

According to purpose of treatment it is classified into different types: -

1. Diffusion annealing
2. Isothermal annealing
3. Spherodizing annealing
4. Full annealing
5. Recrystallisation annealing

Diffusion Annealing: -

1. It is also known as homogeneity annealing used to remove structural non-uniformity.
2. Dendrites, column grains and chemical in homogeneity are generally observed in ingots.
3. These defects promote brittleness and reduce the ductility and toughness of steel.
4. In diffusion annealing, steel is heated above the upper critical temp (1000-1200°C) and is held at this temp for prorogated period for (10-20 hr) followed by slow cooling. Then chemical homogeneity steel is obtained by this treatment as a result of defect.

5. Heating to such a high temperature result coarsening of austenite grains and heavy scale formation this coarse austenite further transforms to pearlite on cooling which hinders in the mechanical property.
6. The coarse grain structure can be further refined either by plastic working or ingots or by complying a 2nd H/T for casting.

Full Annealing: -

1. Full annealing consists of heating steel to austenite temperature followed by slow cooling.
2. Steel is heated to about 30-50₀C above the upper critical temperature (A_3) for hypoeutectoid steel. The steel is held at this temp for predetermined time allowed by cooling at a very slow rate.
3. Steel is heated above the upper critical temp in order to get a homogeneous austenite structure.
4. Alloy steel which contains strong carbide forming elements, need higher annealing temperature than plain carbon steel and other alloy steel.
5. The Interlamellar spacing will depend mainly on the annealing temperature and the cooling rate.
6. The objective of this treatment is to improve ductility, remove internal stress and refine grain structure.
7. The austenite grain size is minimum just above the upper critical temp (A_3) for eutectoid steel.
8. This process is mainly employed for medium carbon steel.

Isothermal Annealing: -

1. In this process hypo-eutectoid steel is heated above the upper critical temp (A_3) and held for sometime at this temperature in order to get a complete austenite structure and main purpose of this annealing is to eliminate any temperature gradient within the steel components.
2. Then the steel is cooled rapidly to a temperature less than the lower critical temp (A_1) i.e., 600-700₀C.
3. Faster cooling can be achieved by rapidly transforming steel to another furnace maintained at desired temperature.
4. It not only improves machinability but also gives better surface finish and
5. It is carried out on small object.

Partial Annealing: -

1. It is also known as Inter Critical temperature or in complete annealing.

2. In this process steel is heated between the lower critical temp (A_3) followed by slow cooling.
3. Generally hypereutectoid steel re subjected to this type of annealing. Here the resultant structure is fine per.....10-30°C above for hypothetical steels
4. Due to low temperature, it is quite cheaper than full annealing which involves higher temp.

Recrystallisation annealing: -

1. Heavily cold worked structures are subjected to this type of annealing.
2. This process consists of heating steel above the recrystallisation temp, holding at this temp and cooled.
3. The main purpose of this annealing is to decrease in hardness or strength and increase in ductility.
4. This process obtains both intermediate operation and final treatment.
5. It is mainly employed in industries manufacturing steels wire and sheets and strips.
6. It depends on chemical composition, holding time and initial grain size.
7. It is a very cheaper process because the time duration is very less.
8. It improves the machinability and surface finish and mainly carried out for small object.

Spheroidizing: -

1. Spheroidizing is a heat treatment process which gives structure consists of globules or spheroids of carbide in a matrix of ferrite.
2. The degree of spheroid zing depends on heat treatment temperature and holding time
3. The process can be completed short time by increasing the treatment temperature.

Normalizing: -

1. Normalizing consists of heating the steel to about 40-50°C above the upper critical temp (A_3) holding for 1 hour and them cooling in still air or room temperature.
2. Cooling rate can be controlled either by air temp or air volume.
3. The structure of Normalizing is pearlite.
4. Normalizing gives finer pearlite structure than annealing due to high temperature.
5. Grain size of normalized steel is governed by section thickness.

6. As the temperature varies from case to core there is a variation of grain size from case to core.
7. After achieving homogeneous structure heat treatment is required in order to get chemical homogeneity.
8. Refining is done by normalizing steel at lower temperature.
9. Normalizing treatment is applied to steel in order to achieve grain refinement, improvement in machinability and enhanced the hardness strength and toughness, uniform structure.

HARDENING: -

1. The process by which we get high hardness values known as Hardening.
2. Hardening treatment consists of heating to hardening temperature, holding at this temperature followed by rapid cooling.
3. The rapid cooling results martensite structure which is very hard because of rapid cooling.
4. Internal stress are developed in the steel therefore hardening steel are subjected to tempering.

Ex- Quenching is one of the hardening processes.

Factors affecting hardening process:

1. Chemical composition of steel
2. Size and shape of steel
3. Hardening cycle i.e., heating rate hardening temp
4. Homogeneity and grain size of austenite.
5. Quenching media
6. Surface condition of steel

Chemical composition of steel: -

1. Chemical composition of steel largely determined the hardening temperature.
2. The alloy carbide is generally hardened than cementite. So, carbide forming elements products hardened steel.

Size & Shape of steel: -

1. Larger parts or variable thickness of section are heated at very slow rate. So as to avoid thermal gradient between outer and inner layer.
2. For complete hardening temperature should be such that homogeneous austenite with minimum grain size is produce. This is achieved by hypo-eutectoid steel to 30°
– 50°C above AC.

3. Cooling rate equal to greater than upper critical cooling rate give complete hardening.
4. Quenching medium affects the hardening process because cooling rate depends upon density, thermal conductivity and latent heat of vaporization of the boronium.

Different Hardening Method: -

There are various types of hardening methods.

1. Conventional direct quenching.
2. Quenching in stages in sequence of different media.
3. Spray quenching
4. Quenching with self tempering
5. Austempering or isothermal quenching.
6. Martempering or stepped quenching

CONVENTIONAL QUENCHING: -

1. It consists of quenching the steel component from hardening temperature in the quenching medium then it is allowed to cool up the temp of quenching bath.
2. Cooling rate can be controlled by adopting less severe quenching media means use oil in place of water.

Quenching in stages in sequence in different Media: -

1. It consists of quenching the steel component to a hardening temperature in a bath maintained at a predetermined temperature which is higher than the MS temperature.
2. In general, the medium used is water.
3. Oil and air are preferred for second quenching.
4. Internal stress developed in this process is less than those found in direct quenching.

Spray Quenching: -

1. In this process, steel part is cooled rapidly from the hardening temperature by spraying quenchants.
2. In this process, rate of heat extraction from the steel part is much higher than direct quenching.
3. Water is used as quenchant for this process.

Quenching with self-tempering: -

1. Hardening is followed by tempering in order to have required combination of hardness, strength and toughness.
2. In this process steel part is quenched from the hardening temperature without allowed it to cool completely in the quenching medium.
3. In this way some amount of heat will be retained in this central portion.
4. Then the components are cooled in a media quenching medium such as oil and air.
5. This first produces martensite and then second produces pearlite in place of martensite.

TEMPERING: -

1. Hardening treatment develops maximum hardness excellent wear resistance and high strength in the steel.
2. It affects ductility, toughness and impact strength of steel.
3. It also increases the brittleness of steel.
4. Tempering treatment consists of heating hardened steel below the lower critical temperature followed by cooling in air.
5. Higher the tempering temperature more is the ductility and toughness.

Structural changes of Tempering: -

Structural changes include isothermal transformation of retained austenite ejection of carbon from body centered tetragonal lattice of martensite growth and spheroidizing of carbon particles and formation of ferrite and carbide mixture.

1st stage

1. The tempering temperature is about 250°C in this stage.
2. This results the formation of low carbon Martensite and a carbide
3. Low carbon martensite is independent of carbon content of original martensite.
4. The carbide precipitated from higher carbon martensite during 1st state of tempering is not cementite. This carbide is known as E carbide which has hexagonal closed packed structure.
5. The carbon content of E carbide is more than that of cementite (Fe_3C) and formula $\text{Fe}_{2.4}\text{C}$.
6. $\text{Fe}_{2.4}\text{C}$ forms at low temperature range in which martensite is metastable.
7. These results decreased hardness and strength and toughness increased.

2nd stage

1. 2nd stage of tempering consists of heating steel in the temperature range from 350 to 500°C.
2. During this stage retained austenite transform to bainite.
3. In this stage ductility and toughness increases and strength and hardness decreases.
4. This process is mainly used for a coil and laminated spring.

3rd stage

1. It consists of heating the steel in temperature 500 – 680°C and reactions formation of ferrite and cementite.
2. This process consists by diffusion and nucleation mechanism.
3. This process is well suited for medium nucleation mechanism.
4. This process is well suited for medium alloy steel and medium carbon steel.

Martempering – (180 – 250°)

1. It involves heating the steel components above the austenizing temperature followed by quenching in constant temperature above MS Point (between 180-250) steel is held in the bath to attain uniform equilibrium.
2. It results minimum internal stress cracking and improved mechanical properties.
3. The microstructure of martempering is martensite.
4. Alloy steels are best suited for the process,
5. Any steel which can be hardened by oil quality can be martempered.
6. Advantage of using alloy steels in that it increases the incubation period

Austempering: - (250 – 400°C) within bainite range

1. It is the heat treatment process in which austenite is transformed to bainite.
2. It consists of heating the steel above austenizing temperature then it is quenched in both maintained at a constant temperature above MS point, then all the austenite transforms to bainite.
3. After completely transformation steel is taken out of the bath and cooled in air.
4. It imparts ductility high hardness, impact and fatigue strength & less distortion.

Subzero treatment: -

1. The main structure of hardened steel is martensite.
2. It is very difficult to obtain complete martensite structure.
3. Some amount of austenite is generally present in the hardened steel.

4. Retained austenite is converted into martensite by this treatment.
5. It increases the hardness and dimensional stability of steel.
6. This process consists of cooling the steel to a temperature lower than MF temp of steel (-30° to -70°C)
7. During this process large no. of internal stresses are develop and hence tempering is done after the treatment.

Difference between Annealing and Normalizing: -

Annealing		Normalizing	
1.	Annealing steel are less hard.	1.	Normalizing steel are more harder.
2.	Annealing steel is more expensive due to prolonged heat treatment time and higher energy consumption	2.	Normalizing steel is less expensive
3.	Annealing steel has more impact transition temperatures	3.	Normalizing steel has lower transition temperature
4.	Annealing improves the machinability of medium carbon steel	4.	Normalizing improves the machinability of low carbon steel
5.	It consists of heating the steel to a predetermined temp and holding at this temp for 1 hr and followed by cooled at a very slow rate.	5.	Normalizing consists of heating the steel to about 40-50°C above the upper critical temp and holding at this temperature for 1 hr and cooled in still air, slightly agitated air to room temperature.
6.	Grain size is coarse than normalizing due to very slow rate of cooling	6.	Fine grain size due to moderate rate of cooling
7.	Precipitation of carbon occurs at grain boundaries for hypo-eutectoid steelmainly.	7.	Carbide precipitation at grain boundaries are eliminated through normalizing.

HARDENABILITY

Hardenability: -

Hardenability is defined as the susceptibility of the steel to hardening when quenched and is related to depth and distribution of hardness across a cross-section.

The minimum hardness depends on the carbon content in to the steel.

On the other hand, hardenability depends on the addition of alloying elements and grain size of austenite.

Therefore, hardenability of steel is reflected by its ability to harden throughout its cross-section while avoiding drastic quenching.

Determination of hardenability

Hardenability of steel is determined by two methods.

1. Gross Man's critical diameter method.
2. Jominey end quench method.

Gross Man's Critical diameter method: -

The depth at which 50% martensite and 50% pearlite structure are present in a steel bar depends upon the number of parameters i.e., composition, grain size of austenite, the severity of quench and the size of the bar.

It is a direct method. In this method a number of steel bars of different diameters are quenched under identification condition.

1. The length of each bar must be at least five times the diameter to avoid end effect.
2. If the carbon content is $\geq 0.6\%$ a hardenability of about R_c65 is obtained throughout the section.
3. As the diameter of bar increases, the cooling rate at the centre of the bar decreases and gives rise to a soft-core containing pearlite. Due to this the hardness values decrease.
4. The portion of this section which contains 50% martensite is considered as hardened region and the portion which contains $< 50\%$ martensite is considered as unhardened region.
5. In Round bar, the area containing less than 50% martensite is called unhardened core.
6. The bar having dimension of 1" shows 50%. This dimension is called critical dimension.

Journey End Quench Test: -

1. The Gross man method of determination the ideal critical diameter D_1 are time consuming a very large steel bar quenched and tested.
2. This method is a fundamental one and is helpful in explaining the concept of hardenability and ideal critical diameter
3. In this test a steel bar of 1 inch diameter and 4 inches long is heated to proper austenizing temp after being soaked for sufficient time, the specimen is quickly placed in a fixture.

4. A water jet is opened quickly and comes out at a constant pressure through an orifice of $\frac{1}{2}$ inch diameter.
5. The distance between orifice and the bottom end of the steel bar is kept at $\frac{1}{2}$ inch. The free jet height is 2.5 inch and the temperature of water is kept around 24°C .
6. The water strikes the lower end of the specimen. The end quenching is continued about 20 minutes to cool the bar nearly to ambient temperature.
7. The cooling rate is very rapid at the lower end and gradually decreases with increase the distance from the lower end where complete transformation occurs.
8. The hardness is determined at intervals of $\frac{1}{16}$ inch along one end of the flat surface of the bar.
9. The distance is measured from the quenching hand in limits of $\frac{1}{16}$. Thus, called journey distance.

Method of Estimation of hardenability from chemical composition: -

1. The ideal critical diameter is generally determined experimentally. It is also possible to estimate it from chemical composition and the grain size of the steel.
2. This method based on the fact that hardening of steel is controlled basically by the carbon content.
3. Every steel has a base hardenability which depends on carbon content and grain size.
4. Alloying addition change the rate of reaction further, the effect of each alloying element is independent of other alloying elements. This effect is also independent on carbon content and grain size.

Fracture test: -

1. There is a contrast in the nature of fracture undergoing by martensitic and pearlitic regions where as martensite formed on the case exhibits brittle fracture, the pearlite formed in the core undergoes ductile fracture.
2. In fracture test, there is change from martensitic to pearlitic structure; there is corresponding sharp change from brittle to ductile fracture.
3. It is similar to a sudden change in hardness or Microstructure as one phase from martensitic to pearlitic regions.
4. This region of sudden change is the one that contains 50% pearlite and 50% martensite.
5. This method based on the nature of fracture which is successful when the transformation process is quick and a sharp boundary is formed.

6. When the transformation is sluggish the method cannot be applied and it is not possible to get a clear demarcating boundary.

Factors affecting hardenability: -

Effect of austenitic grain size

1. In this process, austenite grains form by nucleation and growth process at cementite and ferrite interfaces.
2. In the beginning the number of austenite grains formed is large because of the larger interfacial area available for nucleation.
3. The size of the austenite plays an important role in determining the hardening response of steel.
4. It is clear the fine-grained steel shows lower hardenability. This is so because there is more number of sites for heterogeneous nucleation of pearlite provided by the austenite grain boundaries.

Surface Hardening Methods: -

Induction Hardening

1. Induction hardening used for local surface treatment, generally used to surface, harden crankshaft, camshaft, gears and axles.
2. In this process heating the component is achieved by electromagnetic induction.
3. The depth to which the current penetrates and rises the temperature is given by following relation for steel component.
In cold state (at 20°C), $d_{20} = 20/\sqrt{f}$
In hot state (at 800°C), $d_{800} = 500/\sqrt{f}$
4. In this hardening the component is heated usually for a few second only. Immediately after heating the surface is quenched by jet of cold water. Due to quenching the martensite structure is formed.

Flame Hardening: -

1. Flame hardening is the simplest form of surface hardening.
2. This process consists of heating the work piece such as crank shaft, angle, gear or any complicated shapes by an oxyacetylene blow pipe followed by spraying of jet of water as coolant.
3. After hardening, reheating is done in a coil or bath at about 180-200°C in order to remove internal stresses.
4. Hardness in flame hardened steel is due to martensite and lower bainitic structure.
5. Carbon content required for flame hardened steels varies from 0.3 to 0.6%.

Electron Beam Hardening: -

1. This process is used for hardening those components which cannot be induction hardening.
2. Automatic transmission clutch cams are hardened by this process.
3. The work piece is kept in vacuum at 0.06m bar pressure.
4. Election beam is focused on the work piece of heat the surface.
5. Normally case depth up to 0.75 mm can be achieved by this method.

Laser hardening: -

1. Laser beams are used for surface hardening treatment.
2. Therefore, a lens is used to reduce the intensity by producing a defocused spot or scans from 1-25 mm)
3. Case depth of about 0.75 mm is obtained by self quenching.
4. This process required less time than induction and flame hardening process.
5. the relation between depth of hardening and power is follows: -

$$Y = -0.11 + \frac{3.02P}{(D_b V)^{1/2}}$$

Where Y = case of depth

P = Laser power

D_b = Incident beam diameter (mm)

V = Transverse speed

6. This increases the probability of pearlite nucleation. Once austenite to pearlite transformation takes place, the austenite to martensite transformation is suppressed accordingly hardenability decreases.

Effect of Carbon content: -

1. The hardenability of steel is greatly influenced carbon content.
2. In spite of this, Fe-C alloys have very low hardenability and the base diameter for a eutectoid steel and ASTM No. 8 is only 0.28 inch.
3. Normal quench will not be effective to harden this steel.
4. Practically, in the commercial grade carbon steel, there is some amount of manganese and other alloying elements which increases the hardenability of steel.
5. Beyond 0.8% carbon hardenability decreases this is due to the fact that

Effect of Alloying elements: -

1. The important role of alloying elements is to shift the nose of C-curve to the right in the T.T.T. diagram.
2. This increases the hardenability of steel even at slow cooling rate.
3. The presence of cobalt is helpful for nucleation and growth of pearlite.
4. Hardenability depends not only in the presence of alloying element but also in the mode of distribution of the allowing elements.
5. Undisclosed Inclusions, such as carbides or nitrides non-metallic inclusions and in homogeneity of austenite decrease the hardenability.
6. On the other hand, the dissolved element in austenite and homogeneity of austenite increases the hardenability of steel.

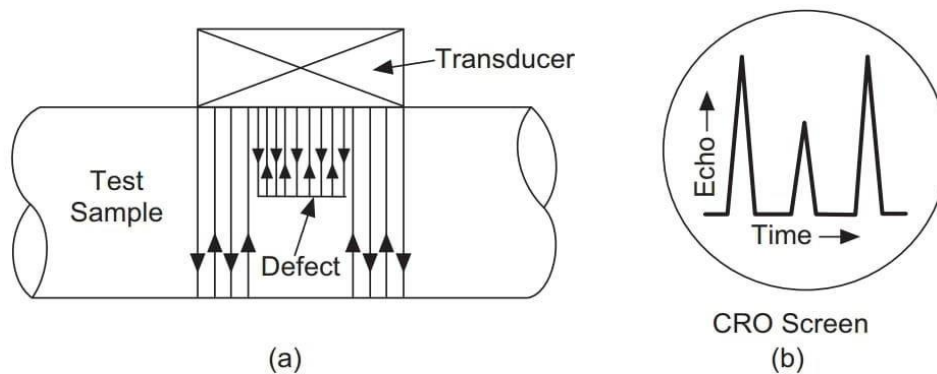


Figure 18.23 Diagram illustrating the principle of ultrasonic testing.

Advantages

1. It can achieve high production rate.
2. Input distortion is quite low because specific energy is very low.
3. It is possible to give localized treatment with this process.
4. No external quenching is needed.
5. It controls the process with the help of computer

Case Depth Measurement of Steel: -

Case depth is defined as the “perpendicular distance from surface of the steel to the point of which the change in hardness, chemical composition or microstructure of case and core cannot be distinguished. There are four methods of measuring case depth.

1. Hardness method
2. Chemical method
3. Micro structure method
4. Microscopic method

Hardness method: -

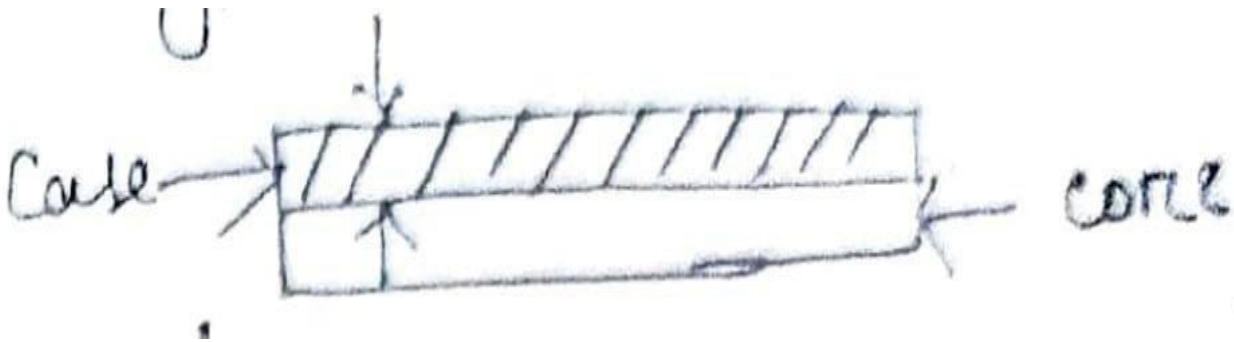
In this method hardness values are taken along the case and core. It is very accurate method since shape changes in hardness across case and core region can be measured.

The specimen for this method is prepared by: -

1. Cross section procedure
2. Taper grind procedure
3. Step grind procedure

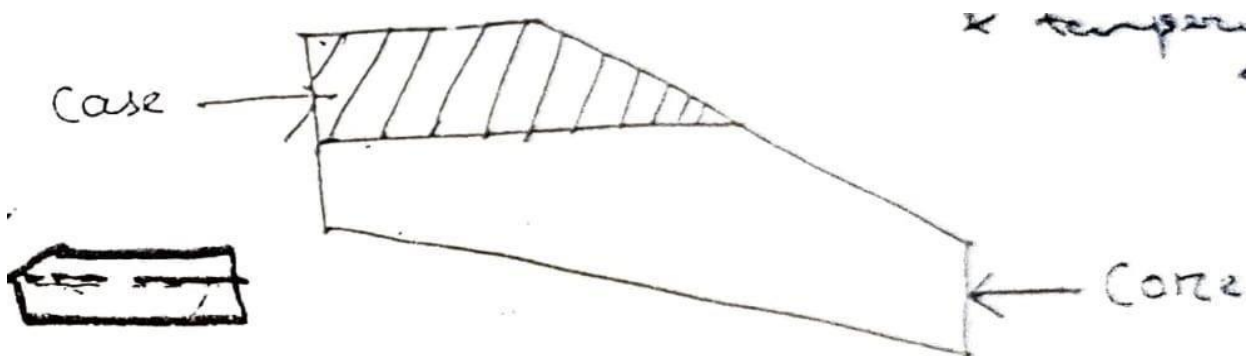
Cross-section procedure

The specimen is cut perpendicular to the hardened surface at a broad-sided area. Thus, care should be taken to ensure that no change in hardness takes place as a result of cutting. The surface area is polished up to 4/0 emery paper.



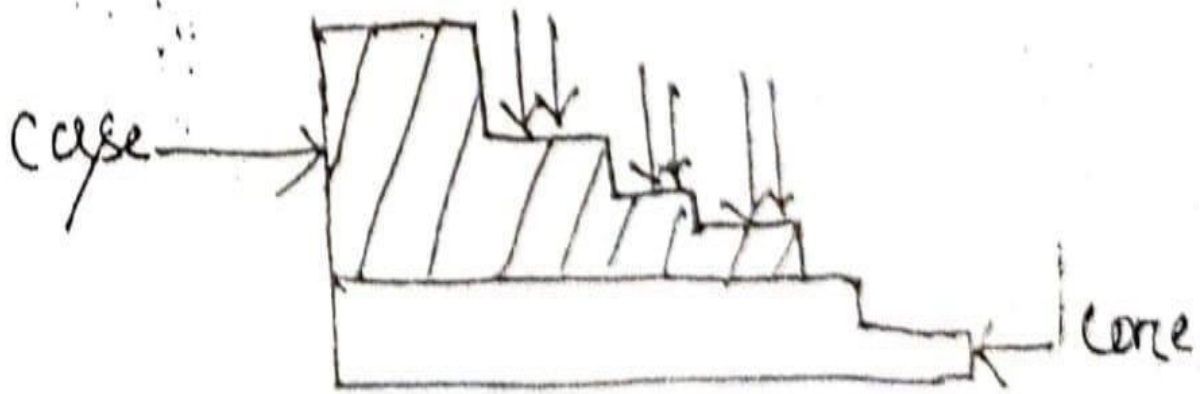
Taper grind procedure

1. This method is suitable for light and medium case.
2. The shallow taper is ground through the case of steel and the hardness values are found along the surface of the prepared taper care should be taken to avoid rusting, erachy and tempering of steel during cutting.



Step grind procedure

1. For medium and heavy cases, step grind procedure is suitable.
2. In this case, the hardness values are taken below the surface.



Chemical Method:

1. This method is applied only to carburized case.
2. This method is also applied to other case hardening method which involves change in chemical composition i.e., Nitriding & carbonizing.
3. Carbon content is determined at various depths below the surface of case-hardening specimen.
4. This is the most accurate method of determining case depth.

Micro Structure Method: -

1. In this method the specimen is cut perpendicular to the hardened surface and the cut surface is ground polished and etched. The specimen is examined under microscope with calibrated eye piece.
2. The total case depth is the distance from the surface to the point up to which modified micro structure is observed.

Carburizing: -

1. It is used for surface hardening of steel.
2. It is mainly done on low carbon steel which contain 0.1% to 0.25% known as carburizing steel.
3. It is carried out in temperature range 900 – 930°C.
4. In this process carbon is diffused into steel by heating above transformation temperature and holding the steel in contact with a carbonaceous material which is either solid liquid or gaseous medium.
5. Under such condition carbon is observed in the solid solution in austenite.

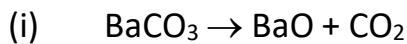
Depending upon the carbonaceous material the carbonization process is divided into 4 groups: -

1. Pack carburizing
2. Liquid carburizing
3. Gas carburizing

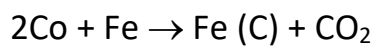
4. Vacuum carburizing

Pack carburizing: -

1. It is also known as solid carburizing.
2. In this process steel components to be heated treated are packed with 80% granular coal and 20% barium carbonate as energizer. This is heated in a heat resistance boxes at a temp of 930°C in electric chamber F/C.
3. Energizer decomposes to give 'Co' gas to the steel surface.

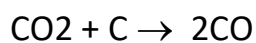


- (ii) Co reacts with the surface of steel



- (iii) Diffusion of carbon into steel

- (iv) CO_2 reacts 'c' in the coal



SO case depth = $k\sqrt{t}$

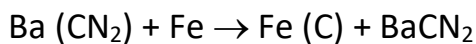
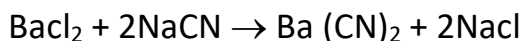
Where K = constant

t = time

Liquid carburizing: -

1. It is also called salt bath carburizing
2. This carburization occurs the rush a molten cyanide bath in low carbon steel in a F/C which is heated by oil or gas.
3. Bath temperature is maintained between 815° – 910°C

4. Reaction →



Gas Carburizing

1. Gas carburizing is carried out in retort, quench type F/c
2. These F/C are either as fired or are heated electricity.
3. Gas carburizing temperature varies from 870° – 950°C.
4. Gas atmosphere for carburizing is produced from liquid or gases hydro carbon.
5. An endothermic gas generator is used to supply endothermic gas.

6. A mixture of propane or methane with air is cracked in hot retort of an endogas generator to form carrier gas. Carrier gas contains $N_2 = 40\%$ $H_2 = 40\%$ $CO = 20\%$ $CO_2 = 0.3\%$ $CH_4 = 0.5\%$ Water Vapor = 0.8%
7. The F/C is heated with gas to maintained a slightly high positive pressure.
8. This also prevents the oxidation of steel during heating.
9. When the material reaches to carburizing temperature propane and methane is introduced to maintain a specific carbon potential.
10. $C_3H_8 \rightarrow 2 CH_4 + C$
 $CH_4 + Fe \rightarrow Fe (c) + 2H_2$
 $CH_4 = CO_2 \rightarrow 2CO + 2H_2$
 $2CO + Fe \rightarrow Fe (c) CO_2$

Vacuum Carburizing: -

1. This is carried out either in-vacuum or in reduced pressure.
2. Carburizing in vacuum or in reduced pressure is carried out in a stage.
 - a. Carbon is made available to the steel to absorption.
 - b. Diffusion of carbon takes place with in the steel piece in order to maintain high core of carbon.
3. The specimen is introduced into the furnace which is then evacuated.
4. After heating a required degree of purity the F/C is heated to a carburizing temp ($925^{\circ}C - 1050^{\circ}C$)
5. As soon as the hydrocarbon comes in contact with the surface of particle, it cracks.
6. The carbon is immediately absorbed by the steel till saturation is attained.
7. This process is continued till the required case depth is achieved.
8. The inflow of gases is stopped and it is removed by vacuum pump.

Post Carburizing heat treatment: -

- (1) This process is done in order to improve by: -
 - (a) Improve the microstructure refine the coarse grains of core and case of carburized steel.
 - (b) Achieve high hardness at the surface.
 - (c) Break of carbide network in the carburized case which may be formed due to higher carbon content.
2. This process is carried in number of steps: -
 - (a) The work piece is carried out at a temp of $104^{\circ}C$ followed by oil quenching.

(b) Tempering at 370°C for converting retained austenite to bainitic structure

(c) Rapid austenizing by induction heating followed by oil quenching.

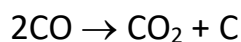
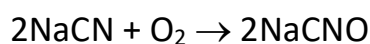
(d) Then followed by final tempering to 180°C.

Nitriding: -

1. Nitriding is carried out in a ferrite region below 590°C. So, there is no phase change after nitriding.
2. Before nitriding proper heat should be done to 390°C and quenching in oil to develop bainitic structure which increases the strength and toughness.
3. The portion which are not to be nitrided are covered by thin coating of tin deposited by electrolysis.
4. The treatment time varies from 21 hours to 100 hrs.
5. After nitriding, the steel part is allowed to cool in F/c in presence of ammonia.
6. During nitriding process a white layer of Fe₄N and Fe₂N on the outer layer of surface.

Cyaniding: -

1. Cyaniding is carried out in a liquid bath of NaCN.
2. It is mainly carried out at a temp of 800 – 900°C.
3. The steel is immersed in liquid bath of NaCN with conc varying from 25% - 90%.
4. Gases oxygen is passed through molten bath and the reaction is



5. This process is not suitable for hardening those parts which are subjected to shock, fatigue and impact because nitrogen addition affects the properties of steel.

Carbo-Nitriding: -

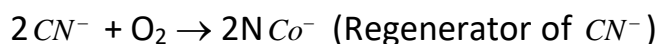
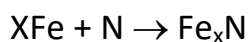
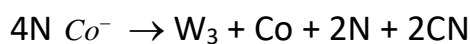
1. Carbo nitriding is carried out in a gaseous atmosphere.
2. It is mainly used for improving the wear resistance of mild steel and plain carbon steel.
3. It is carried out at lower temp (800-870°C) in a gas mixture consisting of carburizing gas and ammonia.
4. Both C and N₂ are diffused at the same times into the surface of steel in austenite ferritic condition and give a thickness of 0.05 – 0.75mm.
5. After carbo nitriding, quenching is done in avoid cracking.

Plasma nitriding: -

1. It is also known as ion nitriding process.
2. In this process the steel component to be nitrided is kept at 450°C in vacuum at negative potential of 1000 volts.
3. Then a mixture of nitrogen and hydrogen passed at a pressure of 0.2 – 0.8m bar.
4. Then plasma formation of these gases takes place.
5. It occurs at low temp (350°C)
6. The time required for achieving case depth is about 20 hours at 450°C.

Salt bath nitro carburizing: -

1. In this process, besides nitrogen and carbon atoms are diffused into the case of steel components at 570 – 580°C in salt baths.
2. The salt bath are two types namely those contain cyanide and other which do not contain any cyanide.
3. Free flow cyanide both is more popular because it is not hazardous.
4. This salt contains a mixture of sodium and potassium cyanates and carbonates.



Boronising: -

1. It is used for surface hardening of carbon and tool steels.
2. Both pack and gaseous techniques can be applied for surface hardening.
3. Boron diffuses inwards and iron boride (FeB and Fe₂B) layers are formed.
4. Other outer surface FeB phase forms and while Fe₂B phased forms in the interior.
5. FeB phase is more brittle. The Bromide layer are very hard and having hardness greater than 1500 VPN.

Chromizing: -

1. It is used for surface hardening of both carbon and tools steels.
2. there are two types of chromizing
 - a. pack chromizing
 - b. gaseous chromizing
3. The components to be chromized are packed with fine chromium powder and additives.

4. This treatment required 12 hours for achieving a case depth of 0.02 – 0.04 mm at 900-1120°C.
5. Hardness of chromium carbide layer is about 1500 VHN.

Toyato Diffusion Process: -

1. In this process the hardness which is achieved is of order of 3000 – 4000 VHN.
2. In this process the component is kept in salt both of proprietary composition based on borax.
3. This process is carried out of a temp of 1050°C.
4. After salt bath treatment, the component re quenched and tempered.

ALLOY STEELS

Alloy Steel:

Alloy Steel may be defined as the steel to which elements other than carbon are added in sufficient amounts to produce improvements in properties.

Different Alloy Steel: -

There are two different alloys steel such as: -

- Low alloy steel
- High alloy steel

Low alloy steel

1. The steel which retains high hardness are known as low alloy steel.
2. In low alloy steel, the temperature is maintained up to 250°C.

High alloy steel

1. It is also known as high-speed steel which retained high hardness
2. Temp up to 620°C.
3. It is used in electric F/C and open-hearth F/C

Effects of alloying elements: -

1. Nickel provides toughness, corrosion, resistance and deep hardening.
2. Chromium improves corrosion, resistance, toughness and hardenability.
3. Manganese deoxidizes, contributes to strengths, hardness, decreases the critical cooling rte.
4. Silicon deoxidizes, promotes resistance to high temperature, oxidation, rises the critical temperature for heat treatment.
5. Molybdenum (M) promotes hardenability increases tensile and creep strength at high temperature.

6. Vanadium dioxides and promotes fine grain structure.
7. Copper increases the resistance to corrosion and acts as strengthening agent.
8. Aluminum deoxidizes and promotes fixed grained structure and aids nitriding.
9. Boron increases hardenability.

Die steel

1. It possesses high toughness, high hardness and high wear resistance.
2. Generally, die steel are used for cutting, drawing operation, draw plates for wear drawing.
3. Small die of simple form made of carbon steel which are easily machinable in the annealed condition.
4. Longer or complex die are made of alloy steel which have high hardness.
5. They are generally quenched in oil.

High speed steel: -

1. High speed steel gets their name from the fact that they may be operated at cutting tools at much higher cutting speed.
2. High speed steels operated cutting speed 2 to 3 times higher than for carbon steel.
3. The temp range varies from 550 – 1200°C
4. These steel demand high red hardness and elevated temp wear resistance.
5. These steels are alloying with strong carbide forming elements such as tungsten molybdenum, chromium and vanadium.
6. Alloying elements should be added in sufficient amount so the carbon combines with them to form alloy carbide.
7. For high-speed steel cobalt is used as alloying elements order to enhance its cutting ability of the tool.
8. The alloy content is varying from 20% - 40%.
9. The carbon content varies from 0.75 – 1.015
10. High speed steel has high hardness and wear resistance.
11. Composition of high-speed steel is
 - C → 0.7% vanadium → 1%
 - 14% → chromium 18% → Tungsten
12. Depending upon the composition high speed steel is up two types: -
 - a. Tungsten base
 - b. Molybdenum base high speed steel

13. The hardening temperature for high-speed steel is 1150 – 1250°C. So, it creates some problem like oxidation and decarburization.

14. Salt bath furnace is used in order to avoid and decarburization.

High Strength low alloy steel:

1. If the tensile strength is 600 – 1000 megapascal then it is called high strength low alloy steel.
2. The percentage of carbon in high strength low alloy steel is 0.15 – 0.35% and small amount of alloying elements.
3. The function of alloying elements is to increase the hardenability.
4. The microstructure of high strength low alloy steel is ferrite and bainite or ferrite and tempered martensite.
5. It has good weldability
6. It has less amount of carbon.
7. Cold cutting and working dies made of high hardness and increase toughness.
8. When the chromium steel is heated above the eutectoid temp then the carbide dissolves and alloyed the austenite with chromium.
9. So higher the heating temperature, higher will be the carbide formation, so higher is the stability. So, more is the corrosion resistance and more is the wear resistance.

Stainless Steel

Properties: -

1. They exhibit high corrosion resistance.
2. They exhibit high oxidation resistance.

Depending upon the chromium and carbon content stainless steel is classified into three types: -

1. Ferritic stainless steel.
2. Martensitic stainless steel.
3. Austenitic stainless steel.

Ferritic stainless steel: -

1. If the chromium (Cr) percentage is 17% and $> 12.7\%$ then it is called ferritic stainless steel.
2. It is in ferritic state, so it can undergo heat treatment.
3. So, the strength is increased means recrystallisation occurs below 723°C then it is hot working.

4. If we add 2% MO to the steel containing 18% Cr or 25% Cr then it increases the oxidation of corrosion resistance.
5. It is used to household and transformation purpose.

Martensite Stainless steel: -

1. If the Cr percentage is 17% and $< 12.7\%$ then it is called martensitic stainless steel.
2. Composition of martensite stainless steel is
Cr – 12 – 14%
C – 0.15%
So, it is called low carbon martensite as it consists of 0.15%
3. Martensitic stainless steel can undergo heat treatment so the strength is increased by heat treatment.
4. It is used in
 - a. Surgical instrument
 - b. High quality ball bearing

Austenitic stainless steel: -

1. It generally undergoes intergranular corrosion.
2. The corrosion which takes place along the grain boundary is called intergranular corrosion.
3. When the steel is cooled from 800°C chromium carbide are precipitated along the grain boundary.
4. So, in the grain boundary chromium content exceeds 70% i.e., the adjacent region losses itself passivating property and become anodeing the grain interiors which contents 18% chromium.
5. so Galvanic cell is created which attacks the thin region resulting in intergranular corrosion.
6. It is used in chemical industry and household application.

