

LECTURE NOTES

On

Heat Treatment



ORISSA SCHOOL OF MINING ENGINEERING

Government of Odisha

ଓଡ଼ିଶା ଶାସ୍ତ୍ରୀୟ ଯାତ୍ରୀକ ବିଦ୍ୟାଳୟ, କେନ୍ଦୁଝର

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Metallurgical Engineering Department

**Orissa School of Mining Engineering
Keonjhar**

Course code: Th2

Semester: 5th

Vision and Mission of the Department

VISION: To offer quality technical education In the field of Metallurgical Engineering with orientation towards industry, entrepreneurship, higher education and to strive for developing professionally competent technicians meeting the needs of the global economy.

MISSION:

M1 :To develop students in the field of Metallurgical Engineering as highly motivated, skillful and qualified manpower for employment and higher learning

M2 :To promote a conducive environment for all round development of students.

M3 :To promote linkages with external agencies to meet changing needs of industry and society.

M4 : To Improve Laboratories

Program Education Objectives (PEOs)

PEO 1:Diploma professionals will be able to make a successful career in metallurgical industries or higher studies to meet the needs of future requirements.

PEO 2:Diploma metallurgists will have technical and behavioral competencies throughadequate exposure to industry.

PEO 3:To impart technological knowledge and skills for solving real-time engineeringproblems.

PEO 4:To develop human resources with capabilities of effective communication, moral values and social responsibilities.

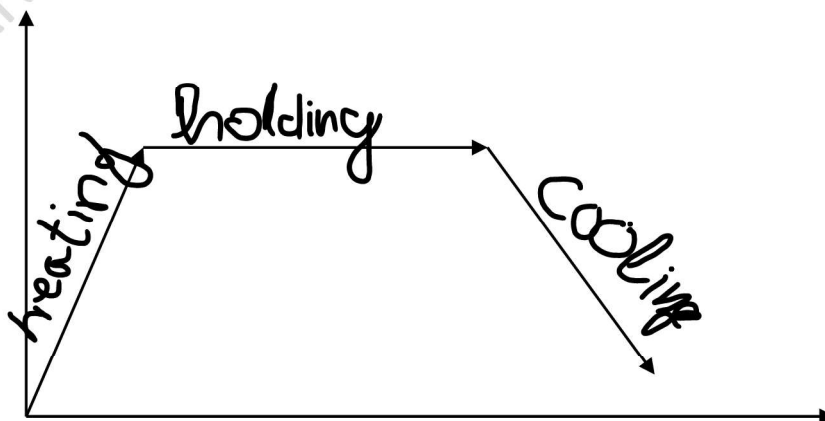
Lecture-1

Introduction:

- Most of the engineering properties of metals and alloys are related to their atomic Structure Crystal structure and microstructure.
- Equilibrium microstructure can be predicted for an alloy with the help of an equilibrium diagram.
- Mechanical properties can be changed by varying the relative proportions of microconstituents.
- In practice change in mechanical properties is achieved by a process known at heat treatment.

Heat treatment

- Heat treatment is a very important tool of a metallurgist to alter the properties of a steel easily depending on the demanding a steel conditions.
- Steel can be made to have a wide range of mechanical properties if subjected to different heat treatment process.
- Heat treatment mainly defined as a Combination of heating and cooling operations timed and applied to a metal or alloy in Solid state in a way that will produce desired properties.
- Heat treatment is a operation or combination of operations heating and cooling of a Solid metal So as to obtain the desired properties.
- Heat treatment cycle involves a change of Phase in Solid state when heating or Cooling takes place.
- A heat treatment Process can be represented graphically with temp and time as coordinates.



- Above figure is the simplest possible heat treatment Cycle in which the metal alloy is heated held at the elevated temp for some time and then cooled to room temperature.

Purpose of heat treatment

Heat treatment may be undertaken for the following purposes

- (1) Improvement in ductility
- (2) Releaving internal stresses
- (3) Refinement of grain size.
- (4) Increasing hardness on tensile strength

Iron - Cementite phase diagram:-

- The Fe-C (or more precisely the Fe-Fe₃C) diagram is an important one. Cementite is a metastable phase and 'strictly speaking' should not be included in a phase diagram. But the decomposition rate of cementite is small and hence can be thought of as 'stable enough' to be included in a phase diagram. Hence, we typically consider the Fe-Fe₃C part of the Fe-C phase diagram.
- In the phase diagram, temperature is plotted against composition. Any point on the diagram therefore represents a definite composition and temperature. The phase diagram indicates the phases present and the phase changes that occur during heating and cooling. The relative amounts of the phases that exist at any temperature can also be estimated with the help of lever rule. Iron-Cementite phase diagram Cementite phase diagram the help of lever rule.
- A portion of the Fe-C diagram – the part from pure Fe to 6.67 wt.% carbon (*corresponding to cementite, Fe₃C*) – is technologically very relevant.
- Cementite is not a equilibrium phase and would tend to decompose into Fe and graphite. This reaction is sluggish and for practical purpose (at the microstructural level) cementite can be considered to be part of the phase diagram. Cementite forms as it nucleates readily as compared to graphite.
- Compositions upto 2.1%C are called steels and beyond 2.1% are called cast irons.

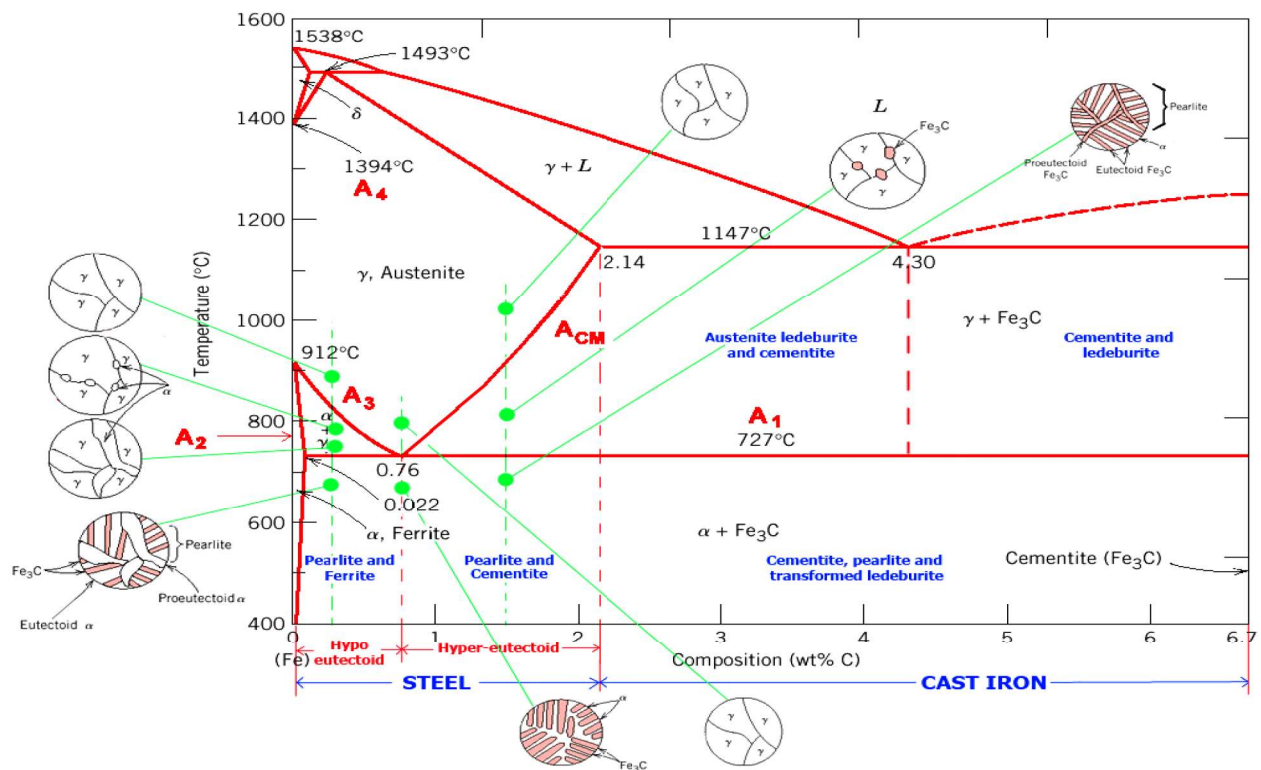
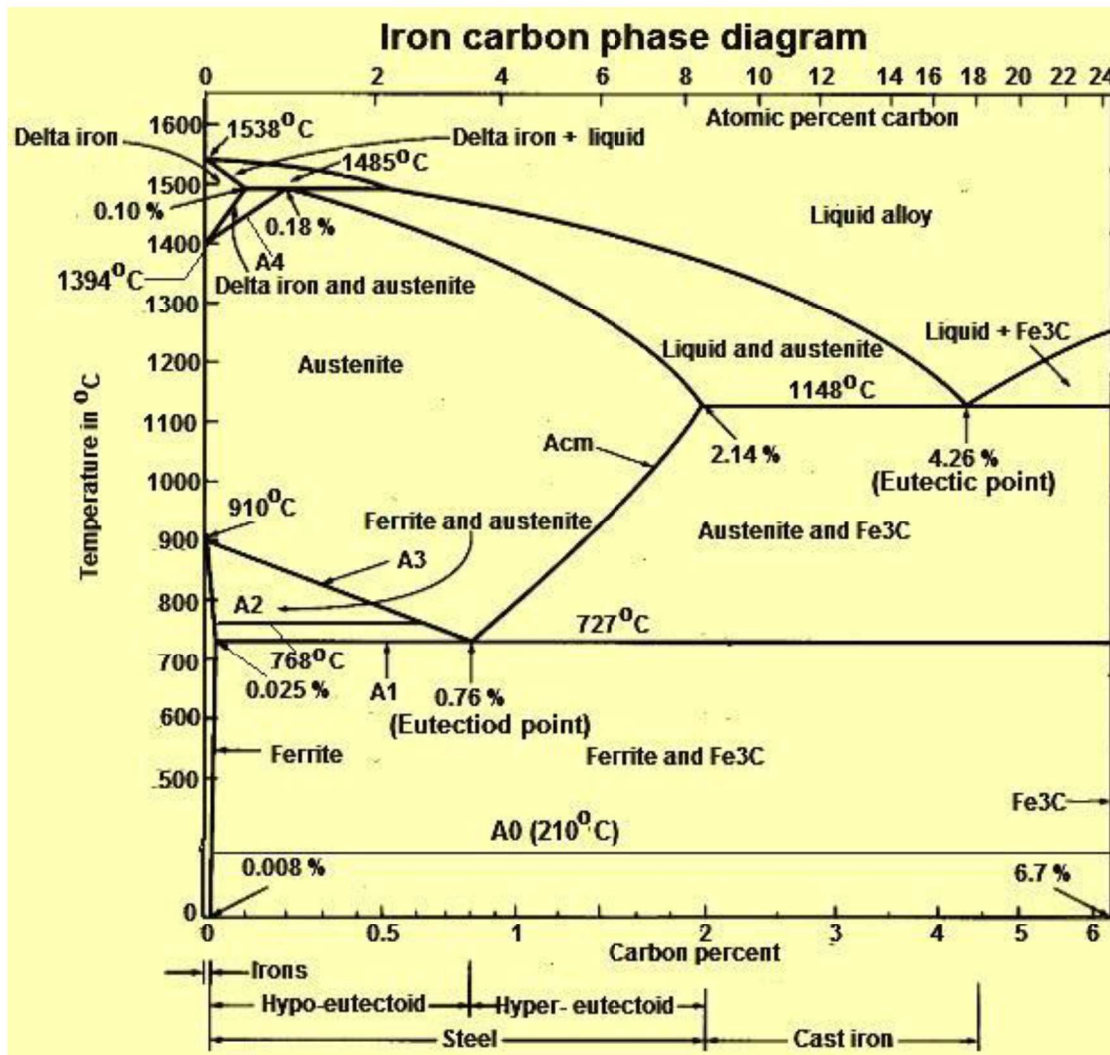


Fig: Iron cementite diagram

What are Critical Temperatures?

Critical temperatures are the specific temperatures at which phase transformations occur in iron and steel during heating or cooling. At these temperatures, the crystal structure of iron changes, which directly affects the mechanical properties of steel.

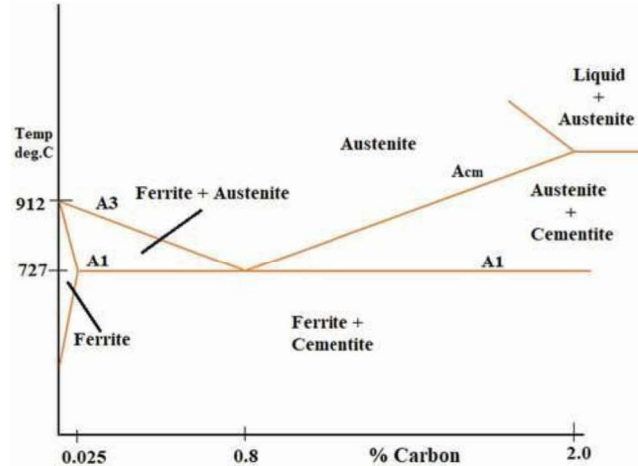
These temperatures are represented by important horizontal and curved lines in the Iron–Carbon Phase Diagram.



Important Critical Temperatures

Critical Temperature	Value	Significance
A ₀	210°C	Magnetic change in cementite
A ₁ (Eutectoid)	727°C	Austenite transforms into pearlite
A ₂ (Curie Point)	768°C	Iron loses magnetism
A ₃	Variable	Ferrite changes into austenite
A ₄	1394°C	Austenite changes into delta ferrite
Acm	Variable	Cementite dissolves into austenite

Important Critical Lines



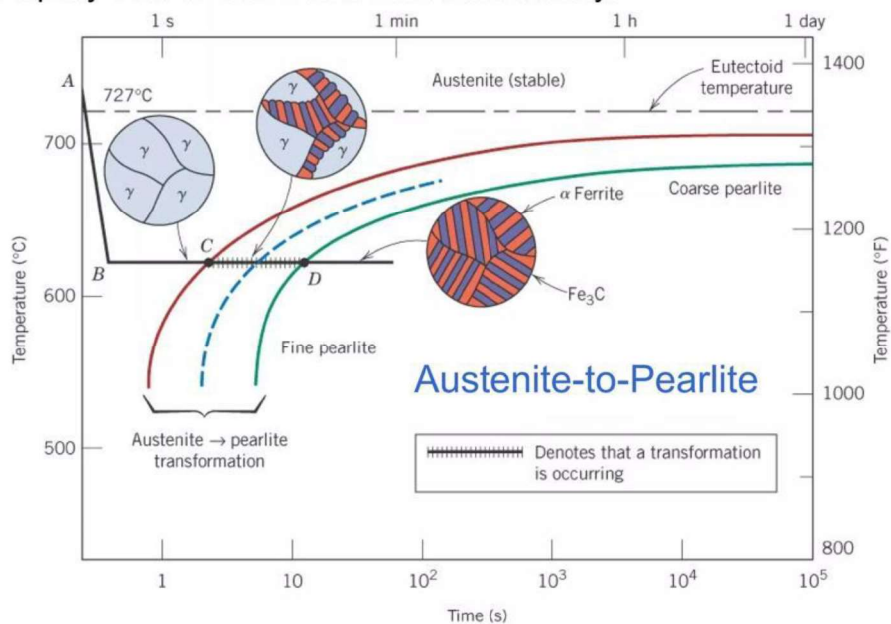
The three most important critical lines are:

- A₁ Line – Lower Critical Temperature
- A₃ Line – Upper Critical Temperature for Hypoeutectoid Steel
- A_{cm} Line – Upper Critical Temperature for Hypereutectoid Steel

1. A₁ Temperature (Lower Critical Temperature)

Isothermal Transformation Diagram

- Eutectoid iron-carbon alloy; composition, C_o = 0.76 wt% C
- Begin at T > 727°C
- Rapidly cool to 625°C and hold isothermally.



- Temperature: 727°C
- Also called Eutectoid Temperature.

- Present for all steels.

During Heating

Pearlite changes into Austenite.

Pearlite → Austenite

During Cooling

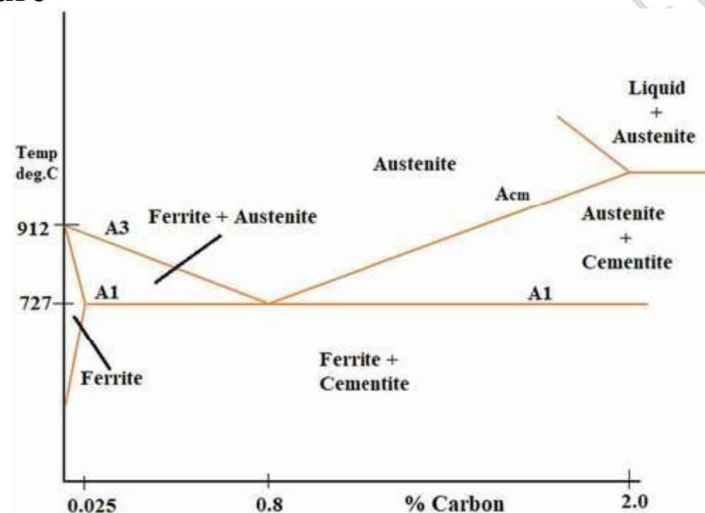
Austenite changes back into Pearlite.

Austenite → Pearlite

Metallurgical Significance

- Basis of heat treatment processes.
- Annealing and normalizing require heating above A_1 .
- Determines formation of pearlite.

2. A_3 Temperature

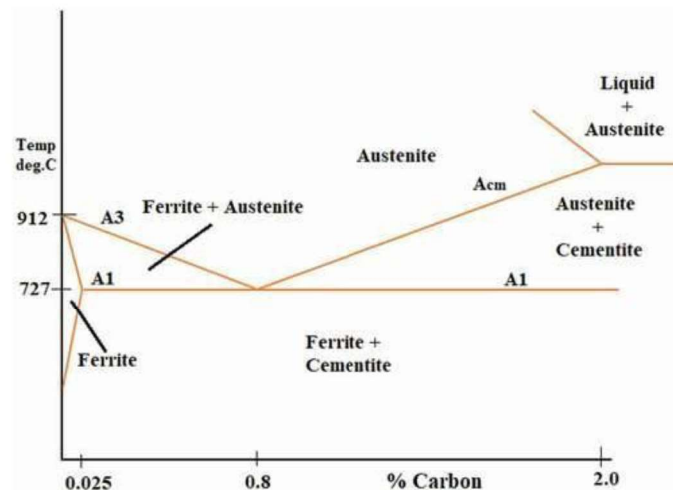


- Applies to Hypoeutectoid Steel (Above A_3 , the steel becomes 100% Austenite.

Metallurgical Significance

- Required temperature for full austenitization.
- Used before quenching.
- Prevents incomplete hardening.

3. A_{cm} Temperature



- Applies to Hypereutectoid Steel ($>0.77\% \text{ C}$).
- Temperature increases with carbon content.

Transformation

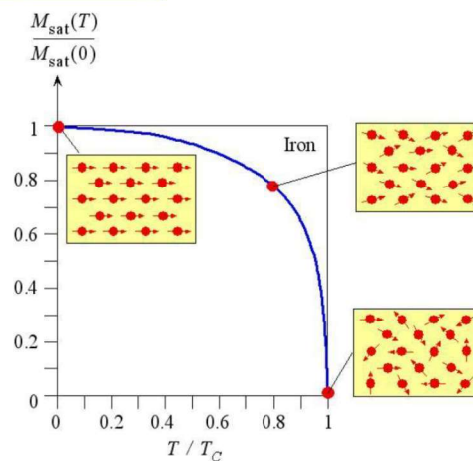
Cementite + Austenite $\rightarrow$ Austenite

Metallurgical Significance

- Complete dissolution of cementite.
- Important for tool steels.
- Controls hardness after heat treatment.

4. A_2 Temperature (Curie Point)

Curie Temperature



- Temperature: 768°C
- No structural change occurs.
- Only magnetic property changes.

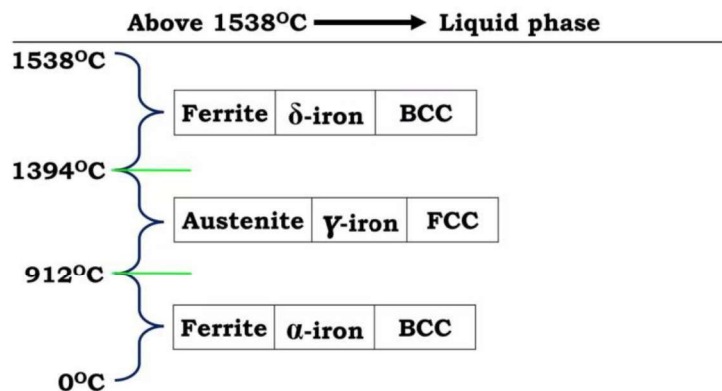
Transformation

- Below $A_2 \rightarrow$ Iron is magnetic.
- Above $A_2 \rightarrow$ Iron becomes non-magnetic.

Significance

- Used in magnetic testing.
- Important in electrical steels.
-

5. A_4 Temperature



- Temperature: 1394°C
- Austenite transforms into Delta Ferrite.
 $\gamma \rightarrow \delta$

Significance

- Important during steel casting.
- Influences solidification.

6. A_0 Temperature

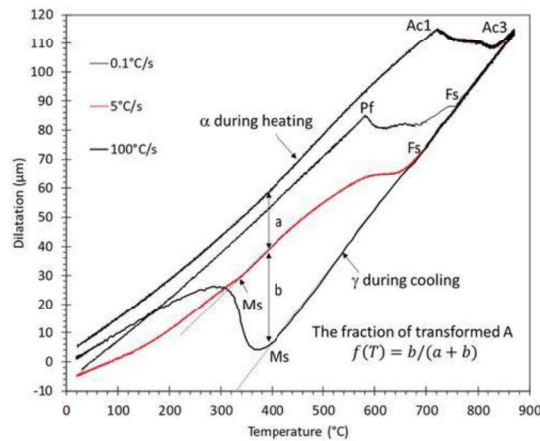
- Around 210°C.
- Cementite undergoes magnetic transformation.
- Limited practical importance.

Critical Temperatures During Heating and Cooling

Different symbols are used because transformations occur at slightly different temperatures.

Symbol	Meaning
Ac_1	Heating through A_1
Ac_3	Heating through A_3
A_{cm}	Heating through A_{cm}
Ar_1	Cooling through A_1
Ar_3	Cooling through A_3

This difference occurs due to thermal hysteresis.



Metallurgical Importance of Critical Temperatures

1. Heat Treatment

- Annealing
- Normalizing
- Hardening
- Tempering

Heating temperatures are selected based on A_1 , A_3 , and A_{cm} .

2. Grain Refinement

Proper heating above critical temperatures produces fine austenite grains, improving toughness.

3. Hardness Control

Quenching from the correct critical temperature forms martensite with high hardness.

4. Microstructure Development

Different critical temperatures produce different structures:

Cooling Condition	Structure Formed
Slow cooling	Pearlite
Moderate cooling	Bainite
Rapid cooling	Martensite

5. Industrial Applications

- Forging
- Rolling
- Welding
- Steel casting
- Tool steel manufacturing

Temperature	Remember
727°C	A ₁ – Pearlite ↔ Austenite
768°C	A ₂ – Magnetism disappears
912°C	Pure iron becomes Austenite
1394°C	Austenite becomes Delta Ferrite

Critical Point	Temperature	Main Transformation
A ₀	210°C	Magnetic change in cementite
A ₁	727°C	Pearlite ↔ Austenite
A ₂	768°C	Magnetic to non-magnetic
A ₃	Variable	Ferrite → Austenite
A _{cm}	Variable	Cementite → Austenite
A ₄	1394°C	Austenite → Delta Ferrite

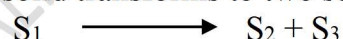
1.0:- SOLID STATE PHASE TRANSFORMATION

- During heat treatment a particular phase transformation might have to be induced or suppressed for this purpose.
- In order to do this effectively, it is necessary to understand all aspects of the corresponding phase transformation.
- A phase transformation or a phase transition is defined as the change from one or more phases to one or more other phases.
- Change in composition and crystal structure in the solid state clearly require the movement of atoms within the solid.

We previously know two kinds of solid state transformation.

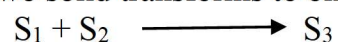
1.EUTECTOID TRANSFORMATION:-

In which one solid transforms to two solids.

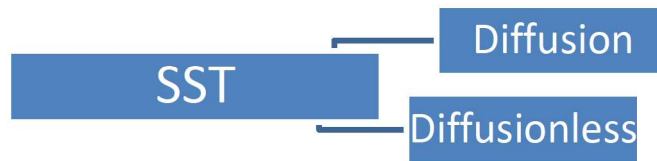


2.PERITECTOID TRANSFORMATION:-

In which two solid transforms to one solid.



- A number of phases transformation in solids are brought about by the process of diffusion.
- Solid state transformation (SST) is occurring by the mechanism.



1.1 Diffusion:- (Movement of atoms)

Diffusion is a mass flow process.

- For example in liquid, if we add one drop of ink in a glass of water then the mixing of ink in water or ink is diffused in water quickly
- Another example in gas, smoke of Agarbati diffuses more quickly in air
- Like wise diffusion occurs in solid due to thermal energy, concentration gradient, stress, electric field, etc.
- Diffusion is defined as the mass flow process by which atoms or molecules change their position relative to their neighbours within a phase under the influence of thermal energy and a gradient.
- This gradient may be of chemical potential resulting from a concentration gradient or a gradient due to temperature, stress, electric field or gravitational field.
- Here we will deal with concentration gradients only.
- In solid State atomic position change is diffusion.

Fick's law of diffusion:-

- The concentration gradients are used in laws first proposed by Adolf FICK in 1855.

FICK'S FIRST LAW:-

First law of Fick states

$$J \propto dc/dx$$

Diffusion Flux(J):-

How many atoms moving at how much time at how much area is called Flux. Denoted by J.

- Diffusion flux is the amount of matter flowing through a unit area in unit time.
- If time is related to this then it can be denoted as dc/dt .

Concentration gradient:-(dc/dx)

Rate of change of concentration per unit change of position.

1st Law:- (For steady state)

- This law describes the rate at which diffusion occurs.
- This law states that diffusion flux is directly proportional to the concentration gradient.

i.e $J \propto dc/dx$

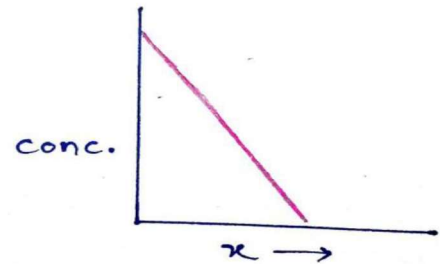
i.e the number of atoms crossing unit area of cross section per seconds is proportional to concentration gradient.

Here, $J \propto dc/dx$

$$J = -D dc/dx$$

Where, D= diffusion coefficient or diffusivity.

- Here negative sign indicates flow occurs from higher concentration to Lower concentration.
- In this case flux will be independent to time so, fick's first law is time independent.



Fick's Second law - (Time dependant) (For non- steady flow)"

- This is an extension of fick's first law of non-steady.
- Here, the diffusion flux (J) is the function of both space and time.
- Fick's Second Law relates the change of concentration with respect to change in time & change in position.

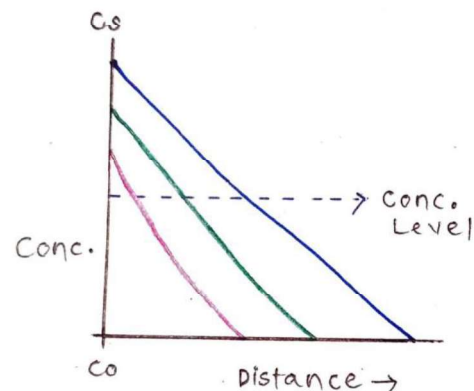
The law is –

$$J = -D(dc/dx)$$

$$Du/dt = -d/dx[-d(dc/dx)]$$

$$dc/dt = D (d^2c/dx^2)$$

- Here concentration level changes with time.
- This law is applicable to real systems.



Steady & non steady state diffusion-

Steady state diffusion:-

- when diffusion flux(J) remain the same as Come see with time, during the whole process, then we say that the process steady state diffusion.
- Fick's first law is associate with Steady State diffusion.

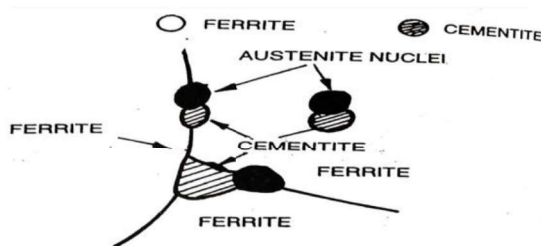
Non-steady state diffusion:-

- When the diffusion flux changes with change in time then it is said to be non-steady state diffusion.
- Diffusion flux itself is a function of time.
- So 2nd law is associated with non-steady state of diffusion.

1.2 AUSTENITE FORMATION:-

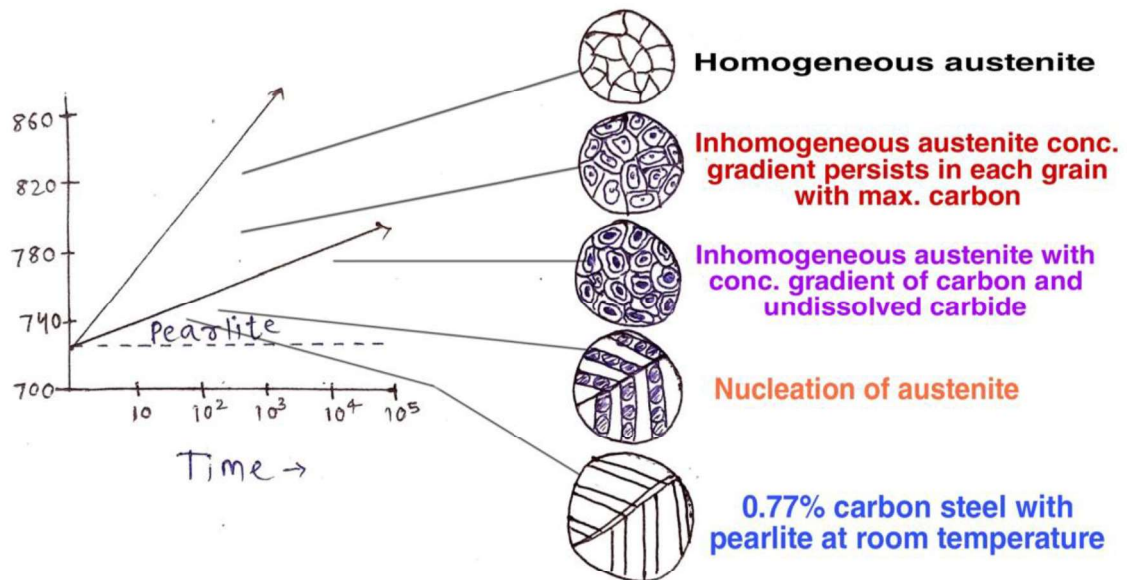
1ST STEP OF HEAT TREATMENT-

- Heating the steel to a high predetermined temperature i.e austenising range called austenisation.
- Heating the steel above critical temperature (Ac_1) i.e pearlite starts to change to austenite.
- This formation occurs by the nucleation of austenite at the interface between ferrite and cementite of pearlite through most preferred sites are at the boundaries of pearlite colonies.



- The rate of austenite formation increases with increase in temperature because it increases the rate of diffusion and also the concentration gradient of carbon in austenite.
- Nucleation of austenite from pearlite change of ferrite and cementite into austenite by change of crystal structure and diffusion.
- Even when austenite grain has formed some residual carbides are left in it because cementite dissolves more slowly than ferrite.
- Homogenisation of austenite is the last stage. These stages take place at high temperature.

- To remove the heterogeneity of austenite, higher temperature and time or both are required.

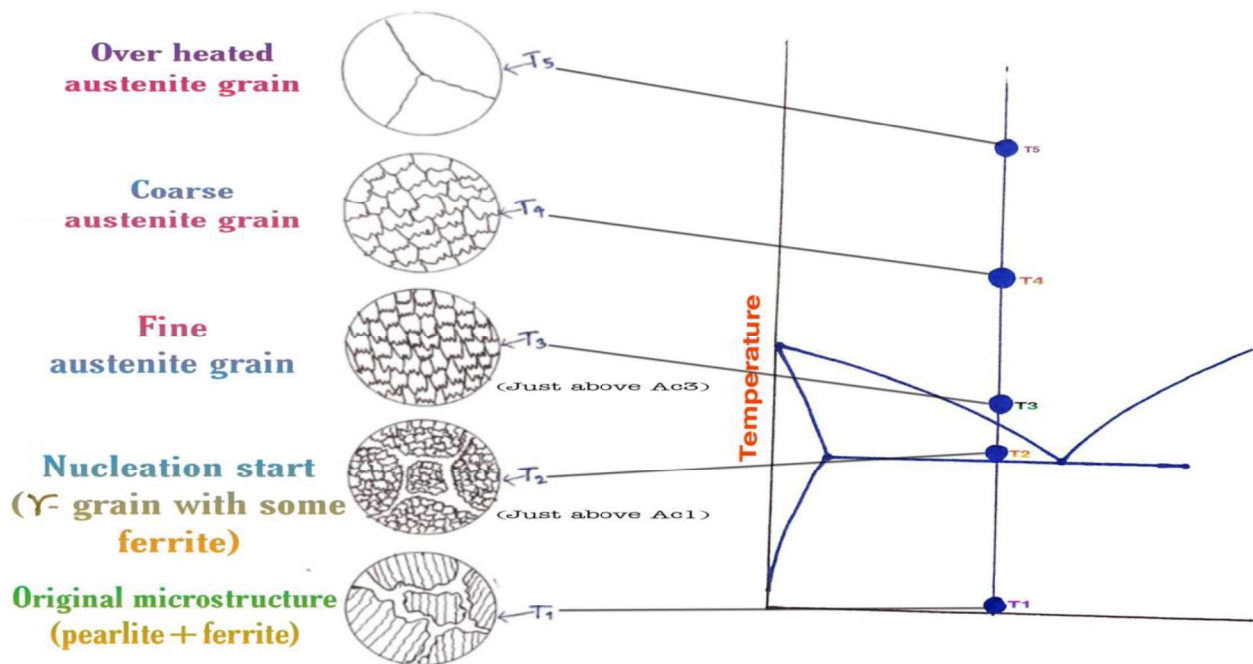


- In hypoeutectoid steel the austenisation process takes place rapidly as the carbon content of steels increase because of increasingly larger amount of pearlite present which results in increasingly large interfacial area between ferrite and Fe_3C . (That is why AC_3 temperature line decreases continuously with the Increase of carbon content of steel)
- In hypereutectoid steel, austenisation of free cementite requires much high temperature because much more diffusion of carbon is required for the formation of homogeneous γ .
- As the carbon increase in hyper eutectoid Steels increasing amount of free cementite is present, which requires higher temperature for austenite to become homogeneous (Thats Why Acm line is so steep)
- In case of alloy Steel carbide forming elements are present as alloyed cementite $[(\text{FeMn})_3\text{C}]$ or alloy carbide.
- Alloy carbides dissolved much more slowly than alloyed cementite.

1.3 Austenite grain growth on heating:-

- When a steel is heated for heat treatment than above the lower critical temperature (AC_2) austenite nuclei form and grow.
- At temp just above the upper critical temperature the of transformation is just complete the structure is fully austenite.
- At this stage, the grain size of Austenite is always small.

- As the temperature or time or both are increased then grain coarsening of Austenite occur.
- The grain coarsening characteristics is effected by the deoxidation particles used while producing that steel.
- Once the steel is above upper critical time the austenite grain growth is a naturally spontaneous process which takes place faster at high temperature.



- The large size of the grain obtained by heating to high temperature remain same sized when cooled to above Ac_3 temperature.

Overheating:-

- It is the state of Steel in which the impaired normal properties can be restored by heat treatment / mechanical working.
- Over heated by steel shows slightly reduce ductility in the subsequent forging process due to precipitation of MnS fine particle an Austenite grain boundaries.
- Over heating occurs when the steel is heated over a certain minimum temperature below solidus where dissolution of MnS takes place in Austenite.

Physical properties of Steel:-

- A Physical property a measurable whose value describes a state of a physical system.
Ex- cooling point, boiling point, heating point, freezing point, melting point, elasticity, density & ductility etc.

Mechanical properties of Steel:-

- A force property that involves reaction to the applied force.
Ex- Hardness, toughness, ductility, fracture, strength, UTS, density, resilience.

1.4 Austenitic grain size:-

Grain - Grain in metallurgy, any of the crystallite of varying randomly distributed small sizes that composes a solid metal.

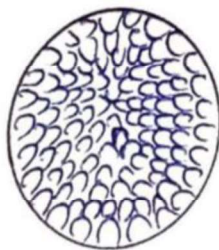
- The Structure and size of the grain determine important properties of the solid material

Grains size:-

- Grain size is the diameter of Individual grains of Sediment.
- Smaller grain have greater ratio of surface area to volume which means greater ratio of grain boundary to dislocation.
- The more grain boundaries that exist the higher the strength becomes.

Austenitic Grain:-

- Grain Size of Austenitic grain is the most important Structural characteristics of a heated steel or heat treated steel.
- It is the nature and distribution of the transformation product of Austenite which control the desired properties.
- Size of austenite grain or austenite grain size depends on.
 - i. Temperature to which steel is heated
 - ii. Holding time at that temperature
 - iii. Nature of the original steel
- Depending on the tendency of steel to grain growth steel can be classified into two broad groups.
 1. Inherently fine grained Steel
 2. Inherently coarse grained steel



(Fine grained)



(Coarse grained)

- Inherently fine-grained steel resists the growth of austenite grains with increasing temperature.

- On the other hand, grains of inherently coarse-grained steel grow abruptly with increasing temperature and so a steel with coarse grain is obtained.
- Intensive grain coarsening of fine-grained steels above a particular temperature is due to the dissolution of ultrafine particles of Carbon oxides and nitrides in the matrix (austenite). After dissolution no particles are left to offer resistance to grain growth.

1.5 Measurement of austenite grain size :-

There are two methods by which we can measure austenite grain size

1. ASTM method (American society for testing of material)
2. Heyn's intercept method

1. ASTM method:-

- American society for testing of material.
- This is the most common method of measuring grain size, where grain size is reported as ASTM grain number. The method is used for equiaxed grains.
- ASTM grain size number determined for the formula.

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

Where N = number of grain per square inches at magnification 100X.

n = ASTM grain size number

- As finer grains more grains, grain size number with ASTM has a modified formula.

$$G = -2.9542 + 1.442 + \ln(n_a)$$

Where, G = ASTM grain size number

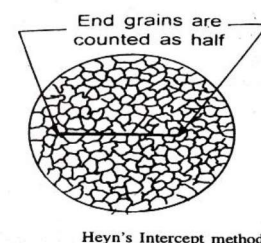
n_a = number of grain per mm^2 at 1x.

(However, steel with ASTM grain size number below 3 definitely mean coarse grained steel while 6 to 8 means fine grained steel).

2. Heyn's intercept method : -

Length = 0.005 inch

- Counts the number of grains intercepted by a line of known length (0.005 inch) at a magnification of 100x or a micrography.
- This method is used to measure austenite grain size when the grain are not equiaxed.
- This line appears on the glass screen of microscope.
- Measurements are made a 10 different places and then the average is taken to calculate (1).



1.6 Importance of grain size:-

- For applications at the normal temperature fine grained Steels are preferred over coarse grained steels.
- Because fine grained steels have better impact resistance (toughness).
- Fine grains improve the strength.
- A modern Steel maker changes the grain size of mild steel from.

Example

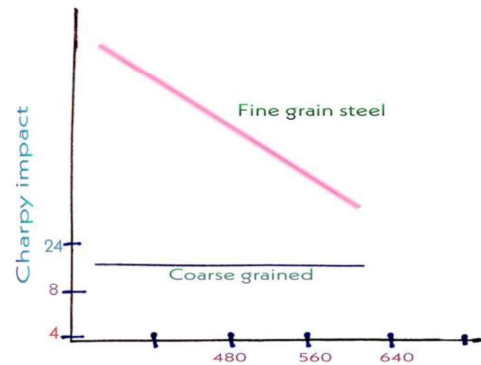
$$d^{-1/2} = 2$$

$$d^{-1/2} = 20$$

$$d = 0.25\text{mm} \quad \text{to} \quad d = 0.0025\text{mm}$$

Increase yield strength

$$\sigma_y = 100\text{MNm}^{-2} \quad \text{to} \quad \sigma_y = 500\text{MNm}^{-2}$$



- Relationship between yield Stress and grain diameter is given by two-scientist Hall & Petch so, it is called hall-Petch equation.

Hall Petch equation: -

$$\sigma_y = \sigma_0 + k * d^{-1/2}$$

It means

$$\sigma_y \propto 1/\sqrt{d}$$

where

σ_y = yield stress

σ_0 = friction stress

d = diameter of the grain

k = constant (locking parameter)

- Grain boundaries act as obstacles to dislocation motion. Fine grains have large grain boundary area. So that dislocation moves only a short distance before meeting a grain boundary and thus increases the strength.
- As fine grained steels have better room temperature properties must heat treatments are carried out to obtain fine grained structure.
- As most of the treatments done on steels alter the grain size, it is essential to control the grain size of the steel to achieve better properties.

Decomposition of Austenite :-

After completing the first step of heat treatment cycle i.e heating the steel is cooled to room temperature at a cooling rate depending on the treatment and properties required. Cooling rate such as :

- Furnace slow cooling (Annealing)
- Air Cooling (Normalising)
- Oil/ water quenching (Hardening)

slow cooling → decomposes pearlite

Speed Cooling → decomposes → martensite

- These cooling rates are much faster than equilibrium cooling rate.
- So, Fe-Fe₃C diagram has serious limitations we can not predict the phases from Fe-Fe₃C diagram.

1.10 TIME TEMPERATURE TRANSFORMATION :-

The Temperature of transformation control the nature of decomposed product (of γ) which in turn decides the resultant properties of steel.

- The kinetics of austenitic transformation can be studied best at a constant temperature rather than by continuous cooling.
- This TTT curve is done at a constant temperature so it is also called as *isothermal transformation curve*.

STUDY OF ISOTHERMAL TRANSFORMATION and CONSTRUCTION OF TTT- CURVE :-

- A number of sample are heated to predetermined austenitizing temperature and held at this temperature for a sufficiently long period to obtain homogenous austenite.
- These austenized, sample are transferred quickly to another bath, maintained a constant temperature below eutectoid temperature bath is at 600°C.
- These sample are taken one by one from the bath with some time interval.
- Then the sample are quenched immediately.

Equipments for determination of TTT Diagrams

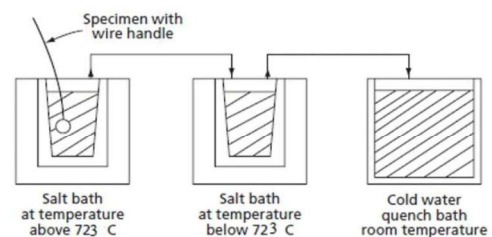


Fig: simple experimental arrangement

- The quenching of sample results in the formation of martensite from the untransformed austenite, which is taken away from salt bath after 1 sec.

- After a particular time, all the austenite will transform to an aggregate of ferrite and cementite i.e pearlite at a given temperatures.
- It is clear from the figure that transformation of austenite does not start immediately on quenching austenized to a constant temperature bath.
- Transformation of austenite to pearlite (ferrite -cementite mixture) occurs after a definite time t_1 : this time during which transformation does not proceed is known as *incubation period*.
- *Smaller the incubation period means lesser the austenitic stability larger the incubation period to greater the stability of austenite.*
- This transformation diagram has one limitation is only on constant temperature but for austenitic transformation both temperature and time have significant impact on the nature of transformation and morphology.
- Thus a diagram which includes all the three parameters i.e time , temperature and transformation will be of great importance , specially to the heat treatment transformation (TTT-curve).

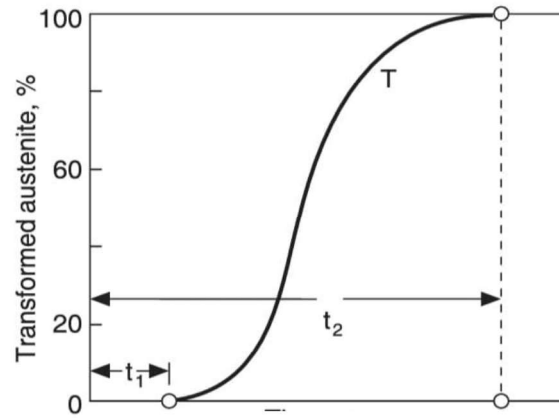


Fig. Isothermal transformation of austenite

This TTT-diagram is also known as isothermal transformation (IT) diagram or the C curve .

- TTT curve is the extension of isothermal transformation of austenite diagram.
- For the construction of TTT-curve for a steel, a larger number of smaller sample of steel (eutectoid steel) are taken.
- These samples are treated in a way similar to that already mentioned for the study of isothermal transformation of austenite.
- The only difference now is that the same process is repeated a number of times at varying transformation temperature instead of single temperature.

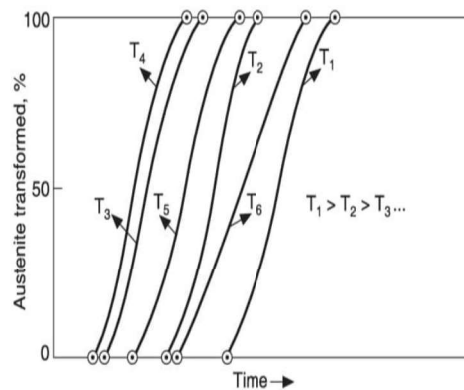


Fig: Isothermal transformation of austenite to pearlite at temperatures

- The temperature t_1 is greater than $t_2, t_3, t_4, t_5, \dots$
- In next diagram data of IT diagram transferred to TTT curve which is a graph between long time and temperature. Similar experiments at other subcritical temperature i.e below 727°C , down to 230°C . Show different of start and finish the transformation.

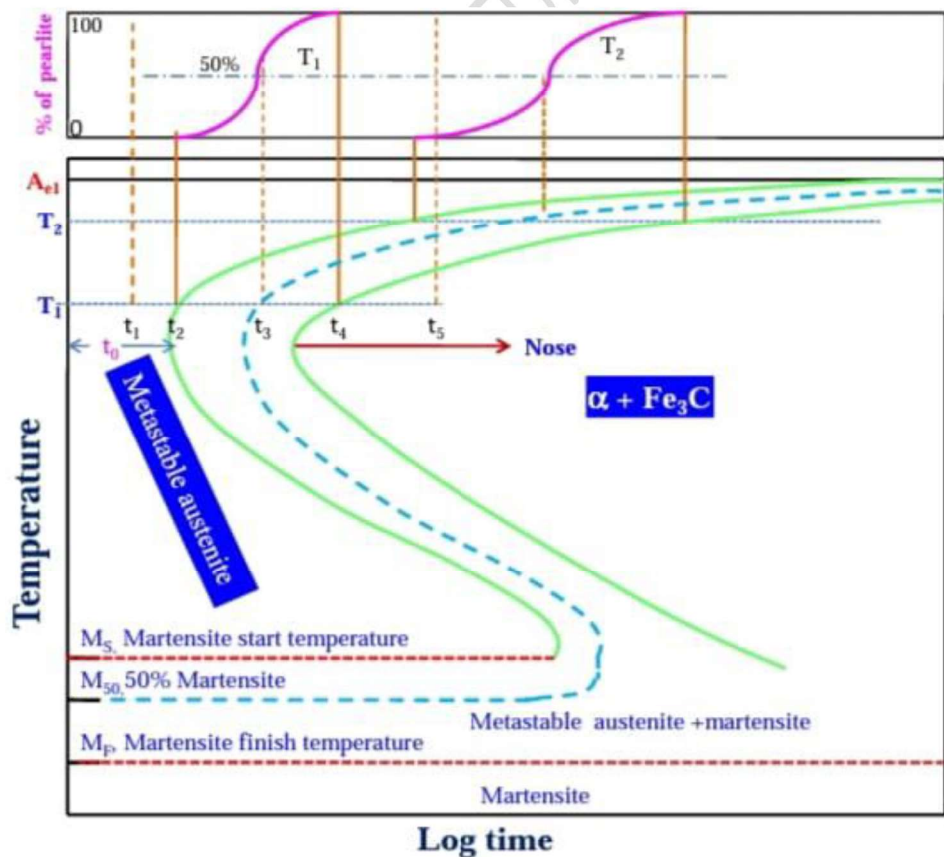


Fig: construction of TTT diagram

- A curve is drawn joining the points at which the transformation begins, and another curve for time to finish of transformation is known as TTT curve or "c" or "s" curve.

- Each steel composition has its own different "s" curve.

- For point below 230°C, the subcritical bath (second bath) is kept at this temperature.

- The specimen is heated to 750°C and then kept in 230°C bath for few second then quenched in water immediately.

- In 230°C the specimen is started to formation of martensite and in water bath retained austenite transform to complete martensite.

- The temperature at which martensite starts forming is designated as M_s and at which finish of transformation of austenite to martensite occurs is designated as M_f temperature.

- TTT diagram assumes a characteristic "c" shape.

- The region of fastest transformation where incubation period is least (here 550°C) is called *nose of the curve*.

- **Incubation period:** It is that period in which transformation doesn't proceed because enough diffusion has not taken place in austenite for transformation to start.

- Larger the incubation period, greater the stability of austenite, and slower is the rate of decomposition.

- The "c" shape of curve illustrate that stability of austenite first decreases sharply to reach minimum (at nose) and then increases again due to slow diffusion at low temperature.

- TTT diagram illustrates 3 different types of transformation products.

- The products are formed at different temperature range depending on the degree of undercooling of austenite.

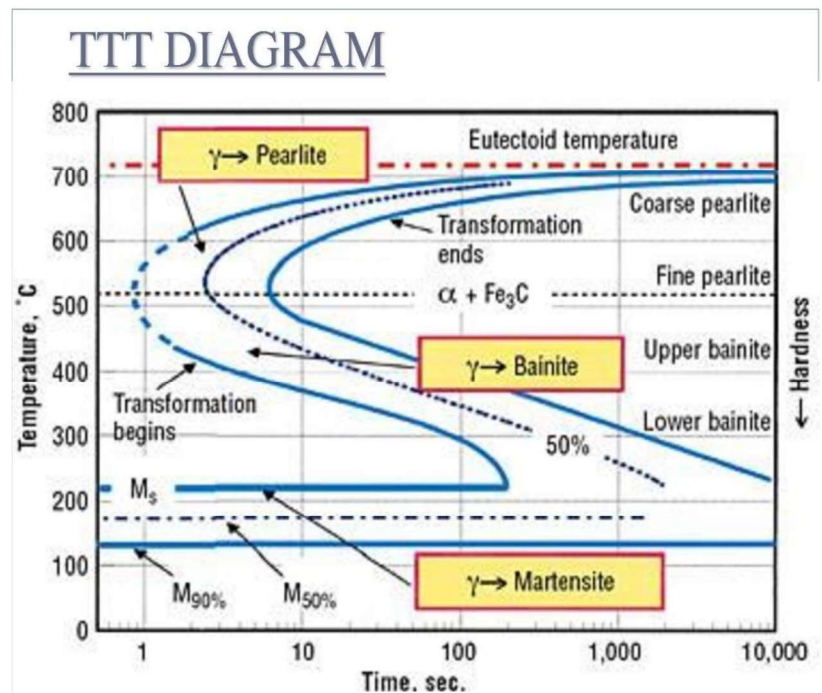


Fig: TTT diagram

- 1) **Pearlitic range** (high temp transformation range)
- 2) **Bainitic range** (intermediate temp transformation range)
- 3) **Martensitic range** (low temp transformation range)

- 1) *Pearlite range* in “s” curve of plain carbon steels over a temp interval below A1 to nose of the curve (550°C). As the temperature of transformation is lowered fine and finer pearlite forms i.e. *layered structure*.
- 2) Bainite range is 550°C to 230°C. In 550°C to 400°C, upper bainite is formed which is feathery bainite as the structure of upper bainite is feather like. From 400°C to 230°C lower bainite is formed i.e. *acicular structure*.
- 3) Martensite range is below 230°C with higher hardness. With lowering the temperature, hardness of the steel increases.

Critical cooling rate is defined as the fastest cooling rate at which produces fully martensitic structure.

- **Critical cooling rate** is not same for all steels.
- Carbon steel have critical cooling rates between 800°C to 200°C.
- Normally alloying elements decrease the critical cooling rate.
- TTT diagrams able to provide a lot of information about the nature and the rate of transformation, the type of phases, temperature to start, finish and the hardness of transformed phases with microstructure.

TTT Diagrams of plain carbon steels:-

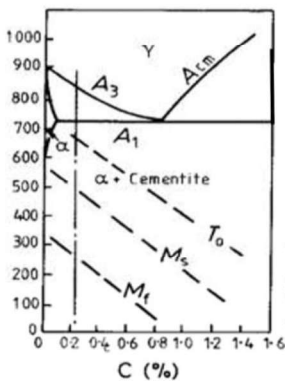
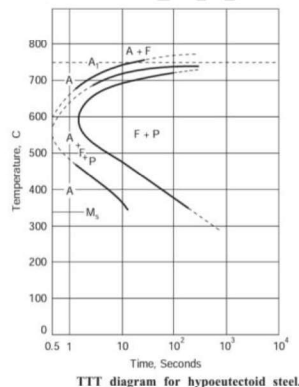
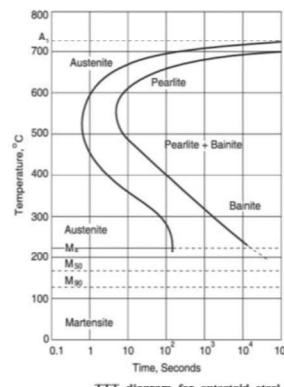


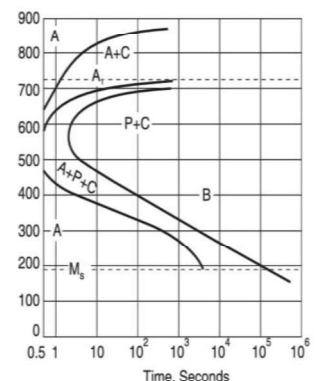
Fig: iron carbon diagram



TTT diagram for hypoeutectoid steel.

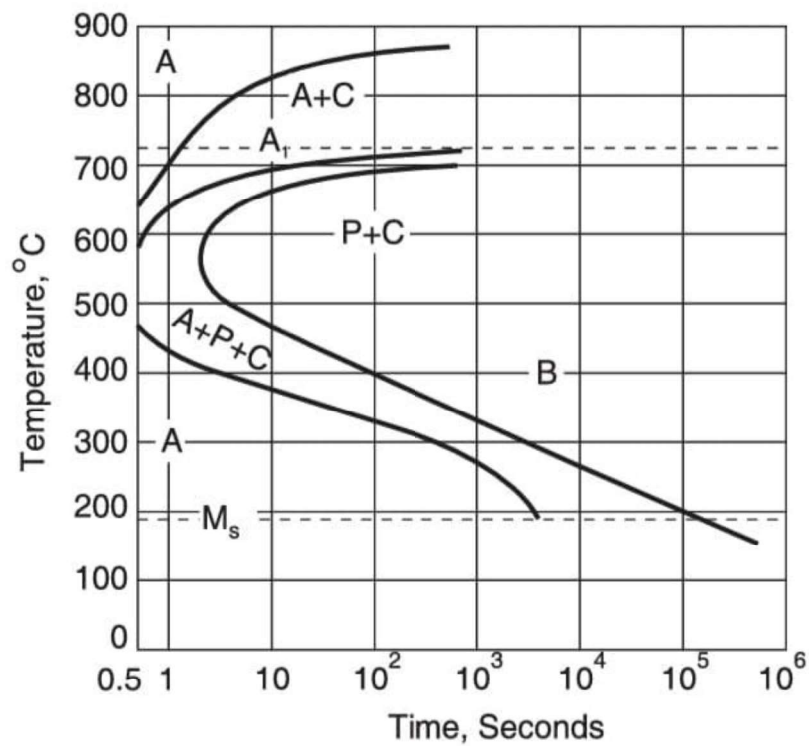


TTT diagram for eutectoid steel.



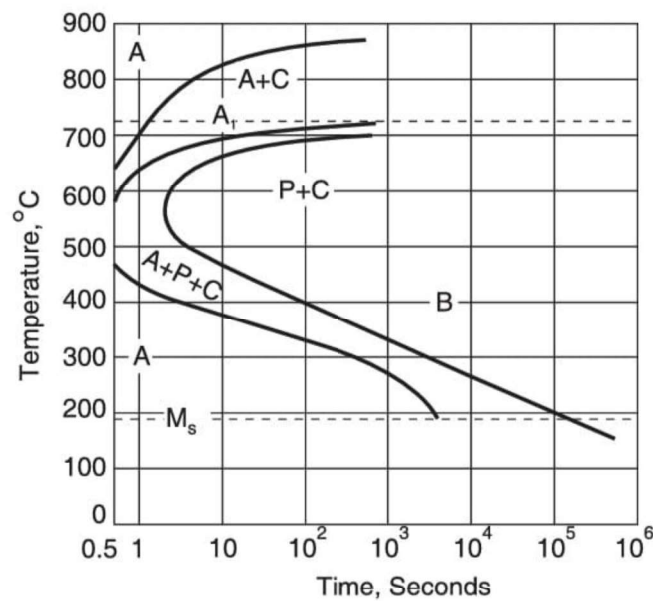
TTT diagram for hypereutectoid steel.

1.11 TTT diagram of hypo eutectoid steel:-



TTT diagram for hypereutectoid steel.

TTT diagram of hypo eutectoid steel:-



TTT diagram for hypereutectoid steel.

Factors Effecting TTT – Curves:-

Factors affecting TTT – curves are

1) Composition of Steel

- i. Carbon
- ii. Alloy elements

2) Grain size

3)

1) Composition of steel:-

i. Carbon:-

- As ferrite is the nucleating phase for pearlite in hypo-eutectoid steels, nose of the 's' curve becomes more and more on the *right hand side* (incubation period increases and maximum at eutectoid steel)
- Nose of the increases up to 0.77%C as carbon increases.
- After 0.77%C then increasing, with C. Free cementite increases which is act as nuclei for pearlite transformation now. So, nose of the curve shift toward left hand side in hyper eutectoid steel.
- With increasing 'C' percentage bainite range of 's' curve shift toward right because ferrite is the nucleus for bainite transformation.

ii. Alloying elements:-

- All alloying elements (except cobalt) shifts 'S' Curve toward *right hand side* in both pearlite and bainite region.

2) Grain size:-

- All the decomposition products of austenite nucleate preferentially at the grain boundaries.
- As fine grained steel has larger grain boundary area than coarse grained steel, fine grained steel reduces the incubation period i.e 'S' curve is more towards *left*.

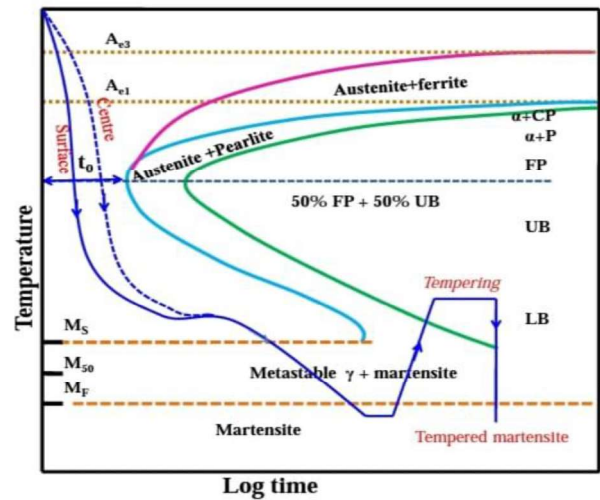
Applications of TTT diagram:-

- TTT diagram form the basis of certain heat treatments in which transformation occurs isothermally such as:
 - 1) Martempering
 - 2) Austempering
 - 3) Patenting

1) Martempering :-

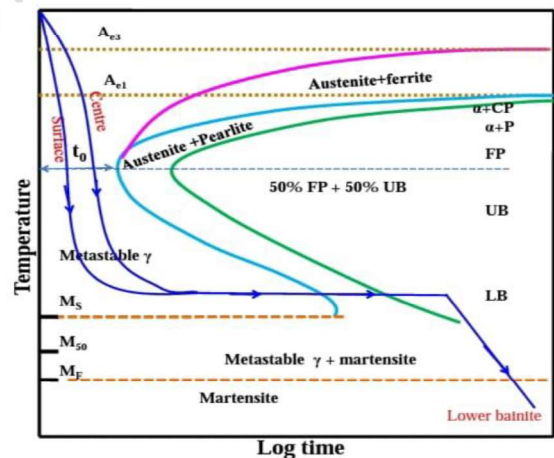
- It is a hardening process with an and objective to minimize distortion Cracking

- Steel is heated to austenitic temp, then quench in a salt bath. Salt bath has a temperature above M_s temp i.e. 180-250°C.
- Then holding the steel for a time and then air cooled through M_s to room temperature.
- Then the steel is formed martensitic at room temperature the whole section of the steel.
- Tempering is then done as required for the process of Martempering.
- Result of the treatment is *tempered martensite*.



(2) Austempering :-

- Austempering is a hardening process with an objective to reduce distortion and cracks in high carbon steel.
- In this treatment austenite transform isothermally to lower bainite.
- The heat treatment cooling of austenite in a salt bath. The bath has kept a temperature at lower bainites temp (above M_s) temperature.
- Sample is cooled rapidly avoiding the nose of the TTT diagram and holding it to bainitic finish time
- At the end bainitic Sample is air cooled.
- Result of microstructure is *Fully lower bainite*.
- The product has improved ductility & toughness and do not require to be tempered.

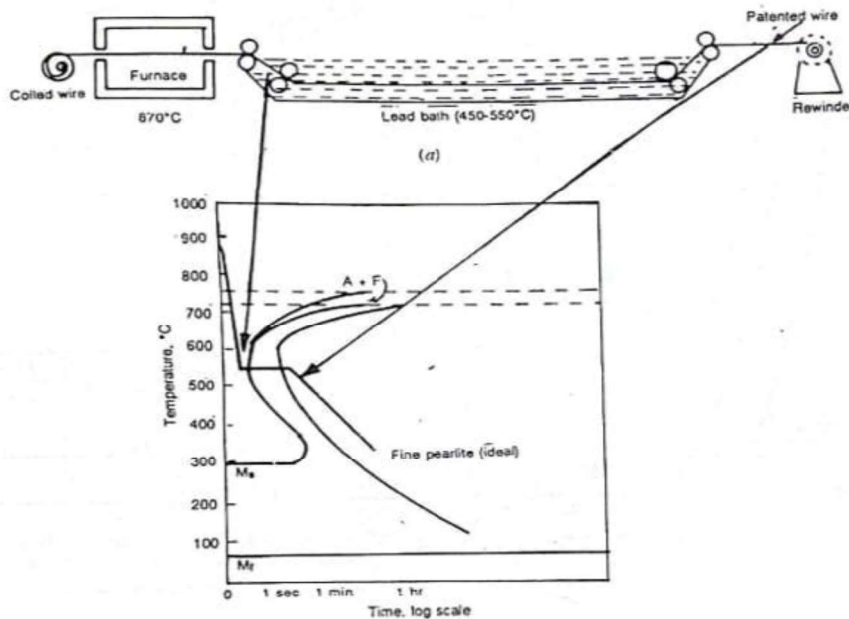


Advantages of austempering :-

- ✓ Improved ductility at the same hardness.
- ✓ Freedom from distortion & crack
- ✓ No tempering is needed.
- ✓ improved impact strength.
- ✓ Uniformity of properties.
- ✓ High Endurance limit.

(3) Patenting:-

- Patenting is an isothermal heat treatment Process.
- It is used for producing high strength rope, springs and piano wires of normally 0.45% to 1.0% carbon steel
- Patenting process consists of austenitizing steel in a continuous furnace to temp 150-200°C .



- Steel is heated to austenising range and then cooled rapidly in a lead bath which has 450-550°C temperature.
- And hold some time in lead bath at nose of the 'TTT' diagram for completion of fine pearlite formation.
- This treatment produces *finest pearlite* in whole section of steel.
- Fine pearlite has fine interlamellar spacing structure.
- This treatment Improve the strength and toughness of the steel in twisting and bending.

TTT-diagram is great help in scheduling these treatment as it fixes.

- I. Temperature of holding of the bath.
- II. Duration of holding time,
- III. section which can be quenched to avoid any transformation
- IV. Final product to be achieved.

1.10 CONTINUOUS COOLING TRANSFORMATION(CCT):

The TTT diagrams have gained great importance because they are extremely useful to give information about the hardening response of steels and the nature of transformed products of austenite at varying degrees of supercooling. These diagrams have been of great practical importance to some special heat treatment processes such as austempering and isothermal annealing. But in practically transformation occurs by continuous cooling not in isothermally. Therefore a diagram which correlates transformation, temperature and time during continuous cooling has to be studied.

Continuous cooling transformation (CCT) diagrams can be obtained by the same procedure which is used for the TTT diagram except that in case of CCT diagram points of start and end of austenite are recorded on continuous cooling. For the construction of CCT curve for eutectoid steel a large number of samples are heated above the lower critical temperature (A_1) to get a completely austenite structure. From this temperature, specimens are cooled at a constant cooling rate and repeating the same process at various cooling rates, different sets of start and end points for pearlitic transformation are obtained. On joining start and end points, two curves similar to those in TTT curves corresponding to start and end of transformation are obtained. Fig.6 shows the CCT diagram for eutectoid steel.

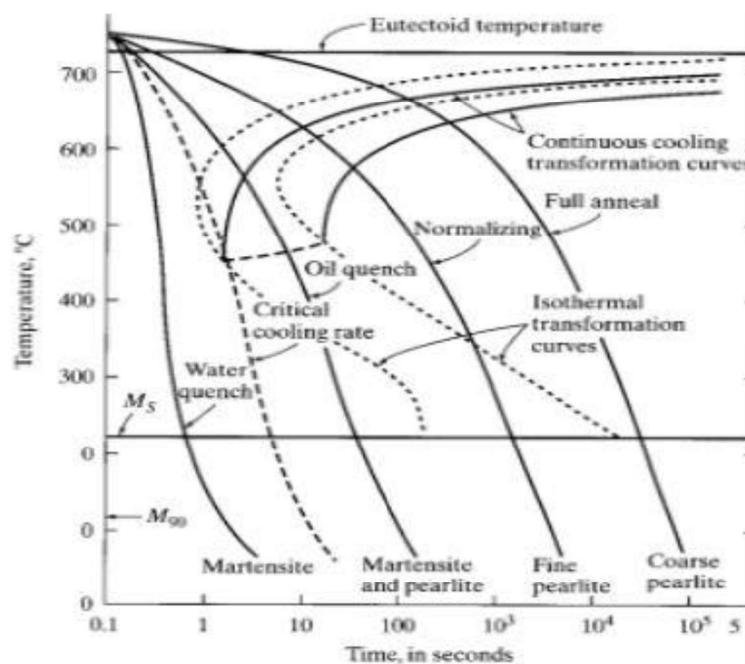


Fig: CCT diagram with diff. cooling rate

-:2.0 Heat treatment process:-

- There are different heat treatment process. mainly Annealing, normalising, hardening process are generally carried out as heat treatment.

Annealing :-

Heating of a material to a pre-determine temperature Soaking at this Temperature and then cooling it slowly normally in a furnace by switching it off.

Normalizing:-

It is a process heating the steel to get homogeneous austenite, soaking for 20 min per cm and allowing it to cool freely in the air.

Quenching/hardening

Process of heating the steel to proper austenisation temperature, Soaking at This Temperature then cooling the steel at a faster rate than its Critical cooling rate then its critical cooling rate.

2.1 Annealing:-

There are a number of annealing process because the aim of the annealing are different

- 2.3 Types of annealing heat treatment are :-

(1) Full annealing:-

For improvement in mechanical properties of cast or hot worked steel by refining the grain size.

(2) Homogenizing annealing:-

Homogenization of segregated casting, and ingots of steel and alloy steels.

(3) Recrystallization annealing:-

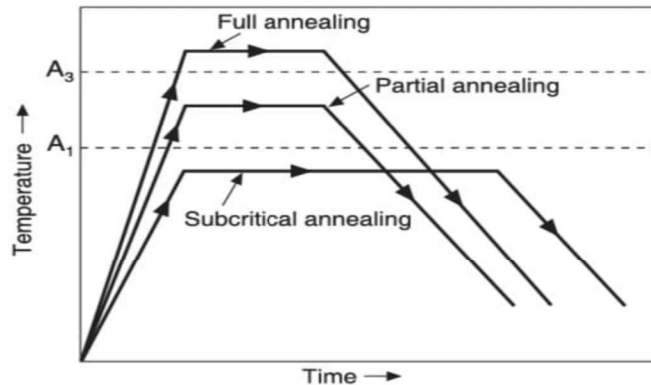
Restore ductility of cold worked

(4) Spheroidization annealing:-

Improve the machinability and cold formability particularly of high carbon steels and alloy steels.

(5) Stress- relieving annealing:-

Relieve the internal stresses of cast, hot worked structure.



1:- Full annealing:-

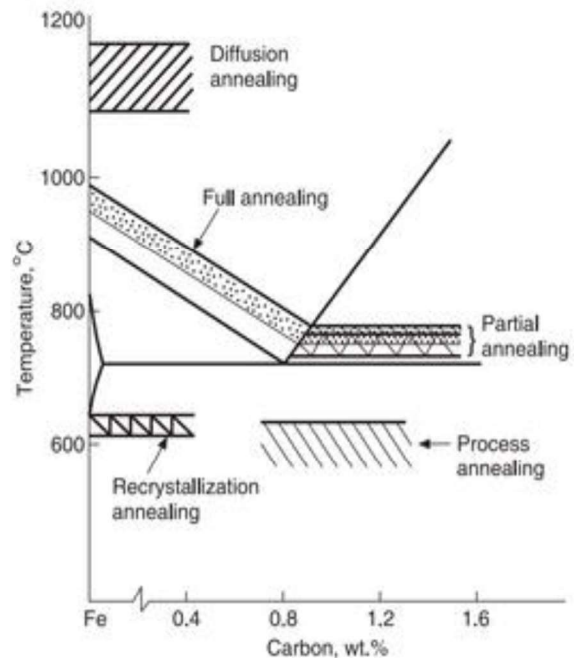
- Full annealing or annealing consists of heating the steel to a temperature above its upper critical temperature, soaking there for sufficient time to obtain homogeneous austenite and then left to cool in the furnace by switching it off to improve mechanical properties.
- Heated above
 - Above A_3 (for hypo – eutectoid steel)
 - Above (for hyper – eutectoid steel)
- Hold
- Then cooled in the furnace to obtain coarse pearlite.
- Three important part of full annealing.
 - Proper astonishing temperature.
 - Soaking/holding time(min 1 hr for 25mm steel to get homogeneous austenite)
 - Very slow cooling ($30-50^{\circ}\text{C/hr}$) Austenite always transforms at A_1 temperature or just below it to obtain coarse grained ferrite as well as pearlite .

Objective of full annealing:-

- To refine grain size of steel casting to improve mechanical properties.
- To soften the steel.
- To refine internal stress.
- To improve machinability.
- To reduce some defect inside steel.

Disadvantages:-

- Time taking process.
- Less productivity.
- More scaling.



2:- Homogenizing annealing/Diffusion annealing:-

- Normally, the carbon steel ingot after solidification has inhomogeneous structure.
- The subsequent heating, Soaking and hot working homogenizes the structure to a large extent.
- This process also known as diffusion annealing.
- The main aim of Homogenizing annealing is to make the composition uniform i.e to remove chemical heterogeneity.
- In this treatment steel is heated – sufficiently above the upper critical temperature (1000°-2000°C) and is held at this periods, usually 10-20hrs, followed by under cooling.
- Segregated zones are eliminated and a chemically homogeneous coarse grain steel is obtained by this treatment.
- Then coarse grained stricker can be refined either by plastic working for ingots or by employing second heat treatment for casting.

(3) Recrystallization annealing/process annealing/sub – critical annealing:-

- It is also known as process annealing or sub – critical annealing.

- Recrystallization annealing consists of heating the cold worked steel above its Recrystallization temperature, soaking at this temperature and then cooling there after.

- Recrystallization temperature is

$$T_r = (0.3-0.5) T_m$$

T_r = Recrystallization temperature

T_m = melting temperature.

_ The Recrystallization annealing of

- Carbon steel heating temperature (650-680°C).
- High carbon alloy steel (730°C)

Time of soaking 1 to 1.5 hours.

Main aim of the Recrystallization temperature:-

- _ To restore ductility.
- _ To refine coarse grains.
- _ To improve electrical and magnetic properties in grain oriented si-steels used for transformer cores & rotating electrical machinery.

4:- Spheroidization annealing:-

It is the process of heating, soaking and cooling slowly to produce spheroidal pearlite or globular form of carbide.

Main aim of Spheroidising annealing:-

- Maximum softness
- Maximum ductility
- Highest machinability
- Minimum hardness
- _ This annealing is generally applied to high carbon steels & high alloy tool steel.
- _ In this method steel is heated to just below A_1 temperature hold at this temperature for a very long period followed by slow cooling.
- _ In industrial method,
Austenite the steel at a temperature not more than 50°C below A_1 temperature.
- _ Normally astonishing temperature used are :-
 - Eutectoid steel = 760-760°C

- Hypo eutectoid steel = 770-790°C
- Hyper eutectoid steel = 770-820°C
- High speed steel = 875°C

- _ During heating, inhomogeneous austenite is obtained.
- _ On cooling, precipitating cementite deposits on carbide nucleus in inhomogeneous austenite as spheroidal particle.
- _ On heating again, the dissolution of spheroidised cementite is resisted. The precipitating cementite deposits on these undissolved cementite particles on cooling.
- _ Spheroidised pearlite can be obtained by hardening and high temperature tempering.

5:- stress – relieving annealing:-

_ Internal stresses are stresses which exist in a part in the absence of external stresses. These stresses develop in the parts during cold working, heavy machining, heat treatment casting or welding etc.

Residual stress is added to the material from different processes.

When steel is heated to below A₁ temperature to eliminate the residual stresses, it is then called stress – relieving annealing.

The main aims of stress – relieving annealing are:-

To relieve the internal stresses, and thus allow higher external loads to be applied.

Increase fatigue life and prevent intercrystalline corrosion.

To reduce chance of warpage or cracking.

To reduce risk of distortion in machining.

To increase impact resistance.

No change of dimensions in service life.

Process:-

For a welded steel structure.

Slow furnace heating up to 650°C

Soaking for a time based on maximum thickness 3-4 min/mm to attain uniform temperature.

Slow cooling to room temperature.

6:- partial annealing:-

Partial annealing is also referred to as inter critical annealing or incomplete annealing.

In this process, steel is heated between the A1 and AE or Acm. It is followed by slow cooling.

Generally, hypereutectoid steels are subject to this annealing treatment.

Pearlite of the steel gets Transformed to fine – grained austenite on heating, steel is partially annealed.

Austenite transforms to coarse and soft – pearlite on cooling.

Partial annealing, this produces soft – ness required for machining.

Though it is not a perfect heat treatment cycle but good practical method reducing cost of processing and improve machinability and ductility.

As low temperature are involved in this process, so it is cost effective then full annealing.

7:- Process annealing:-

In this treatment steel is heated to a temperature below the lower critical temperature and is hold at this temperature for sufficient time and then cooled. Since it is a subcritical annealing, cooling rate is of little importance.

The purpose of this treatment is to reduce hardness and to increase ductility of cold worked steel, so that further working may be carried out easily.

It is an intermediate Operator and is sometimes referred to as in process annealing.

This process is less expensive than Recrystallization annealing.

8:- Isothermal annealing:-

Isothermal means cooling at constant temperature.

In this process steel austenised at a temperature 20-40°C above A3.

Then steel is cooled quickly to the temperature of Isothermal holding (by transferring the steel to the second furnace). Which is below A1 temperature in pearlitic range. Hold there for required time so that austenite transformed completely.

It is then normally cooled in air.

Aim:- To soften the steel.

Improve machinability.

Total time of heat treatment the cost of annealing is lesser with higher productivity of the furnace as the cooling can be done in air after the transformation complete.

As transformation takes place at a constant temperature microstructure is obtained more uniform.

2.4 Normalizing:

Heat above A_3 | A_{cm} → Austenization → Air cooling → Fine Pearlite (Fine Pearlite (Higher hardness))

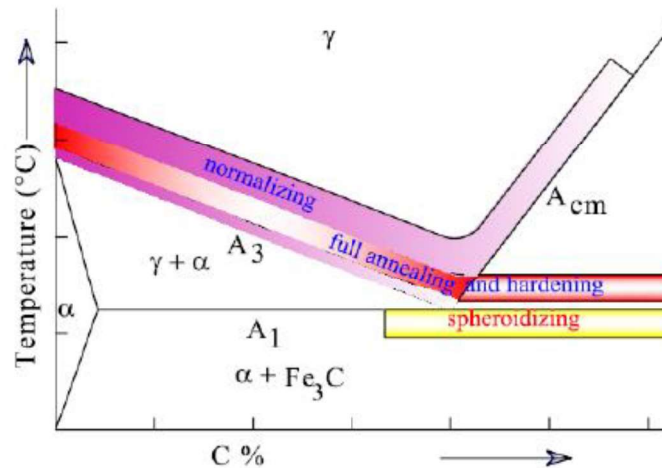
Purposes

- To reduce segregation in casting or forgings
- Refine grain structure prior to hardening
- To harden the steel slightly

In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature.

In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature

In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB.



Difference between Annealing and normalising

Annealing	Normalising
1. Metal is heated and is left at the same furnace for cooling.	Metal is heated and held at for same time and then allowed to cool down freely in the air.
2. Annealing is done before machining.	Normalising is done after forging or wrong heat treatment.
3. Tensile strength is reduced after annealing.	Tensile strength is increased after normalizing.
4. Grain size is changed to larger in the internal structure.	Grain size is changed to very small in the internal structure.

2.5 Hardening and Tempering:

For heavy duty purposes high hardness is required. The process by which high hardness can be obtained is known as hardening. Hardening treatment consists of heating to hardening temperature, holding at that temperature followed by rapid cooling such as quenching in water, oil or salt baths. The high hardness developed by this process is due to the phase transformation accompanying rapid cooling. Hardening temperature depends on chemical composition, for plain carbon steel it depends on carbon content alone.

Hypoeutectoid steels are heated to about 30-50°C above the upper critical temperature, whereas eutectoid and hypereutectoid steels are heated to about 30-50°C above the lower critical temperature. Ferrite and pearlite transform to austenite at hardening temperature for hypoeutectoid steels. This austenite transforms to martensite on rapid quenching from hardening temperature. The presence of martensite accounts for high hardness of quenched steel. If hypoeutectoid steel is heated to a hardening temperature equivalent to that of hypereutectoid steel, the structure will consist of ferrite and austenite. This will transform to ferrite and martensite on quenching. The preferred hardening temperature for hypereutectoid steel lies between the lower critical and upper critical temperature.

Advantages

1. The first is related to the presence of cementite in hardened steel which improves the wear resistance of the steel.
2. Hardening temperature is the attainment of fine martensite in the final microstructure.

Because of rapid cooling internal stresses are developed, so hardened parts are followed by another treatment known as tempering which reduces internal stresses and improves the ductility of the material.

2.6 FACTORS AFFECTING HARDENING PROCESS :

Properties improved by hardening are depends on various factors:

1. Chemical composition of steel
2. Size and shape of the steel part
3. Hardening cycle i.e heating rate, hardening temperature, holding time and cooling rate
4. Homogeneity and grain size of austenite
5. Quenching media 6. Surface condition of steel parts

2.7 Hardening Methods:

Rapid cooling is carried out in order to obtain martensite in hardened steel. Austenite to pearlite transformation is suppressed in this process.

- (i) conventional or direct quenching

- (ii) quenching in stages
- (iii) spray quenching Spray quenching is a specific hardening method in which the steel part is cooled from the hardening temperature by spraying quenchant continuously. The rate of heat extraction from the steel part is much higher as compared to direct quenching.
- (iv) quenching in self tempering
- (v) austempering or iso thermal quenching

This is a special heat treatment process in which austenite is transformed to bainite. Austempering consists of heating steel to above the austenitizing temperature. It is then quenched in a bath maintained at a constant temperature in the bath itself till all the austenite is transferred into bainite. (vi) martempering Heating the steel to the austenitizing temperature followed by quenching in a constant temperature bath maintained above M_s point. The usual temperature of the bath lies between 180 and 250°C. Steel is held in the bath till a uniform temperature is achieved throughout the section and then cooled in air. The cooling rate should be sufficiently high and holding time is short to prevent transformation of austenite to pearlite or to bainite. Martensite is formed in the second stage. The resultant microstructure of martempered steel is martensite. In order to improve properties, martempered steels are generally tempered.

2.9 Tempering

Tempering process:-

- As quenched-steel / hardened steel to find very few engineering applications.
- Because martensite though strong but is very brittle.
- Quenching stresses may cause crack.
- Martensite's properties can be modified. Thus later treatment of hardening called tempering.

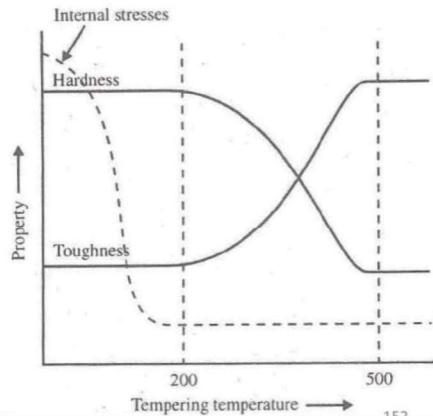
Tempering:-

- Tempering is the process of heating the hardened steel to a temperature maximum up to A_1 temp, soaking at this temperature, and then cooling normally very slowly.
- Tempering temperature used depending.
- On the properties required.

Objective aim of the tempering:-

- To relieve quenching stresses developed During hardening.
- To restore ductility and toughness, with decrease in hardness and strength.
- To improve dimensional stability by Decomposing retained austenite.

- To improve magnetic properties by transforming non-magnetic retained austenite.



Variation in properties with tempering temperature

Stages of tempering:-

- As the temperature is raised, tempering of carbon steel occurs stages. Occurs in four stages.
- (1) First stage of tempering. (upto 200°C)
- (2) Second stage of tempering. (200°-300°C)
- (3) Third stage of tempering. (200°-350°C)
- (4) Fourth stage of tempering.(350°- 700°C)

(1)First stage of tempering (upto 200°C)

- As the hardened steel is heated to 200°C.
- In this stage of epsilon carbide (Fe_3C) precipitates out and decrease the tetragonality of martensite.
- Decrease the tetragonality decrease the hardness and increase the toughness of hardened steel.

(2)Second stage of tempering (200°-300°C)

- Second stage of tempering temperature lies in between 200°-300°C.
- In the second stage of tempering retained austenite transforms to lower bainite.

(3)Third stage of tempering (200-350°C)

- Third stage of tempering lies Between 300-350°C.
- In this stage martensite completely loss tetragonality and dissolution of E-carbide occurs.
- Cementite forms as rods at interfaces of E-carbide.
- Hardness decrease continuously and sharply.
- structure is ferrite and small particles of cementite.
- Contraction occurs in volume in this stage.

(4)Fourth stage of tempering (350°-700°C) :-

- Fourth stage of tempering temperature lies between 350-700°C.
- During this stage of tempering grain coarsening takes place. As ferrite and cementite already nucleated during the third stage.

Industrial tempering practice:-

- A steel which has been hardened must be tempered immediately.
- In fact, in some industrial practices, the component is allowed to be cooled during quenching, and then transferred to tempering furnace.
- Heating of the parts for tempering should be done slowly to avoid development of cracks during heating.
- Time of tempering is 1-2 hours per 2.5cm of section thickness.
- Tempering can be broadly divided into three classes depending on the tempering temperature range.
- Tempering temperature range depending on the properties to be developed in hardened steel.

Three types of tempering:-

- (1) Low temperature tempering (upto 250°C)
- (2) Medium temperature tempering (350°-500°C)
- (3) High temperature tempering (500°-650°C)

(1) Low temperature tempering :-

- The main aim to reduce brittleness without much loss of hardness.
- Tempered martensite double phase structure improves strength with some improvement in toughness and there takes place reduction in Internal stresses.

(2) Medium temperature tempering:-

- This range produces **torsite** in microstructure indicating development Of high elastic limit with good toughness.
- Torsite is very fine globular pearlite normally difficult to resolve under optical microscope.
- This tempering range is mainly used for springs of both types, coil and laminated and also for dies.

(3) High temperature tempering:-

- This range tempering produces sorbite structure.
- This results in best combination of strength and toughness for machine components• .
- This treatment for 1-2 hours and removes all stresses completely the residual Stresses.
- Components are normally cooled in a furnace after tempering to prevent development to thermal stresses.
- Sorbite is fine globular pearlite.

Multiple tempering:-

- Alloy steels are tempered in range of 500°-600°C to develop secondary hardening.
- When such a steel is heated for tempering there is little tendency for the retained austenite to transform in the second stage of tempering.

- As fine carbides precipitate in martensite (at 500°-600°) carbon probably diffusion from retained austenite to martensite.
- As the steel is cooled after first tempering from 500-600°C, at least a part of austenite transform to martensite when its M_s is reached.
- As the steel now has a formed martensite and retained austenite, it is again tempered to 500-600°C.
- Double tempering may not be sufficient and thus four or even more cycles are needed to bring the retained austenite to an appreciable low level and decompose the γ martensite.

Tempering of alloy steels:-

- Tempering behaviour of alloy steels significantly different depending on the nature, amount and simultaneous presence of number of alloying elements.
- Alloying elements also lower M_s and M_f temperature increasing further the amount of retained austenite.
- The decomposition of retained. Austenite on tempering, plays quite a significant role on the properties of tempered steels, specially having high carbon and high alloying element.
- First stage is not effected by the stage presence of alloying element. If these above good diffusivity, softening occurs above 500°C.
- 0.5% Cr on less than 0.5% Mo resists Softening.
- In 0.1% C steel with 2.05% Mo cause secondary hardening .So increasing the amount of these alloying element retard the softening and sustain the hardness as it is again.
- Steels with 1-2% Si resist softening up to 400°C as ϵ -carbide is present.
- Carbon steels loose the tetragonality by 300°C, but alloying steels loose the tetragonality up to 500°C even.
- Alloying Elements like Cr, W, Mo, Ti, V, retard the coarsening of cementite particles.
- Alloying elements form their own carbides to replace coarse cementite particles.
- when alloying steels are tempered at 500°-600°C decrease in hardness with improved toughness occurs. This increase in hardness is called secondary hardness also called red-hardness.
- Ex – Because of this property high speed steels continue machining at high speed even when become red-hot!
- Secondary hardening is a process similar to age-hardening. In which coarse cementite particles are replaced by new and much finer alloy carbide dispersion of V_4C_3 , Mo_2C , W_2C .
- The critical dispersion causes a peak in the hardness.
- In Cr-steels, the peak is realised at 500°C.
- In Mo-steel, peak is at 550°C.
- In V-steels, peak is at 550°-600°C, and

- in Ti-steels, peak is at 600°C.
- The amount of secondary hardening is directly proportional to the volume fraction of alloy carbide forming elements present in steel.
- Carbides should be finely and uniformly dispersed.
- Such tool steels should dissolve all the alloying elements as completely during austenisation of the steel to obtain the maximum secondary hardening effects during tempering.
- Non-carbide forming elements do not show secondary hardening.

Temper brittleness / embrittlement:-

- Normally as the tempering progress, the hardness and the strength decrease with increase in ductility and toughness.
- But in certain alloy steels, there is an unexpected decrease of impact strength when tempered in the range of 450° to 600°C.
- This phenomenon is known as temper embrittlement or temper brittleness.
- Temper brittleness does not occur in carbon steels but has been widely observed in alloy steel.

Temper colour:-

- When hardened steel is heated to in oxidising atmosphere for the purpose of tempering, on the surface of the steels exhibits various colours.
- The colours are caused by the formation of iron oxide film.
- As the oxide film thickness increases, colour changes from light

<u>Temper temperature(i)</u>	<u>Temper colour</u>
220°C	Straw yellow
240°C	Light brown
270°C	Brown
285°C	Purple
295°C	Dark blue
310°C	Light blue
325°C	Grey
350°C	Grey-purple
375°C	Grey-blue
400°C	Dull grey

Different tempering process:-

Different tempering process are:-

1. Austempering
2. Martempering
3. Patenting

(We have discussed all of these three in application of TTT-diagram chapter.)

3.0 Hardenability:

- Hardenability is one of the most important properties of a steel because it

describes the ease with which a given steel can be quenched to form martensite or the depth to which martensite is formed on a given quench.

- It is an important property for welding, since it is inversely proportional to weldability, that is, the ease of welding a material.
- The ability of steel to form martensite on quenching is referred to as the hardenability.
- Hardenability is a measure of the capacity of a steel to be hardened in depth when quenched from its austenitizing temperature.
- Steels with high hardenability form martensite even on slow cooling.
- High hardenability in a steel means that the steel forms martensite not only at surface but to a large degree throughout the interior.
- For the optimum development of strength, steel must be fully converted to martensite.
- To achieve this, the steel must be quenched at a rate sufficiently rapid to avoid the decomposition of austenite during cooling to such products as ferrite, pearlite and bainite. Hardenability of a steel should not be confused with the hardness of a steel.

Hardness $\neq$ Hardenability

Hardness	hardenability
The Hardness of a steel is a measure of a sample's resistance to indentation or scratching	Hardenability refers to its ability to be hardened to a particular depth under a particular set of conditions.

- It is a qualitative measure of the rate at which hardness drops off with distance into the interior of a specimen as a result of diminished martensite content.
- Hardenability is more related to depth of hardening of a steel upon heat treat.
- The depth of hardening in a plain carbon steel may be 2-3 mm Vs 50 mm in an alloy steel.
- A large diameter rod quenched in a particular medium will obviously cool more slowly than a small diameter rod given a similar treatment. Therefore, the small rod is more likely to become fully martensitic.
- The hardenability of a steel is the maximum maximum diameter diameter of the rod which will have 50% martensite even in the core when quenched in an ideal quenchants. This diameter is known as D_i or ideal diameter.

3.2 Hardenability of steel is determined by the following methods

- 1) Grossman's critical diameter method
- 2) Jominy end quench test
- 3) Estimation of hardenability from chemical composition
- 4) Fracture test

Grossman's critical diameter method

In Grossman's method, we use round bars of different diameters.

These bars are quenched in a suitable quenchants. Further, we determine the critical diameter (D_c) which is the maximum diameter of the rod which produced 50% martensite on quenching. The ideal diameter (D_i) is then determined from the curve. This type of experiment requires multiple Austenitisation and quenching treatments on specimens of varying diameter just to quantify the hardenability of a single material.

Jominy End Quench method

The most commonly used method for determining hardenability is the end quench test developed by Jominy and Boegehold. Grossman's method requires multiple Austenitisation and quenching treatments on specimens of varying diameter just to quantify the hardenability of a single material. An alternative approach is to develop a more convenient standard test method that can be used for relative comparison of hardenability. The Jominy end-quench test is one such approach. The Jominy end-quench test is specified in ASTM standard A255 and is a widely used method for quantifying hardenability. Its wide use adds to its value, since the utility of empirical relations and data comparison becomes more reliable as more data are accumulated.

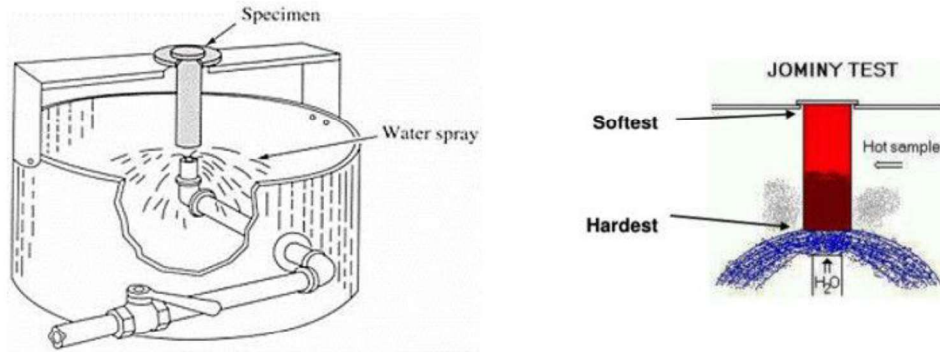
Moreover, Jominy data have been collected on a large enough scale to offer a high degree of statistical certainty for many steels. These data have been correlated with measurements and/or calculations of DC . By using these correlations, a single Jominy test can be used to estimate DC and DI for a given steel (and austenite grain size). Information gained from this test is necessary in selecting the proper combination of alloy steel and heat treatment to minimize thermal stresses and distortion when manufacturing components of various sizes.

Jominy End Quench method –

Principle

The hardenability of a steel is measured by a Jominy test with following procedure. In conducting this test, a 1 inch round specimen 4 inch long is heated uniformly to the proper austenising temperature. It is then removed from the furnace and placed on a fixture where a jet of water impinges on the bottom face of the sample. After 10 min. on

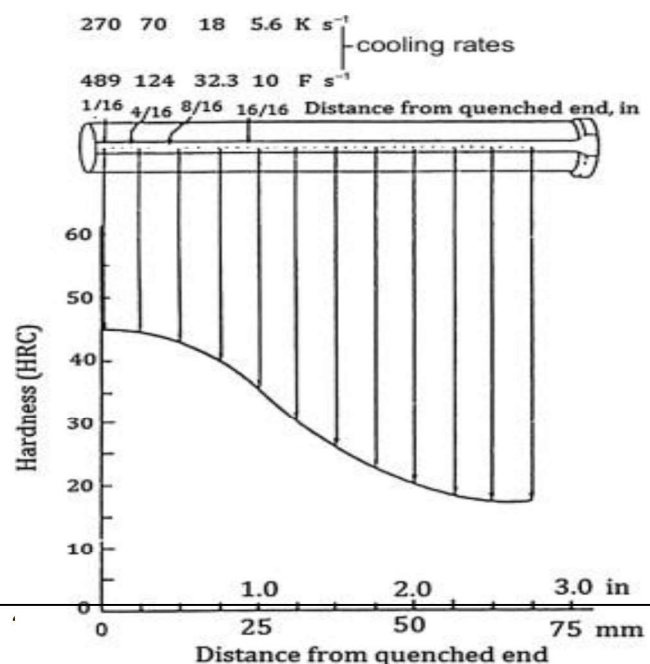
the fixture, the specimen is removed, and to cut along the longitudinal direction. And then Rockwell C scale hardness readings are taken at 1/16 inch, intervals from the quenched end. The results are expressed as a curve of hardness values Vs. distance from the quenched end. A typical hardenability curve shown below for eutectoid steel.



A number of Jominy end quench samples are first end- quenched for a series of different times and then each of them (whole sample) is quenched by complete immersion in water to freeze the already transformed structures. Cooling curves are generated putting thermocouple at different locations and recording temperature against cooling time during end quenching. Microstructures at the point where cooling curves are known, are subsequently examined and measured by quantitative metallography. Hardness measurement is done at each investigated point. Based on metallographic information on investigated point the transformation start and finish temperature and time are determined. The transformation temperature and time are Jominy End Quench method Jominy End Quench method - Principle Principle finish temperature and time are determined. The transformation temperature and time are also determined for specific amount of transformation. These are located on cooling curves plotted in a temperature versus time diagram. The locus of transformation start, finish or specific percentage of transformation generate CCT diagram (see next slide). A, B, C, D, E, F are six different locations on the Jominy sample shown in Figure (before slide) that gives six different cooling rates. The cooling rates A, B, C, D, E, F are in increasing order. The corresponding cooling curves are shown on the temperature log time plot. At the end of the cooling curve phases are shown at room temperature. Variation in hardness with distance from Jominy end is also shown in the diagram.

Determination of Hardenability from Jominy curve

After plotting the Jominy distance Vs Hardness curve, the Jominy distance having hardness equal to 50 % martensite is determined. Then the diameter of a rod



having cooling rate similar to the cooling rate at the Jominy distance having 50 % martensite is determined from the graph correlating the Jominy distance with the diameter of the rod having similar cooling rate for water quenching. This diameter gives the hardenability of the steel in water quenching (having H value equal to 1). Hardenability in any other quenchants can be determined from the same graph. DI (hardenability in ideal quenching medium) can also be determined in a similar manner. We can determine hardenability for any other amount of martensite in the core in any quenchants in a similar way.

4.0 SURFACE HARDENING IN STEELS

A large number of machine components require a combination of diverse properties such as high surface hardness and wear resistance along with good toughness and impact resistance. These processes are flame hardening, induction hardening, laser hardening and induction beam hardening,

4.1 FLAME HARDENING: This process consists of heating the large work piece, such as crank shaft, axel, cam, large gear by an oxy-acetylene or oxy-fuel blow pipe, followed by spraying of jet of water as coolant. After hardening, reheating of the parts is carried out in furnace or oil bath at about 180-200°C for stress relieving. Over heating of the work piece avoided. The carbon content required for flame hardening steels varies from 0.3% to 0.6%. 133 There are four different methods which are used in general for flame hardening:

- (i) stationary
- (ii) progressive
- (iii) spinning
- (iv) progressive spinning
- (v)

INDUCTION HARDENING: It is used to surface hardened crank shafts, cam shafts, gears, crank pins and axels. In this process heating of the component is achieved by electro magnetic induction.

A conductor coil carries alternating current of high frequency which is then induced in the enclosed steel part placed within the magnetic field of the coil. As a result induction heating takes place. The degree of flow of current on the outer surface of a component depends on the frequency, resistivity and permeability of the component. For a given material resistivity and permeability depends on the temperature.

In cold state (20°C), $d_{20} = 20/\sqrt{f}$

In hot state (800°C), $d_{800} = 500/\sqrt{f}$

d =depth to which current flows and f frequency of current

From this it is observed that with increasing the frequency the depth of hardening decreases.

ELECTRON BEAM HARDENING

This process is used for hardening those components which cannot be induction hardened because of associated distortion. Automatic transmission clutch cams are hardened by this process. The work piece is kept in vacuum at 0.06m bar pressure. Electron beam is focused on the work piece to heat the surface.

LASER HARDENING

Laser beams are used for surface hardening treatment. Since these have very high intensity, they may melt the work piece when they are used at such high intensity. Therefore a lens is used to reduce the intensity by producing a defocused spot or scans from 1-25mm wide. A laser beam of 1KW produces a circular spot whose diameter vary from 0.5 mm to 0.25mm. In laser hardening process less time is required than in induction and flame hardening processes and the effect of heat on the surrounding surface is less, leading to less distortion.

ADVANTAGES:

1. It is possible to achieve high production rates since light has no inertia and consequently it is possible to obtain high processing speeds with rapid stopping and starting.
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. There is hardly any contamination during surface hardening treatment.
6. It is possible to control the process with the help of a computer.
7. Those areas which are difficult to be treated by conventional methods can be easily treated with technique.
8. It is not necessary to carry out final machining operation subsequent to hardening.

4.3 CHEMICAL TREATMENT IN STEELS

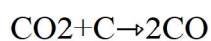
Chemical heat treatment is the process used to achieve different properties in core and steel components. There are situations in which the requirement is such that the outer surface should be hard and wear resistant and the inner core more ductile and tougher. Such a combination of properties ensures that the component has sufficient wear resistance to give long service life and at the same time has sufficient toughness to withstand shock loads.

1. Carburizing

Carburizing is carried out in the temperature range 900-930°C. And the surface layer enriched with carbon up to 0.7-0.9%. In this process, carbon diffused into steel by heating above the transformation temperature and holding the steel in contact with a carbonaceous material which may be a solid medium, a liquid or a gas. As the solubility of carbon is more in austenite state than in ferritic state, fully austenite state is essential for carburizing. The surface hardness depends on the relationship of hardness with carbon content which differs slightly for different grades of steels. carburizing is divided into three categories

(i) Pack carburizing: This method of carburizing is also known as solid carburizing. It is the oldest method of carburizing steel components. In this process, steel components to be heat treated are packed with 80% granular coal and 20% BaCO₃ as energizer in heat resistant boxes and heated at 930°C in electric chamber furnace for a specific period of time which depends on the case depth required.

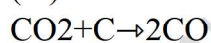
(i) Energizer decomposes to give CO gas to the steel surface: $\text{BaCO}_3 \rightarrow \text{BaO} + \text{CO}_2$



(ii) Carbon monoxide reacts with the surface of steel:

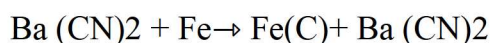
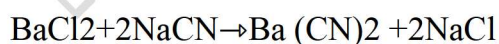


(iii) Diffusion of carbon into steel (iv) CO₂ formed in step(ii) reacts with C in the coal:



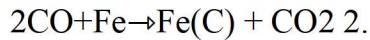
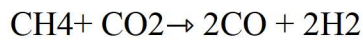
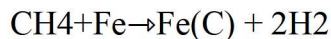
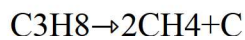
ii) Liquid carburizing

Carburizing occurs through molten CN in low carbon steel cast pot type furnace heated by oil or gas. Bath temperature is maintained between 815 to 900°C.



(iii) Gas carburizing

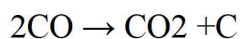
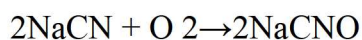
It is carried out in retort type sealed quench type or continuous pusher type furnace. These furnaces are either gas fired or are heated electrically. Gas carburizing temperature varies from 870-950°C. During gas carburizing the following reactions are take place:



(iv) Vacuum Carburizing: Carburizing in vacuum or reduced pressure is carried out in two stages. In the first stage carbon is made available to the steel absorption. In the second stage diffusion of the carbon takes place within the steel piece and results in appropriate concentration of carbon and depth of carburizing.

Cyaniding and Carbonitriding

In cyaniding and carbonitriding processes, the surface layer of steel (with 0.3-0.4%C) is hardened by addition of both carbon and nitrogen. In this case that contain both carbon and nitrogen are produced in liquid salt baths (cyaniding) or by use of gas atmospheres (carbonitriding). The temperatures used are generally lower than those used in carburizing, being between 750-900°C. Exposure is for a shorter time, and thinner cases are produced, up to 0.010in. For cyaniding and up to 0.030in. For carbonitriding. In Cyaniding is done in a liquid bath of NaCN, with the concentration varying between 30 and 97%. Both carbon and nitrogen enter the steel via the following reactions:



Carbon and nitrogen so formed in atomic form diffuse into the steel and give thin wear resistant layer of the carbonitride ϵ -phase. The temperature used for cyaniding is lower than that for carburizing and in the range of 800-870°C. the time of cyaniding is 0.5-3 hour to produce a case depth of 0.25 mm or less. Cyaniding process is not suitable for hardening those parts which are subjected to shock, fatigue and impact because nitrogen addition has adverse effects on such properties of steels.

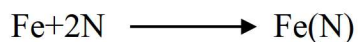
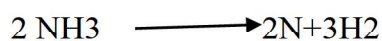
Carbonitriding

It is a case-hardening process in which a steel is heated in a gaseous atmosphere of such composition that carbon and nitrogen are absorbed simultaneously. This process is also known as dry cyaniding or gas cyaniding. It is the gas carburizing process modified by the addition of anhydrous ammonia. The decomposition of ammonia provides the nitrogen, which enters the steel along with carbon. A typical gas mixture consists of 15% NH_3 , CH_4 , and 80% of neutral carrier gas. The temperature used is 750-900°C. With

increasing temperature, a greater proportion of carbon enters the steel. The presence of nitrogen in the austenite accounts for the major differences between carbonitriding and carburizing. Carbon-nitrogen austenite is stable at lower temperatures than plain-carbon austenite and transforms more slowly on cooling. Carbonitriding therefore can be carried out at lower temperatures and permits slower cooling rates than carburizing in the hardening operation. In this process, surface hardenability, wear resistance and corrosion resistance are better than in the carburizing process. But the time required for heat treatment is longer than that for carburizing.

Nitriding:

In contrast to the processes described before, nitriding is carried out in the ferrite region. Consequently, no phase change occurs after nitriding. This part to be nitrided should possess the required core properties prior to nitriding. Pure ammonia decomposes to yield nitrogen which enters the steel:



The solubility of nitrogen in ferrite is small. Most of the nitrogen that enters the steel forms hard nitrides (e.g. Fe_3N). A typical nitriding steel contains alloying elements of 1%Al, 1.5%Cr and 0.2%Mo. Al, Cr, and Mo form very hard and wear resistant nitrides. The temperature of nitriding is 500-590°C. the time for a case depth of 0.02mm is about 2 hour. In addition with wear resistance, it also increases the resistance of a carbon steel to Nitriding. In addition with wear resistance, it also increases the resistance of a carbon steel to corrosion in moist atmospheres. A common problem encountered in nitriding is the formation of γ' nitride (Fe_4N) on the outer layers of the case, known as the “white layer”, as it looks white under the microscope. This layer is very brittle and tends to crack. It must be removed by final grinding operation. Its formation can be minimized by maintaining the correct ratio of NH_3 / H_2 in the gas mixture during the heat treatment.

There are two ways by which white layer can be totally suppressed

- ✓ Floe process or double stage nitriding, where a white layer is first produced and then decomposed
- ✓ Ion nitriding process or Plasma nitriding

6.0 Alloy Steels

There are a number of ways by which steel can be classified. However, the most widely popular classification is based on their chemical composition as provided by the American Iron & Steel Institute (AISI).

Types of Steel based on Chemical Composition

Depending on the chemical composition, according to the AISI, the following four basic types of steel are distinctly grouped. They are:

1. Carbon Steel
2. Alloy Steel
3. Stainless Steel
4. Tool Steel

Carbon Steel:

This type of steel accounts for around 90% of total steel production. Most of the steel we find all around is made from this grade of steel because of its strong and durable nature. Carbon Steel contains less than 2% carbon without any purposeful alloying additions. Depending on the amount of carbon present, Carbon Steel is categorized into three main classes. They are

- **Low Carbon Steel or Mild Steel:** This grade of steel is the least expensive type and quite common in use. Low Carbon Steel or Mild Steel contains up to 0.3% carbon. It possesses very good formability and finds wide structural application.
- **Medium Carbon Steel:** This type of carbon steel contains 0.31% to 0.6% carbon and 0.31% to 1.60% magnesium. Medium carbon steels are stronger than mild steel, but with an increase in carbon content, the formability reduces. They can be found in applications like gears, railroad tracks, cranks, machinery parts, pressure structures, etc. The properties of medium carbon steel lie in between mild steel and high carbon steel.
- **High Carbon Steel:** High carbon steel grades contain more than 0.6% carbon and 0.31 % to 0.9% magnesium. This type of steel has the maximum strength and hardness with the lowest ductility and formability. High carbon steels find their application in bars, plates, spring steel, knives, taps, wire drawing dies, cutters, etc.

6.1 Alloy Steel:

Alloy steels contain one or more alloying elements (nickel, manganese, titanium, copper, silicon, chromium, molybdenum, cobalt, tungsten, vanadium, and aluminum) in varying proportions. Purposeful addition of these alloying elements is done to manipulate the steel's properties as required for different applications. Specific properties like hardenability, corrosion resistance, strength, formability, weldability, or ductility can be improved on alloy steels based on applications. Alloy steels are widely available, costlier than common carbon steels, and find their applications in pipelines, transformers, power generators, auto parts, and electric motors. Depending upon the combination of alloying additions, different grades of alloy steels are available.

6.2 The most widely used alloy steel types are provided below:

- **Tungsten Steel** for high heat resistance
- **Nickel Steel** for toughness.
- **Manganese Steel** for excellent wear resistance and work hardening
- **Vanadium Steel** for high shock and vibration resistance.
- **Chromium Steel** for corrosion and wear resistance.
- **Chromium-Vanadium Steel** for high tensile strength along with ductility.
- **Silicon Steel** for producing permanent magnets.
- **Molybdenum Steel** for good corrosion resistance, weldability, and toughness.
- **Cobalt Steel** for tremendous corrosion resistance, wear resistance, high-temperature strength, and magnetic properties.
- **Aluminum Steel** for low weight along with high strength.

Stainless Steel:

Stainless steels are made of 10 to 20% chromium as the main alloying element. This grade of steel is highly popular due to its appearance and high corrosion resistance. Stainless steels with more than 11% chromium is approximately 200 times more resistant to corrosion as compared to carbon steel. They are expensive and widely used in the form of plates, sheets, bars, tubes, and wires. Depending on the crystalline structure and composition of stainless steels, this type of steel is sub-divided into five categories as provided below:

Austenitic Stainless Steel:

Austenitic stainless steels are non-magnetic and non-heat-treatable, and generally contain 18% chromium, 8% nickel, and less than 0.8% carbon. They form the largest portion of the global stainless steel market and are widely used in food processing equipment, kitchen utensils, and piping.

Ferritic Stainless Steel:

Ferritic steels contain trace amounts of nickel, 12-17% of chromium, less than 0.1% carbon, and molybdenum, aluminum, or titanium in small quantities. They are tough, strong, and magnetic and can be further strengthened by cold working.

Martensitic Stainless Steel:

Martensitic stainless steels contain 11-17% chromium, less than 0.4% nickel, and up to 1.2% carbon. These magnetic and heat-treatable steels are used in knives and cutting tools, as well as dental and surgical equipment.

Duplex Stainless Steels:

This type of stainless contains a combination of ferritic and austenitic structures in their crystal structure. DSS materials are weldable, corrosion-resistant, and possess high strength.

Precipitation Hardening Stainless Steel:

This type of stainless steel comprised of 17% chromium and 4% nickel. Additionally, small amounts of aluminum, copper, and niobium are also added. As the name suggests, this group of stainless steels are a variety of hardened stainless steels and finds application in engine components and nuclear waste casks.

6.3 Tool Steel:

Tool Steels are a variety of abrasion-resistant, high-hardness steel types that make them suitable for use as manufacturing tools. Tool steels are available in form of round, square, or flat bars and used to make hammers, dies, molds, cutting tools, etc. Common alloying elements of tool steels are molybdenum, vanadium, tungsten, and cobalt, which makes them heat-resistant, durable, and strong. Six grades of tool steels are widely used in industries. They are

- Air-hardening tool steels
- Water-hardening
- High Speed
- Hot-working
- Shock-resisting types
- Oil-hardening

Types of Steel Depending on Application

Based on the intended application Steel can be classified into various groups as listed below:

- Structural Steels used in structural applications.
- Tool Steels used for making tools.

- Marine Steel used in seawater applications.
- Boiler Steel to make parts of steam services.
- Bridge Steel
- Spring Steel
- Pressure Vessel Steel, etc

Other Steel Types

Various other types of steel classification can be made as listed below:

- Based on the steel production method: continuous cast steel, electric furnace steel, etc.
- Based on microstructure: ferritic steel, pearlitic steel, martensitic steel, etc.
- Based on heat treatment: annealed steel, quenched steel, tempered steel, etc.
- Depending on the quality nomenclature: commercial quality steel, drawing quality steel, pressure vessel quality steel, etc.
