

HEAT TREATMENT

Introduction: In the manufacturing process of many type tools & parts, heat treatment plays an important role. It is possible to impart certain mechanical properties to metals & alloys by this process.

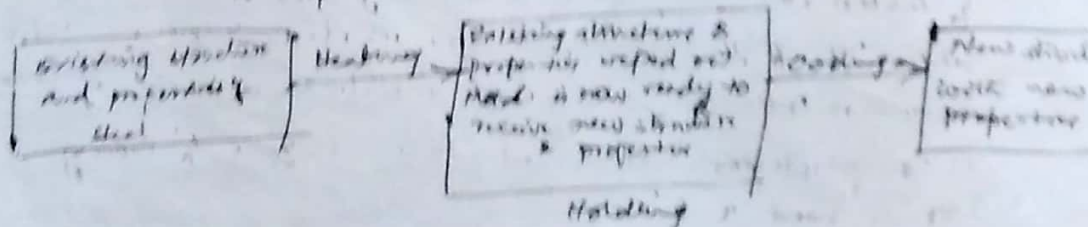
Heat Treatment may be defined as "A combination of heating and cooling operations, timed and applied to a metal or an alloy in the solid state in a way that will produce desired properties".

All basic heat treatment processes involve the transformation or decomposition of austenite. The nature and appearance of these transformation products determine the physical and mechanical properties of any given steel.

Heat treatment cycle: Heat treatment cycle consisting of the

following stages

- 1) Heating - upto austenite temp.
- 2) Soaking - Holding at this temp. for sufficient time to convert entire structure into austenite.
- 3) Cooling - At diff. rates depending upon the properties desired to impart to steel.



Purpose of heat treatment

- 1) To relieve the internal structure.
- ii) To refine the grain size.
- iii) To improve ductility.
- iv) To improve machinability.
- v) To improve metal properties.

Time-Temperature-Transformation (TTT) Diagrams

TTT diagrams also called S-curve, C-curve, Bain's curve or isothermal transformation (I-T) diagram.

- Shows the relationship between temp. and time for the transformation of austenite when the transformation occurs at constant temp. (isothermal).

Importance of T-T.T. Diagram

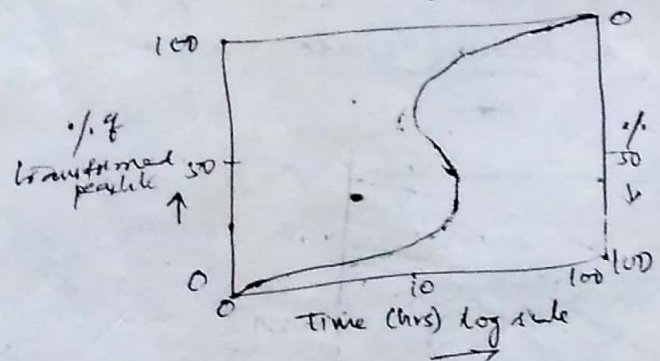
Fe-Fe₃C phase diagram shows the phases that ~~are~~^{are} under equilibrium conditions. But many heat treatment processes involve non-equilibrium rates of cooling. Under non-equilibrium conditions the Fe-Fe₃C diagram has of little value. For ex: at very high rates of cooling (quenching) a metastable phase called Martensite is formed in steels. This phase has no place on Fe-Fe₃C diagram. therefore the use of Fe-Fe₃C diagram is only to fix the austenizing temp. T.T.T. diagram is the main source of information for the decomposition of austenite under non-equilibrium conditions.

Various phases of steel due to non-equilibrium cooling

- i) Martensite: - It is a super saturated solid solution of carbon in body centred tetragonal α -iron. It is obtained if the austenite is cooled rapidly. The minimum rate of cooling at which austenite is transformed into martensite is called critical rate of cooling. It is hard & brittle.
- ii) Bainite: - It is a mixture of ferrite and cementite and it is feather like in appearance. It is obtained by an isothermal decomposition of austenite at about 350°C to 450°C.
- iii) Troosite - It is a mixture of ferrite and cementite and exist in a very fine lamellar structure. Cooling of austenite at const. temp. (500-550°C) produce troosite.
- iv) Sorbite: - It is also a mixture of ferrite & cementite, but it possess finer grain structure than pearlite. It is form. at const temp 600-650°C.

Steps to Construct T-T-T diagram

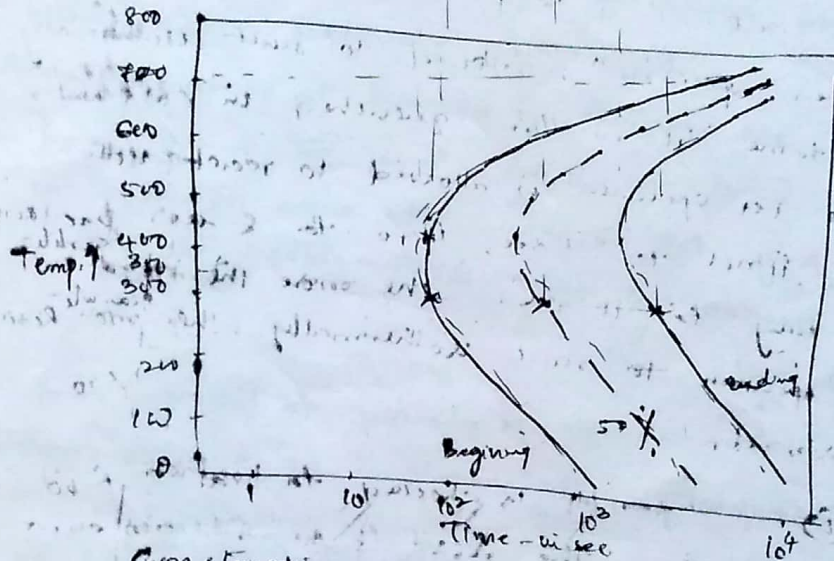
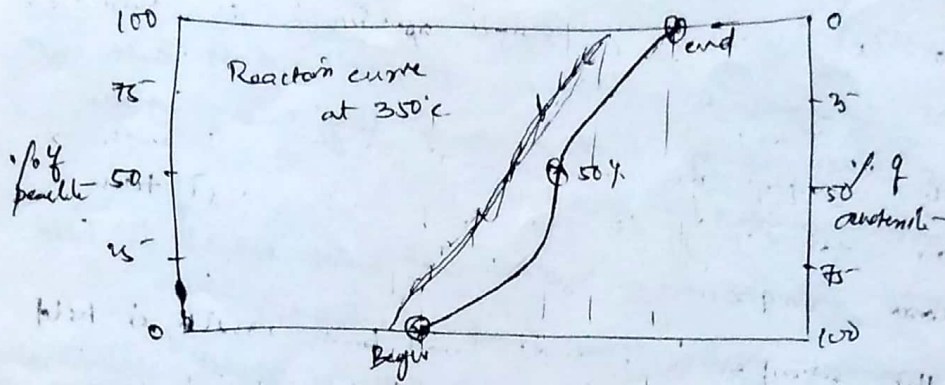
1. prepare a large number of small specimens cut from the same steel bar.
2. place the samples in a furnace or molten salt bath at the proper austenizing temp, for a long enough time to become completely austenite.
3. place the samples in a molten salt bath which is held at a constant subcritical temp. (below A_1)
4. After a given specimen is allowed to react isothermally for a certain time, it is then quenched in cold water. Generally, the 1st specimen is allowed to react isothermally for 2 seconds, 2nd for 4 sec, 3rd for 8 sec and so on up to say for 10 hrs. The more the time is given to a specimen to react isothermally, the more pearlite is formed.
5. After cooling, each sample is checked for hardness and studied microscopically. The result is the reaction curve as shown in fig.



The fig. shows that transformation of austenite to pearlite is not linear.

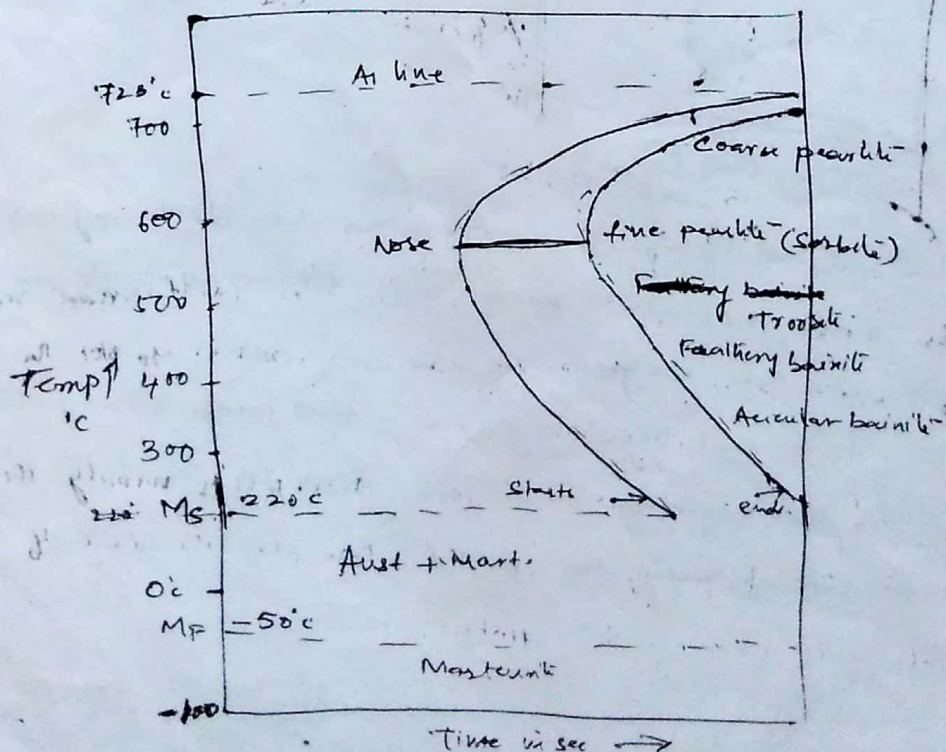
The above steps are repeated at diff. subcritical temps until sufficient points are determined to plot the curves on the diagram.

From each reaction curve, two points namely the time for the beginning and the time for the end of transformation may be plotted.



Construction of T-T-T diagram

⊗ T-T-T diagram for an eutectoid steel

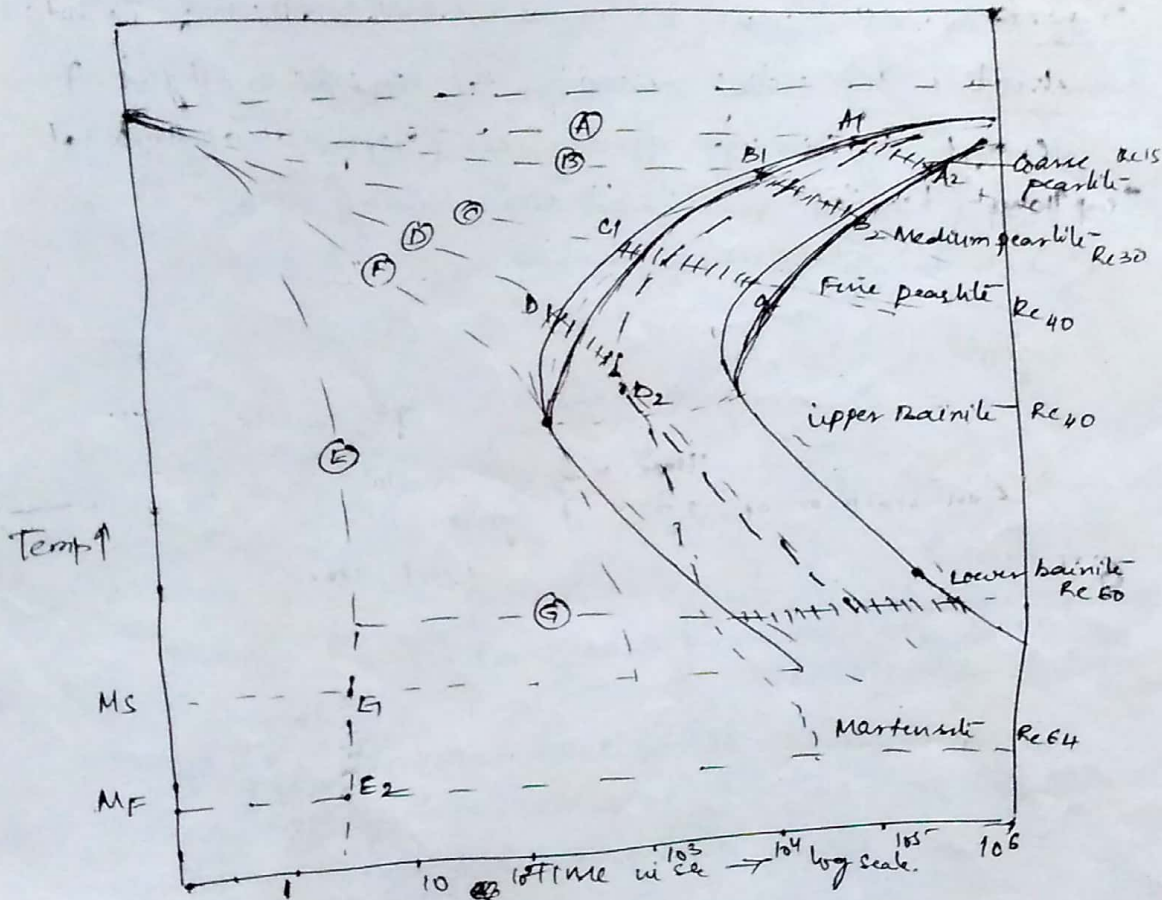


T-T-T diagram for a plain carbon steel of eutectoid composition

③

Continuous Cooling Transformation (CCT) diagram
(T.T.T diagram & cooling curves) :-

The effect of cooling rate on the formation of different reaction products is shown in fig. Since the coordinates of the I-T diagram are the same as those for a cooling curve, it is possible to superimpose various cooling curves on the T.T.T. diagram.



CCT curves. (Red)

cooling curve A - very slow cooling. A₁ - start; A₂ ends. coarse pearlite results.

curve B: faster cooling rate than A. B₁ - start - B₂ ends. medium pearlite results. Due to faster cooling, finer pearlite results than A.

curve C: slow cooling (oil quenching) - mixture of medium and fine pearlite.

curve D: D₁ - D₂ - Aust → pearlite. When M_s line crossed, remaining austenite will transform to martensite.

remains austenite until the line is reached at E_1 .

$E_1 - E_2$ — Aust \rightarrow Martensite.

Final structure is entirely martensite.

curve F — A tangent to the nose of the T.T.T. curve.

The cooling rate equals to the critical cooling rate (C.C.R).

Any cooling rate slower than C.C.R will form some softer

transformation product such as pearlite or bainite.

If cooling rate is faster than C.C.R, martensite will form.

curve G — This curve results in the formation of bainite

structure by cooling rapidly ~~etc.~~ (represented by 'E')

energy to the nose and then holding at a temp at

which bainite will be formed.



Heat Treatment Processes:

1. Annealing.
2. Normalising
3. Hardening
4. Tempering
5. Surface hardening.

ANNEALING : It consists of

- i) Heating the steel to a certain predetermined temp.
- ii) Holding it at that temp for a sufficient time
- iii) Cooling slowly at a predetermined rate.

The main purpose of annealing:

- i) To relieve the internal stresses
- ii) To soften the steel
- iii) To improve electrical & magnetic properties
- iv) In some cases to improve machinability.

Annealing

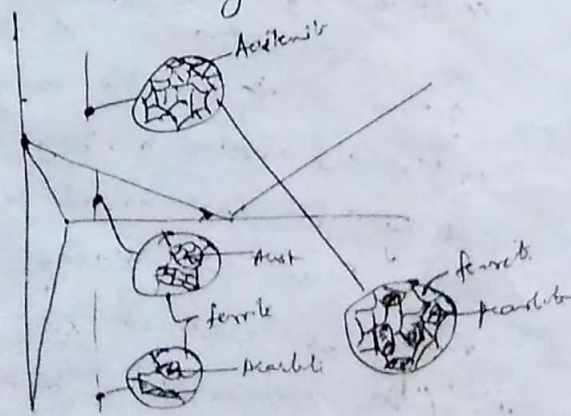
1. Full annealing
2. Spheroidise annealing
3. Stress relief annealing
4. Process annealing
5. Isothermal annealing - Heat ^{above} A_3 , rapidly cooled to 50-100°C less than lower critical temp. holding in air or oil.

Full Annealing:

- Heating hypoeutectoid steel at 30-50°C above A_3 line
- and hypereutectoid steel at 30-50°C above A_{cm} line
- Held at this temp for a definite period and then
- Cooled very slowly in the furnace.

Furnace cooling follows the Fe-Fe₃C diagram

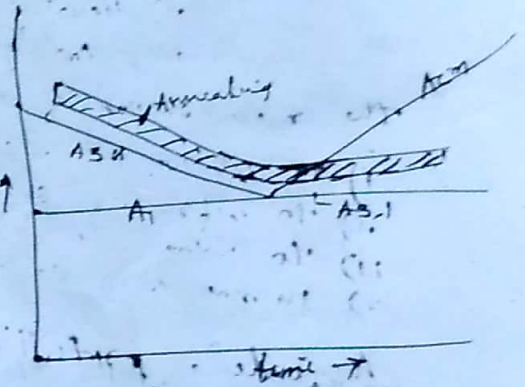
Changes in microstructure during annealing (full) of 0.2% C steel.



- i) To reduce stress
- ii) To improve electrical & magnetic properties and
- iii) In some cases to improve machinability

Slow cooling causes the austenite to decompose at low degrees of supercooling so as to form pearlite and ferrite structure in hypoeutectoid steel, a pearlite and cementite structure in hyper eutectoid steel and a pearlite structure in eutectoid steel.

The microstructure of annealed hyper eutectoid steel will consist of coarse lamellar pearlite areas surrounded by a network of proeutectoid cementite. Because this excess cementite network is



brittle and tends to be a plane of weakness, annealing should never be a final heat treatment for hyper-eutectoid steels. The presence of a thick, hard grain boundary will also result in poor machinability.

Spheroidize Annealing :

The hyper eutectoid steel consisting of pearlite and cementite network will have poor machinability because the cutting tool cannot penetrate the hard & brittle cementite plates.

Spheroidize annealing produces spheroidal or globular form of cementite ~~from~~ from plates of cementite so that the machinability will be improved because the cutting tool can cut the spheroids easily.

One of the following methods may be used to produce spheroidized structure.

- i) Heating the steel, and holding it for prolonged time at a temp. just below the lower critical temp line A_1 . (i.e. 650°C to 700°C)

- i) heating and cooling alternately between temp. (5) that are just above and just below the lower critical temp. line A_1 .
- iii) Heating to a temp. above the lower critical temp. line A_1 and then either cooling very slowly in the furnace or holding at a temp. just below the lower critical temp. line A_1 .

Prolonged time at the elevated temp. will completely break up the pearlitic structure and cementite network. The cementite will become spheroidal.

Low carbon steels are seldom spheroidised for machining because, in the spheroidised condition they are excessively soft & gummy. The cutting tool will tend to push the steel rather than cut, causing excessive ^{heat & wear} on the cutting tip.

Stress-relief Annealing — sometimes called subcritical annealing, is useful in removing residual stresses due to heavy machining or other cold working operations. It is usually carried out at temperatures below the lower critical line (A_1). ($500 - 550^\circ\text{C}$) (usually below recrystallisation temp).

Process Annealing — Used in sheet & wire drawing for industries to remove the effect of cold work. It softens the steel by recrystallisation and permits further cold work.

In this process, the cold worked steel is heated to above recrystallisation temp (650°C) below the lower critical temp line A_1 and held at that temp. for sufficient time and then cooled to room temp. in air.

Isothermal Annealing : Heating to austenitising temp
 - Rapid cooling to 50 to 100 below the lower critical temp
 - Holding to allow transformation
 - Air cooling to room temp.

purpose - To reduce the annealing time.
 - Used for reducing the hardness of alloy steel.
 - Not suitable for heavy sections. (non-uniform structure)

Normalising - It may be employed to achieve the following purposes.

- 1) To produce harder & stronger steel compare to full annealing
- 2) To improve machinability
- 3) To modify & refine the grain structure
- 4) To homogenize the microstructure.

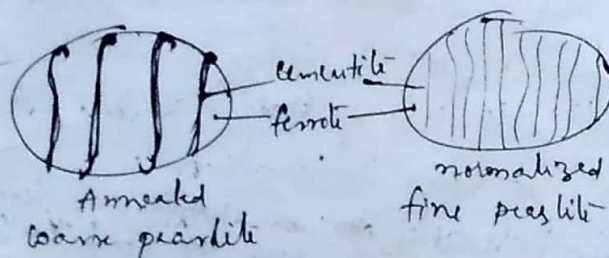
This process consists of

- i) Heating the steel at $30-50^\circ$ above upper critical temp. (above A_3 for hypo eutectoid and above A_{cm} for hyper eutectoid steel)
- ii) Holding at this temp. for a shorter period and then
- iii) Cooling to room temp in still air.

Air cooling which is slightly faster than furnace cooling affects the transformation of austenite and the resultant micro structure in several ways.

- i) During normalizing, there is less time for the formation of the pro-eutectoid constituent.
- ii) Faster the cooling rate, the lower the temp of austenite transformation.
- iii) Faster cooling rate also causes the formation of fine pearlite.

While annealing, spheroidizing and normalizing may be employed to improve machinability, the process to be used will depend upon carbon content.



hardening

(5)

- purpose:
- To increase the hardness of steel & tool steels.
 - To improve wear resistance of steel
 - To improve magnetic properties.

Process:

- Heating the hypo eutectoid steel ~~above~~ $30-50^{\circ}\text{C}$ above A_3 and hyper-eutectoid steel above $A_{3.1}$.

ii) Holding at this temp. for sufficient time

iii) Quenching in water, oil or brine solution.

Due to this rapid cooling, austenite changes instantaneously into martensite, which is a supersaturated solid solution of carbon in B.C.C. α -iron. The highly distorted lattice structure is the prime reason for its high hardness.

Hypo eutectoid steels are always hardened above A_3 temp, to convert the austenite completely to martensite.

If these steels are hardened from above A_1 , the soft ferrite phase will not change to martensite and it will be retained after quenching at room temp.

Ferrite being a soft ~~hard~~ phase, the hardness of steel gets reduced.

Hyper-eutectoid steels are hardened always from above $A_{3.1}$. At this temp, the cementite ~~is not~~ which will not change to martensite during quenching and will remain as cementite at room temp. after quenching. However, as cementite being a hard phase, it will not affect the hardness of steel.

If the hardening is carried out above A_{cm} , it will cause coarsening of the grain and warping of the components during quenching.

Important characteristics of martensitic transformation:

- The transformation is diffusionless and there is no change in chemical composition.

ii) The transformation proceeds only during cooling and ceases if cooling is interrupted. Therefore, the transformation depends only upon the decrease in temp and is independent of time.

iii) The martensitic transformation of a given alloy cannot be suppressed, nor can the M_s temp be changed by changing the cooling rate.

iv) Martensite is probably never in a condition of real equilibrium, although it may persist indefinitely at or near room temp. The structure can be considered as a transition between the unstable austenite phase and the final equilibrium condition of a mixture of ferrite and cementite.

v) The most significant property of martensite is its potential of very great hardness.

Quenching medium : i) 5-10% caustic soda - Very drastic quenching

ii) 5-20% Brine (NaCl)

iii) Cold water

iv) Warm water

v) Mineral oil vi) Animal oil

vii) Veg. oil viii) Air ~~hardening~~ etc.

Hardenability :

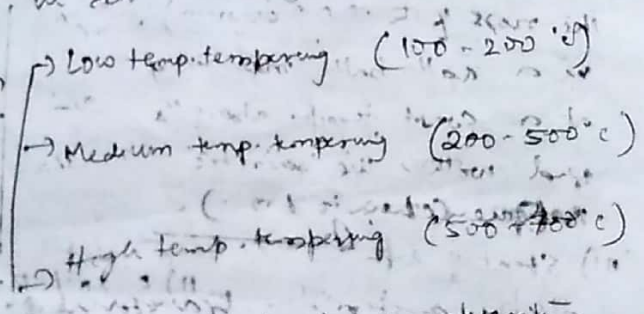
tempering: The martensite formed during hardening is highly brittle, hard and stressed. The hardened steel can not be used in this condition because cracking and distortion occurs.

Also retained austenite is an unstable phase and as it changes with time, the dimensions of the object may change. Therefore hardening is almost always followed by tempering.

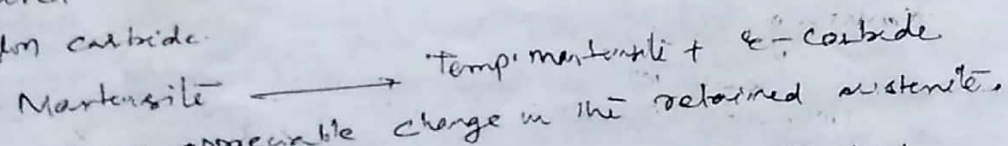
process. Tempering consists of

- i) heating the hardened components below the lower critical temp.
- ii) holding at that period for a specified period and then
- iii) cooling to room temp. in air

Tempering classification



Low Temp. Tempering: During this treatment, martensite decomposes and gives low carbon martensite called tempered martensite and transition iron-carbide called epsilon carbide.



There is no appreciable change in the retained austenite. Due to this change in micro-structure, the steel possesses high strength, high hardness, low ductility, low toughness and internal stresses are relieved.

Medium Temp. Tempering :-

Due to this treatment,

- i) the ϵ -carbide transforms to ortho-rhombic cementite
 - ii) temp. martensite transforms to ferrite.
 - iii) Retained austenite transforms to bainite.
- Hardness \downarrow - ductility & toughness \uparrow .

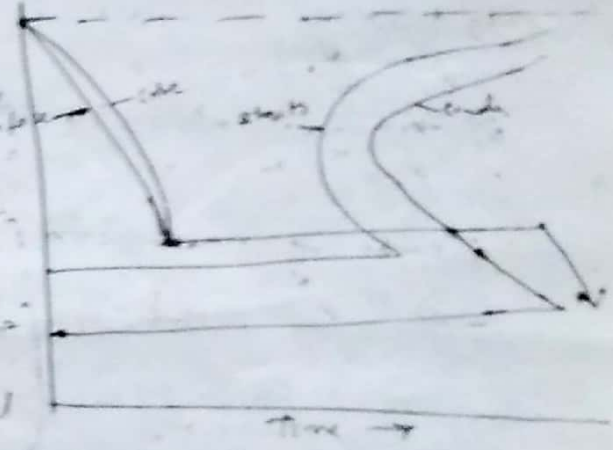
High Temp. Tempering :- In this process, the cementite particles become coarser and appear as spheroidal particles. Except this, there is no other change in the micro-structure. Coarsening of cementite particles results in a slight decrease in hardness and toughness, but because of spheroidal shape, it possess excellent machinability.

Austempering :- It is a special heat treatment process in which austenite is transformed into bainite.

process :-

- i) steel is heated to above the austenizing temp.
- ii) Quenched rapidly (to miss the rest of the TTT diagram) steel in a salt bath maintaining at a const. temp. above M_s and within the bainitic range (200 to 400°).
- iii) Steel is left in the bath until all the austenite is transformed to bainite.
- iv) After complete transformation, cooled in air to room temp.

The bainite thus formed resembles tempered martensite. Hence austempered steel rarely requires tempering.



- Also called isothermal quenching or isothermal hardening. They possess higher toughness, better ductility and hardness as compared to conventional hardening and tempering treatment. However in this process, the size of the objective is restricted to relatively thin sections.

Martempering.

87 wires -

i) Heating the steel to above the austenizing temp.

ii) Quenching in a salt bath maintained at a temp. above M_s .

iii) The steel is held in a bath till the temp. through out the section (from surface to core) becomes uniform and is equal to the bath temp without transformation of austenite.

iv) Cooled in air thru' martensitic range.

This results in the formation of martensite with minimum residual stresses, distortion & cracking.

To improve the properties further, martempered steels are generally tempered.

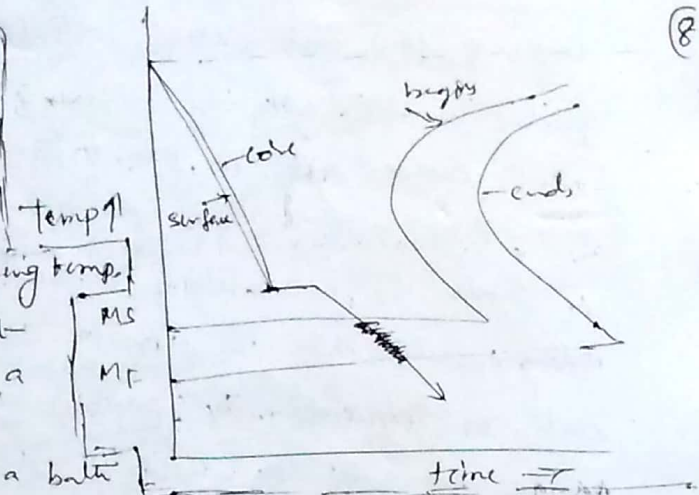
Case Hardening (or) Chemical heat treatment of steels:

Many industrial components such as crank pin, dies, cam shafts, gears etc. require a hard wear resistant surface and with a soft & tough core.

Both these requirements can not be met either by plain carbon steels or alloy steels. However these can be achieved by using low carbon steels with suitable core properties and then hardening the surface layer to a definite depth by changing the chemical composition of the surface. This treatment is known as case hardening or chemical heat treatment. This is based on diffusion.

case hardening processes

- Carburising
- Nitriding
- Cyaniding
- Carbonitriding.



Carburising - It is a method of enriching the surface layer of low carbon steel with carbon in order to produce a hard case.

It is carried out at $900-930^{\circ}\text{C}$ and the surface layer is enriched with carbon upto 0.7 to 0.9%.

Since the solubility of carbon is more in austenitic state than in ferritic state, fully austenitic state is required for carburising. Diffusion of carbon is made by holding the heated steel in contact with carbonaceous material which may be a solid, a liquid or a gas.

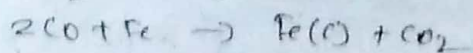
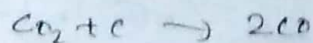
Depending on the form of the carburising medium, carburising can be classified as

Carburising $\left\{ \begin{array}{l} \rightarrow \text{Pack carburising (Solid carburising)} \\ \rightarrow \text{Liquid carburising} \\ \rightarrow \text{Gas carburising} \end{array} \right.$

Pack Carburising - The machined components which are to be heat treated are packed with 80% charcoal and 20% barium carbonate (BaCO_3) (acts as energizer) in heat resisting boxes. ~~these~~ these boxes are then heated between $900-930^{\circ}\text{C}$ for 6-8 hrs.

After heating, the boxes are cooled to room temp.

The following reactions take place at high temp. and the surface layer gets enriched with carbon.



Case depth varies with time of heating. But generally for a carburising time of 6 to 8 hrs, the depth obtained will be 1 mm to 2 mm.

Liquid carburising: It is carried out in molten baths containing 20-50% sodium cyanide, 40% sodium carbonate and varying amounts of sodium or barium chloride.

This mixture is melted and bath temp is maintained between 815-900°C

Then the component is immersed in this bath for a period varying from 5 min to 1 hr depending upon the case depth reqd. This process gives a thin hardened layer of 0.08 mm thickness

In this process, nitrogen may also diffuse thru the cyanides of sodium cyanide.

Gas carburising: In this process, the components are heated to a temp of 900°C for 3-4 hrs in a gaseous atmosphere, which will deposit carbon atoms by decomposition at the surfaces of the components.

The gaseous atmosphere contains hydrocarbons methane (CH₄) and propane (C₃H₈) diluted with carrier gas (consists of nitrogen, hydrogen & CO).

0.08 to 0.8 mm

Heat treatment after carburising

Since carburising involves prolonged heating at 900-930°C, over heating may occur which causes grain coarsening. Hence specific heat treatment is required after carburising.

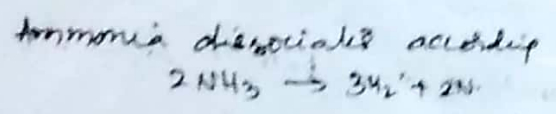
The purpose of this heat treatment is

- i) to improve the micro-structure
- ii) to refine the coarse grains
- iii) to obtain high hardness.

Nitriding: It is the process of enriching the surface of steel with nitrogen by holding for a prolonged period at temp of 500°C in an ammonia atmosphere.

Nitriding can be achieved with the components in ferritic state at 500°C.

In this process, the machined and heat treated components are heated to a temp. of 500°C for about 40-100 hrs (depending upon case depth) in a gas tight chamber thru which ammonia is allowed to circulate.



Case depth 0.02 to 0.4 mm

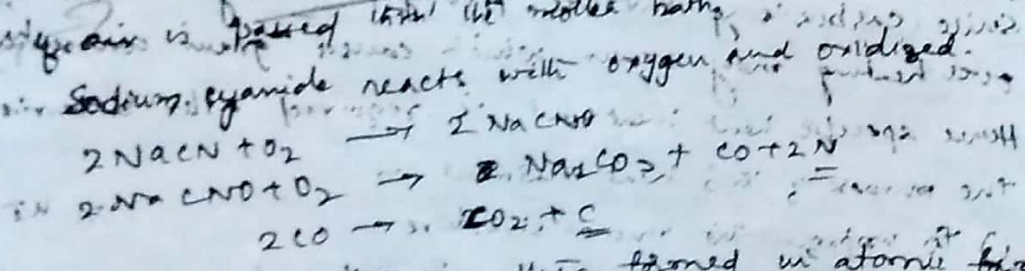
The diatomic nitrogen thus formed diffuses into iron and forms hard nitrides by combining with iron and certain alloying elements present in steel.

The advantage of nitriding is that it gives very high surface hardness and also since nitrided parts are not quenched, there is no chance of distortion or cracking. The surface possesses good corrosion, wear and fatigue resistance.

The disadvantage of nitriding is it takes prolonged time to achieve the required case depth.

Cyaniding

In this process the components are immersed in a liquid bath (of 30% NaCN, 40% Na₂CO₃ and 30% NaOH) maintained at a temp. of 800°C to 850°C. Then a measured amount of cyanide is passed thru the molten bath and oxidized.



Carbon & nitrogen thus formed in atomic form diffuse into steel surface and give thin wear resistant surface layer. This process usually requires 20-90 min. for completion.

After cyaniding, the components are quenched in water and followed by tempering.

Case depth ≈ 0.25 mm

Carbonitriding - In cyaniding the surfaces are enriched with carbon & nitrogen using liquid baths where as in carbonitriding the surfaces are enriched with carbon & nitrogen using gaseous atmosphere.

Carbonitriding is carried out by heating the components in the temp. range of 800-870°C in a gas mixture consisting of a carburising gas and ammonia. (Gas mixture consists of 15% N₂, 5% CH₄ & 80% carrier gas)

Carbon & nitrogen are diffused into the surface of the components and gives a hard wear resistant surface layer. After carbonitriding the components are quenched followed by low temp tempering. (0.05 to 0.15 mm three case)

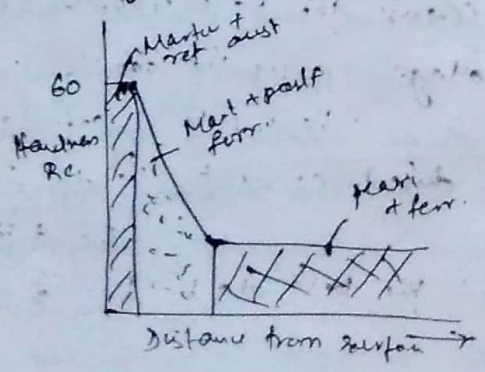
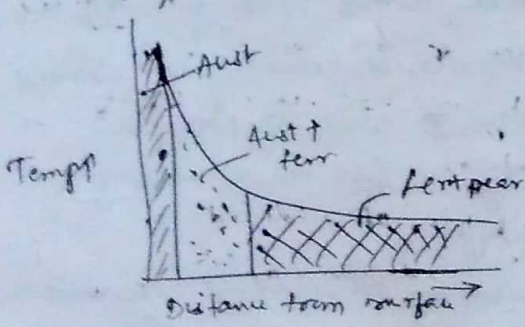
Surface Hardening

This method is based on the fact that the properties of steel not only depend upon the chemical composition but also upon the presence of various phases and microconstituents.

Such distribution of phases at the surface and the centre is obtained by a special heat treatment called surface hardening.

In surface hardening the aim is to obtain hard martensite phase at the surface and soft ferrite phase & pearlite phase at the centre of the steel.

This can be achieved by heating such that the surface to be changed to austenite and then sudden cooling so that austenite can change to martensite.



The steep temp. gradient is possible only by special heating methods, such as flame heat and induction heat. Depending upon the method of heating used, the surface hardening process is grouped as

- 1) Flame Hardening
- 2) Induction Hardening

Flame Hardening: It is a heat treating process in which the surface of steel is heated rapidly above the transformation temp. by a high temp. flame and then quenched to produce martensite.

In flame hardening, the high temp. flame is obtained by combustion of a fuel gas with oxygen or air. ex: oxy-acetylene flame.

After obtaining the reqd. temp. at the surface of the object, the flame is removed and the object is quenched either by spraying or by immersing in water.

The principal operating variables are

- i) Distance between the gas flames and the work surface
- ii) Rate of flame travel
- iii) Type, volume & application of quench.

Induction Hardening

An electrical conductor (such as steel) can be heated by electro-magnetic induction by passing an alternative current thru an inductor or work coil.

When a.c. is passed thru the work coil, magnetic field is established within the coil. This magnetic field induces an electric potential in the part to be heated. Because the part represents a closed circuit, the induced voltage causes the flow of current thru the conductor.

The resistance offered by the coil to the flow of induced current causes heating.

The distribution of induced current in the part to be heated is maximum on the surface

and decreases rapidly towards the centre of the part.

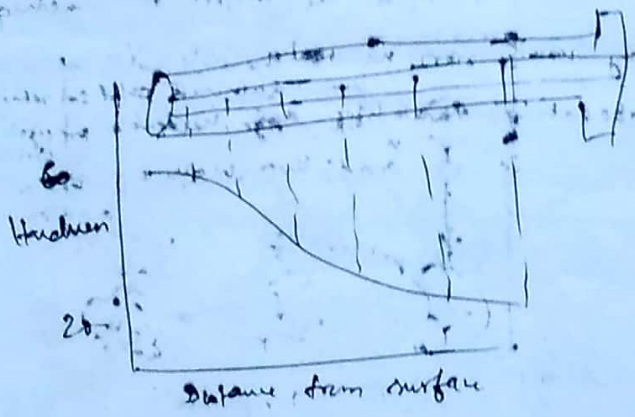
Depth of hardening in induction heating method will depend on the temp. gradient produced during heating.

Hardenability - the response of a steel to a given hardening treatment. ~~is indicated by the~~

It is an index of the depth of the martensite can be formed in a given steel as a result of a given heat treatment.

The term 'hardenability' is used to find the depth of hardness achieved i.e. martensite introduced into the steel section by quenching the steel from austenite state.

Greater the depth of hardness below the surface higher will be the hardenability of steel.



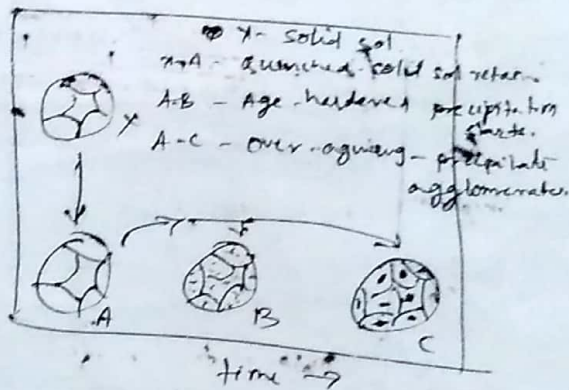
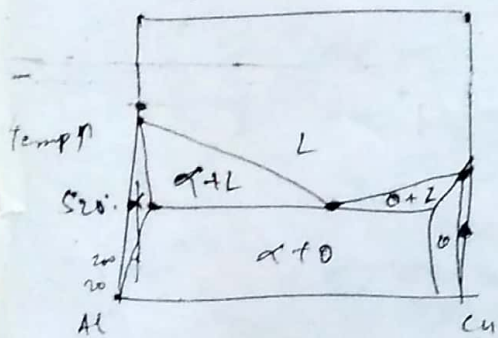
Age Hardening — Heat treatment process for ferrous and Non-ferrous alloys.

Age hardening or precipitation hardening is based on the principle that the solid solubility of one element (solute) in another element (solvent) depends on temp.

Certain alloys can be heated to form a single phase solid solution, and because of the decreasing solid solubility with temp., they revert to two distinct phases upon cooling. i.e., precipitates are formed in the matrix of original phase. This structure is stronger than single phase solid solution.

The process of age hardening consists of two stages.

1. Solid solution treatment and
2. Aging.



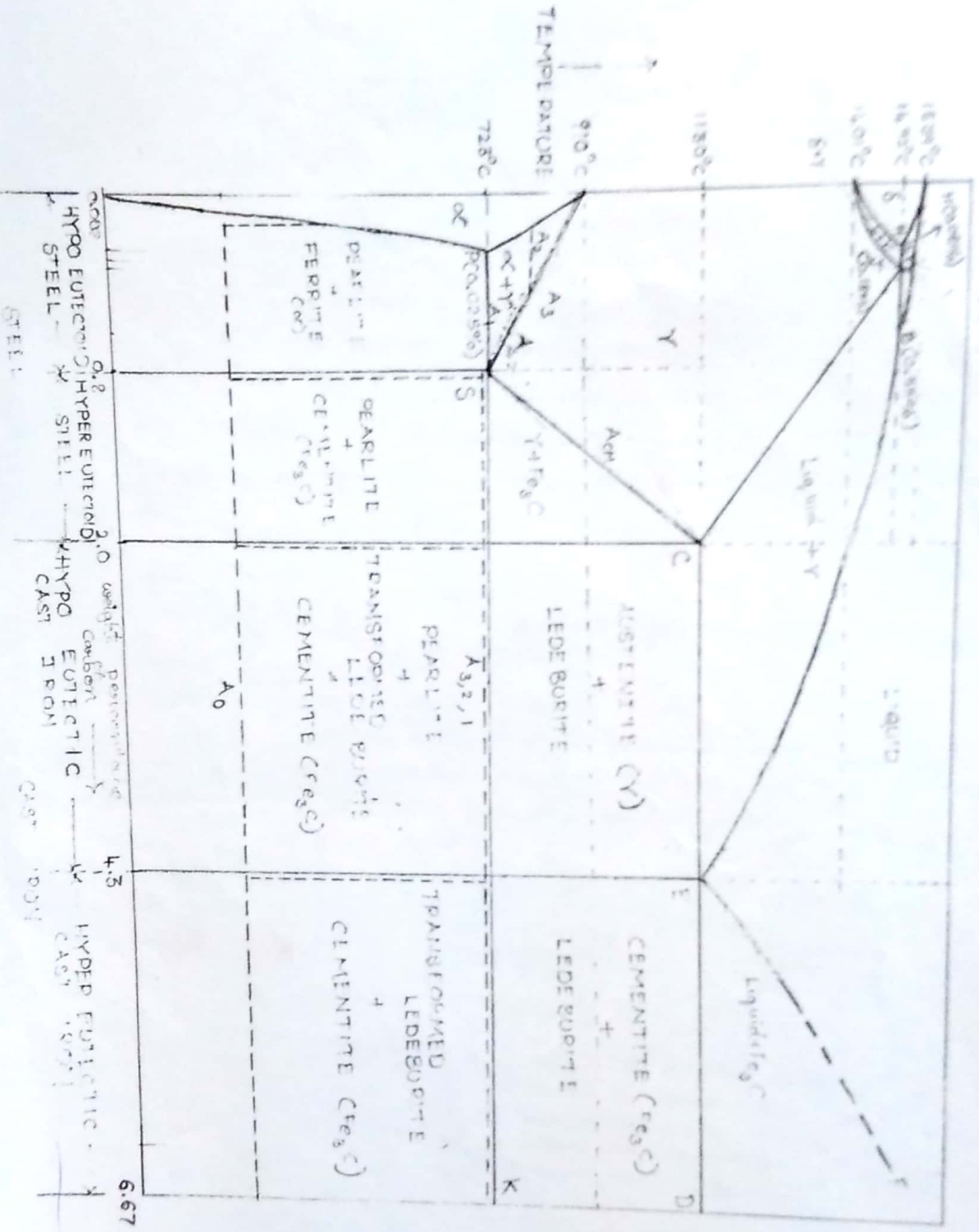
Solid solution treatment — Alloy heated to 1250°C — only α -solid sol.

Quenched in water (α -A) — α -single phase super-saturated solution.

Aging: Structure after quenching is unstable and excess solute precipitate to form two phase stable structure ($\alpha+\theta$). This is stronger & harder than single phase solid solution.

At room temp — natural aging

Above room temp — Artificial aging.



0.000
 HYPO EUTECTIC
 STEEL
 0.8
 HYPER EUTECTIC
 STEEL
 2.0
 HYPO EUTECTIC
 CAST IRON
 4.3
 HYPER EUTECTIC
 CAST IRON
 6.67