

## → Introduction

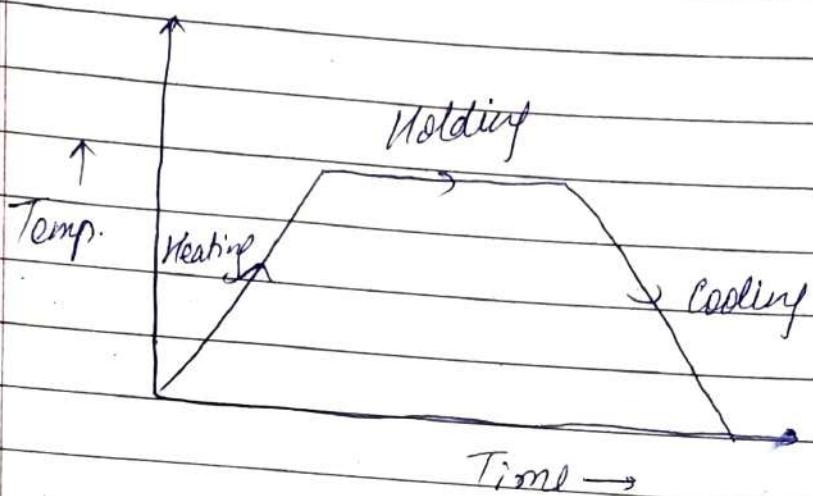
- Effect of alloying elements on microstructure / TTT diagrams.
- Transformation of pearlite to Austenite (mechanism).
- Austenitic grain size.
- Determination of austenitic grain size.
- Transformation of austenite to pearlite.
- Factors affecting interlamellar spacing.
- Transformation of Austenite to Martensite.
- Transformation of Austenite to Bainite.
- Factors affecting hardenability of steel.

## Heat treatment technology :-

- The properties of a material depends upon its atomic structure, crystal structure & microstructure.
- The mechanical properties, in particular, depends upon the microstructure. Thus, the mechanical properties can be modified by altering the proportion of microconstituents. The first hand information about the microstructure can be obtained from eg<sup>m</sup> phase diagrams.

With the help of heat treatment, the proportion of microconstituents in the microstructure can be altered.

Heat treatment process is a thermal cycle which involves heating the specimen to a specified temperature, holding the specimen at this temp for specified period & then cooling it to room temperature.



→ This technology is applicable to only those materials which responds to these kinds of treatments.

### Purposes

- To remove internal stresses
- To improve ductility
- " toughness
- " tensile strength
- " Hardness
- changing chemical compn' of the core
- grain size control
- To impart secondary hardening
- For recrystallization.
- Improving magnetic properties
- " electrical "

W: Cr: V

18: 4: 1

C → 0.7%

→ Compo<sup>n</sup> of high  
steel speed

W is costly so it is  
replaced by around  
7% Mo

Page

3

## Variabiles of heat treatment:-

### 1) Heating rate

→ It depends upon size & shape of the specimen  
for large size, complex shape → slow heating  
rate.

Since majority of metallurgical specimens have high  
thermal conductivity, for small sizes higher  
heating rate may be adopted.

Thermal conductivity  
of high C - steel & stainless steel is poor. Therefore  
slow heating rate may be adopted.

### Advantage of slow heating rate:-

- Less internal stresses
- Uniform temp.; This reduces holding time.

### 2) Holding temperature:-

→ It is decided by chemical compo<sup>n</sup> of steel.  
In case of high alloy steel, in the  
presence of carbide formers, the holding temp.  
is further raised.

### 3) Holding time:-

- Normally holding time depends upon section thickness  
which is 2-3 mm/min. If the specimen has

variable thickness, then holding time is kept as per max. thickness of section.

G)

Cooling rate:-

- The final mechanical properties are highly sensitive to cooling rate.

Fig ①

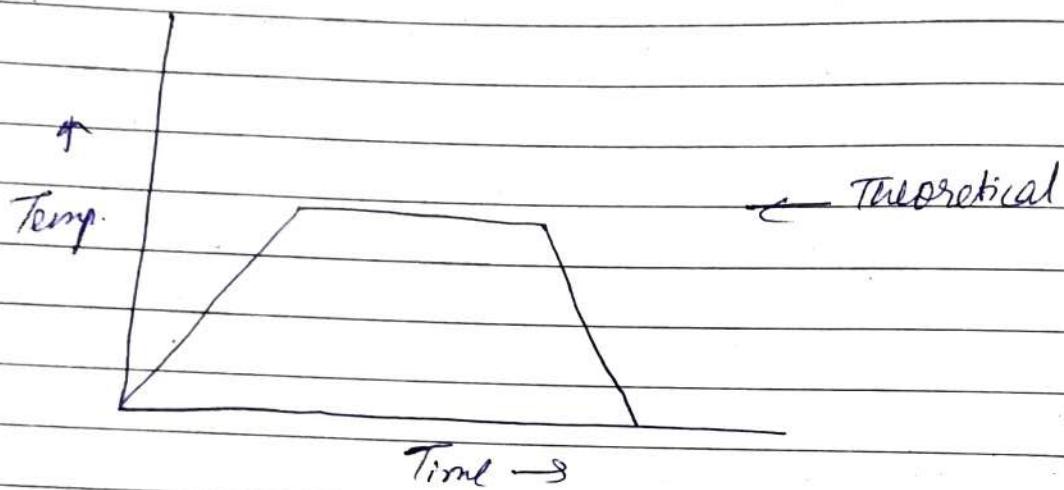
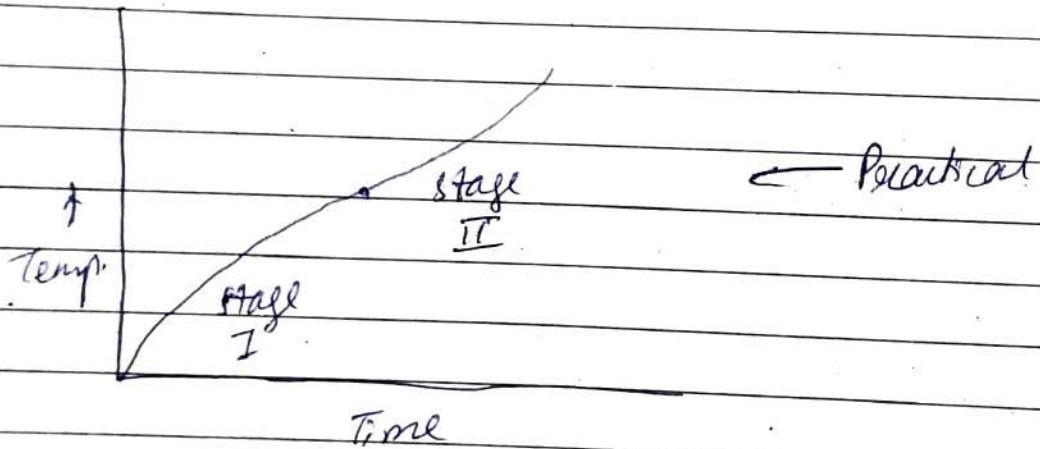


Fig. ②



In the first fig., heating rate is uniform. But in practical heating rate is non-uniform, because the temp. increases.

So, at higher temperatures, heating rate is not uniform, infact, it decreases.

→ In case of prolonged heating of steel at higher temperatures, following problems may occur.

- a) Oxidation of steel
  - b) Grain coarsening of steel.
- To minimize surface oxidation & grain coarsening, heating is carried out in 2 stages.

### Stage I

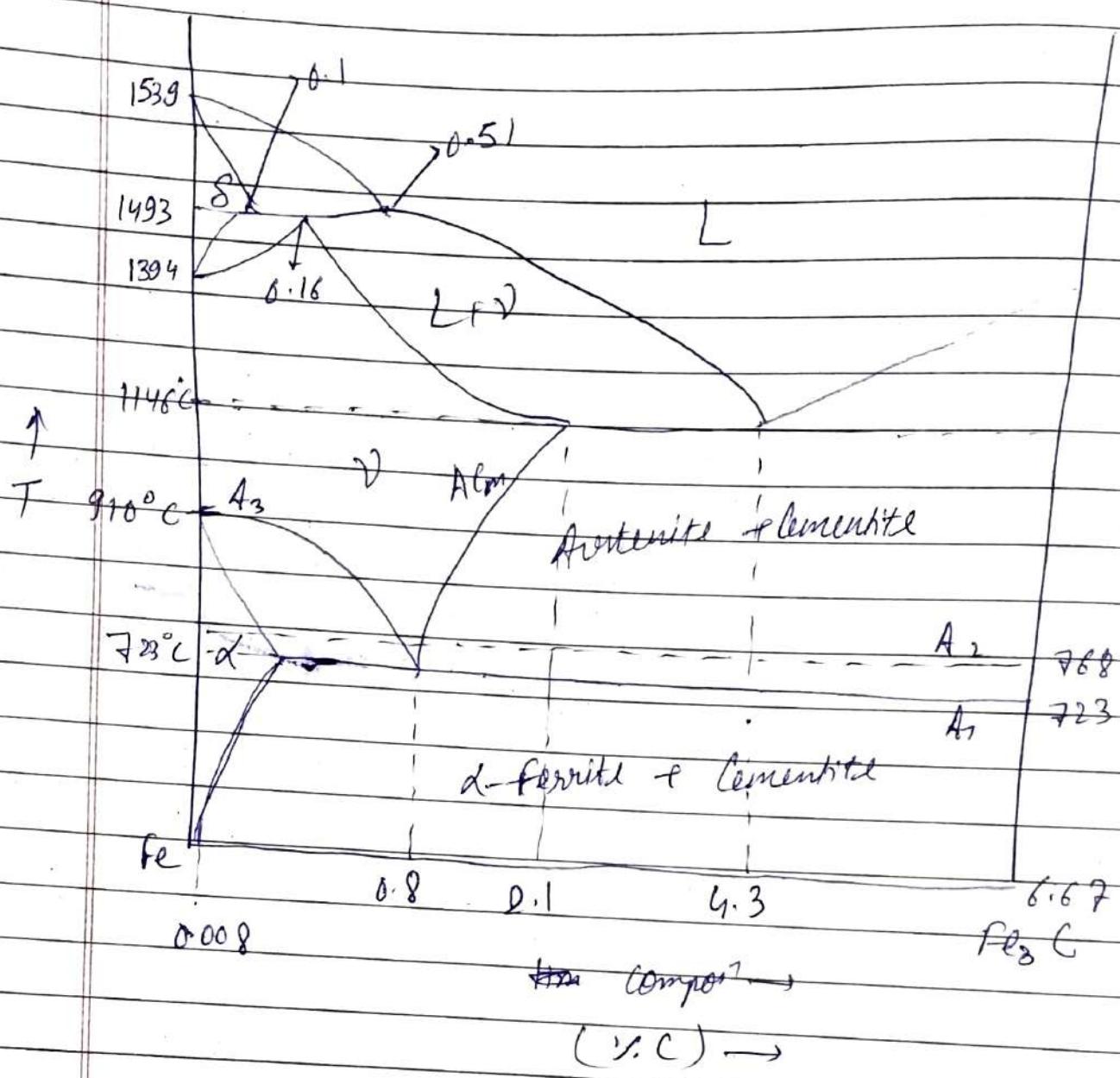
→ The specimen is heated to a temperature where surface oxidation & grain coarsening is negligible.

### Stage II

→ The specimen is now quickly transferred to a furnace which is already maintained at the holding temp.

Effect of alloying elements of Fe-Fe<sub>3</sub>C phase diagram:

P.T.O.



Why Fe<sub>3</sub>C is kept as second component in Fe-Fe<sub>3</sub>C diagram?

→ In case of all steels, carbon is present in combined form i.e. in form of Fe<sub>3</sub>C that's why Fe<sub>3</sub>C is taken as 2nd component.

0.008 → Room temp. solubility of C in Fe.

0.8 → Eutectoid compn'

Max. solubility of carbon at 1st transform<sup>n</sup>  
temp. (A<sub>1</sub>)

2.1 → max. solubility of carbon in V-Fe

4.3 → max. content of carbon in lig. at 1146°C

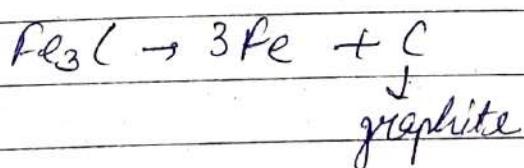
6.67 → max. possible content of carbon.

∴ Atom-% of C in Fe<sub>3</sub>C =  $\frac{12}{3 \times 56 + 12} \times 100 \approx 6.67$

The line is dotted because Fe<sub>3</sub>C is metastable  
& it melts before reaching the temp.

So, Fe-Fe<sub>3</sub>C is a metastable phase diagram  
but not eq<sup>m</sup> phase diagram

→ In the presence of S, at a certain critical value mostly around 2-2.5, graphitisation takes place as -



→ If Al & Ni are present, they also act as graphitizers.

In such cases, when graphite is stable i.e. when graphitizers are present then Fe<sub>3</sub>C is replaced by graphite.

Then Fe-graphite (Fe-C<sub>6</sub>)  
phase diagram. There are minor changes in  
critical temp. & critical compn.

Primary graphite →  
Intermediate graphite →  
Secondary graphite →

A<sub>1</sub> → first Arrest temp.

(A → Arrest)

as at this temp. is const; since phase  
transformation takes place at const. temp  
(i.e. temp. is arrested)

A<sub>c</sub> → (-charriage  
(means heating)

A<sub>2</sub> → α - refroidissement  
(means cooling)

A<sub>2</sub> → It is related to Curie temp. where iron  
loses its ferromagnetic nature to paramagnetic.

i) The tempern depends upon how slowly the  
sample is cooled.

$A_{cm} \rightarrow$  Cementite is formed by gaining surplus amt. of C from austenite. That's why  $A_{cm}$  curve.

\* Rail points, crushing plate of stone crusher had - field Mn steel.

\* Only in white CT; carbon is present in cementite form while in all other CT it is present in graphite form.  
White CT is very brittle.

Now,

The alloying elements can be broadly divided into 2 categories:-

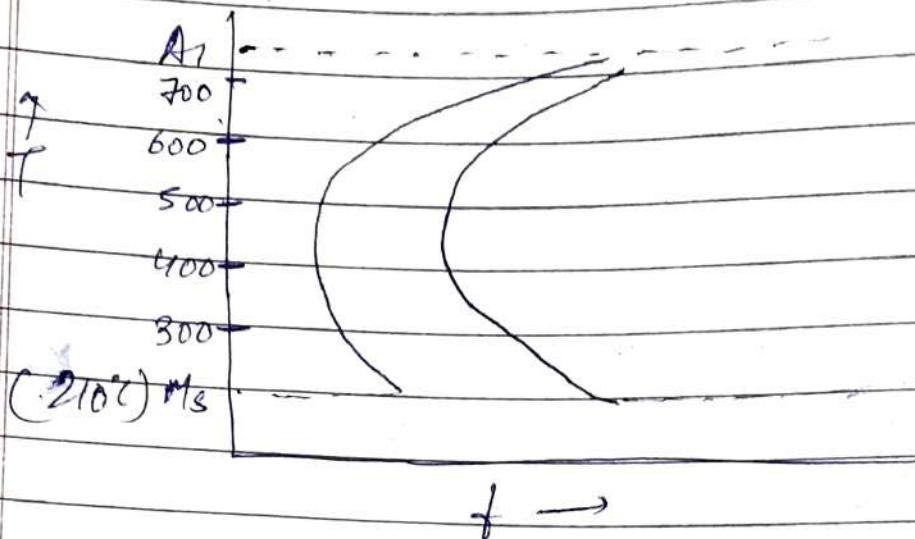
A) Ferrite stabilizers:-

→ Cr, W, V, Mo, Si, C, etc.

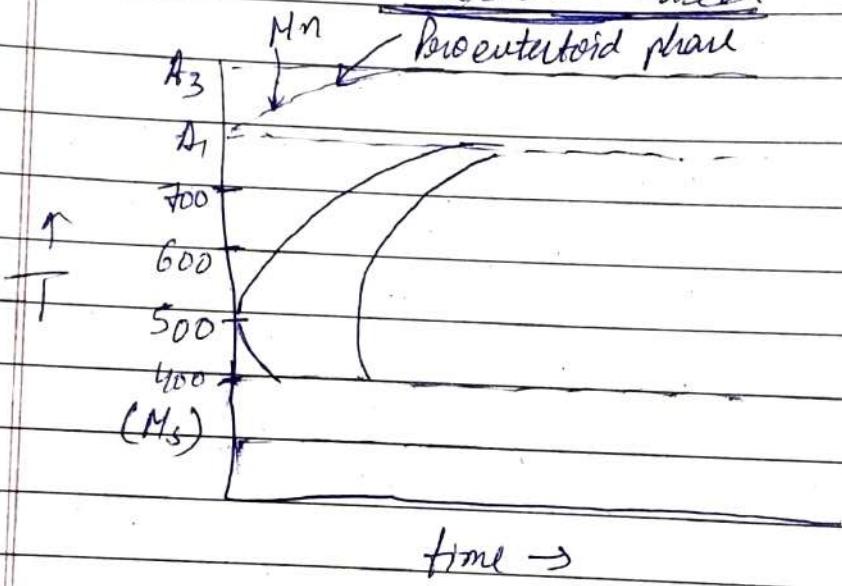
B) Austenite stabilizers:-

→ Mn, Ni, Cu, Co, Al. (Pec metals)

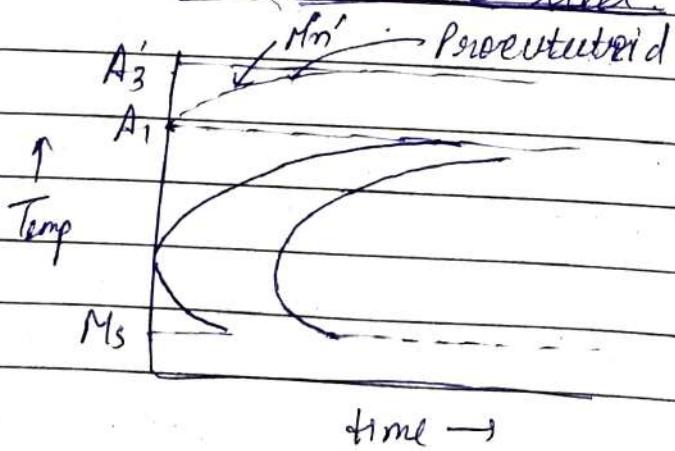
TTT diagram for plain-C steel



(i) Euteutoid steel



(ii) 0.35% C steel

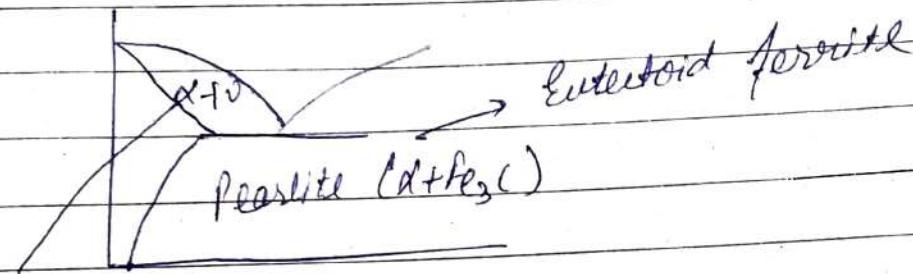


(iii) 1.1% C-steel

(i) In case of 0.8% C-steel (euteutoid steel),  $M_s$  is about  $210^\circ\text{C}$ .

$M_f$  temp is not indicated because rate of diffusion of carbon in sub-zero temp. is very very small.

(ii) In case of hypo-euteutoid steel ( $< 0.8\%$ )



This  $\alpha$ -ferrite is called proeutectoid  $\alpha$ -ferrite

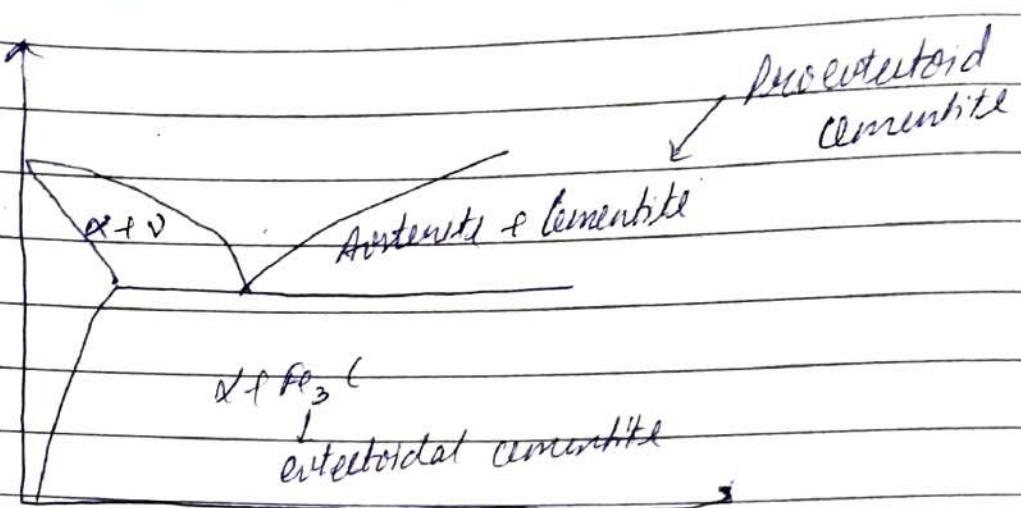
that is the boundary which indicates the form of beginning of  $\alpha$ -ferrite (proeutectoid)

That's why a gap is observed in due C-curve to presence of proeutectoid  $\alpha$ -ferrite

$\rightarrow M_s$  temp T<sub>es</sub> as C. less

In this case it is  $400^\circ\text{C}$

(iii) Hyper-euteutoid steel (1.1% C)

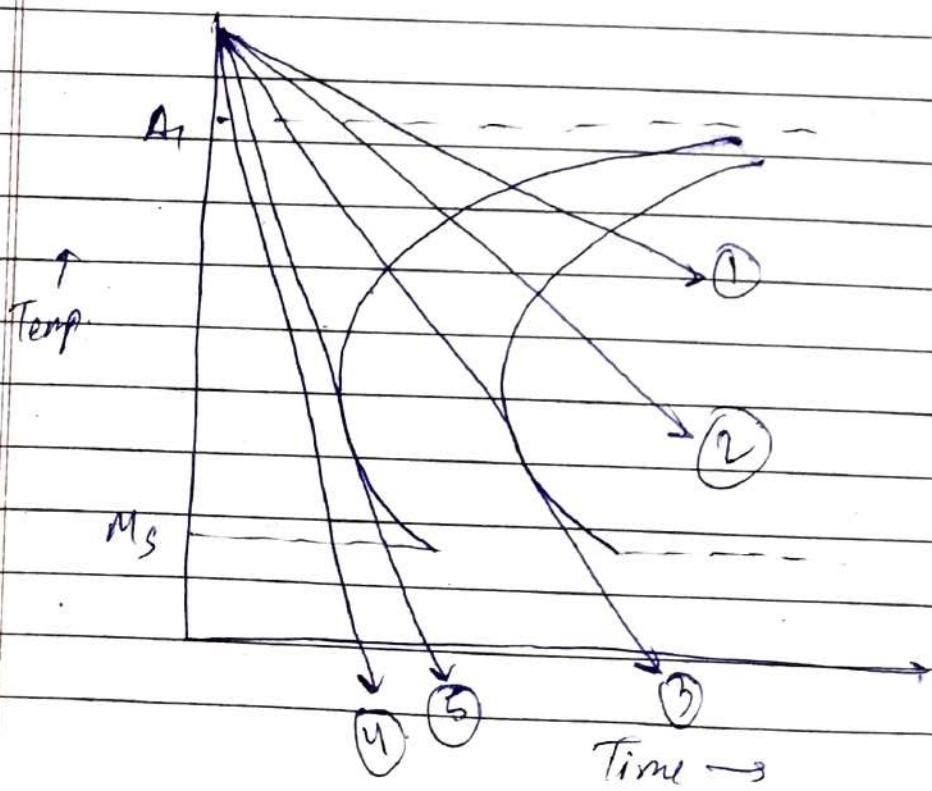


The gap in left hand of C curve is due to presence of pro-eutectoid cementite.

As C% has Red, Ms temp. goes down

In this case, it is  $180^{\circ}\text{C}$

### Cooling curves



① → coarse pearlite (bcc to fcc transform<sup>n</sup>) is taking place at high temp. which allows for coarsening of pearlite)

② → fine pearlite

③ → lower bainite (resembles martensite)

④ → Martensite

⑤ → the cooling rate corresponding to this is called critical cooling rate.

\*) In case of plain carbon steel, min % of carbon to have 100% martensite is 0.6.

### Hardenability:

Ability of a steel to harden itself even with milder quenching rates.  
or

Rate of hardening.

How to ↑ hardenability:

↗ Increasing C-content

(With increase in C content, hardness increases but it also results in

increased brittleness which is not desired)

→ Austenite grain size

$$n = 2^N - 1$$

$n \rightarrow$  no. of grains per sq. inch at 100X.

$N \rightarrow$  ASTM austenitic grain size no.

Less no. of grains → coarse

Large no. of grains → fine

Nucleation of pearlite takes place at ~~all~~ austenitic grain boundaries. The austenitic grain boundary area is large in case of fine austenitic grain size. Which means pearlite formation is favoured in case of finer grain size.

Since pearlite is a softer phase, it is not desired.

So, to obtain higher hardness, coarse austenite grain size is desired

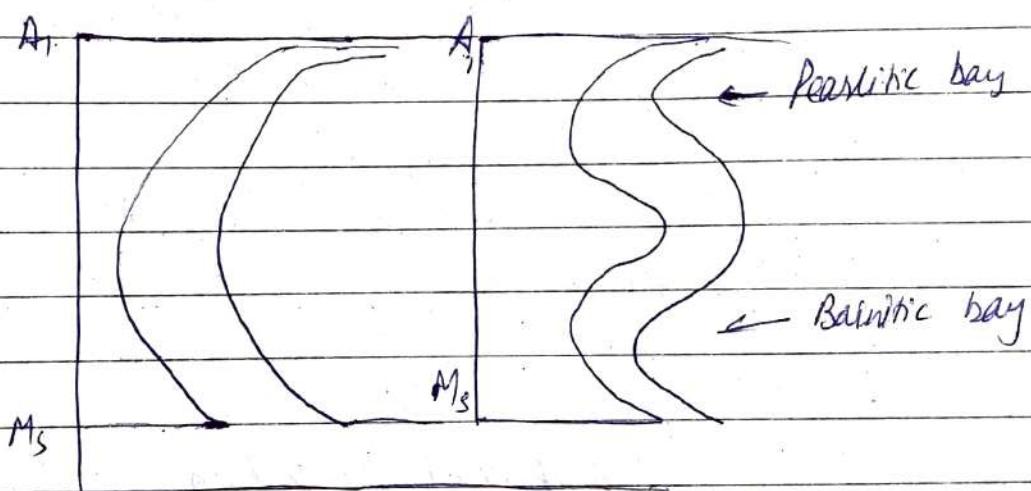
But coarser grain size has ill effect on other mechanical prop.

## ~~→ Add<sup>n</sup> of alloying elements~~

Due to add<sup>n</sup> of certain alloying elements like Mn, the TTT curve is shifted towards right. Therefore, even with a milder quenching rate, Martensite can be obtained.

All alloying elements either ↑ hardenability (shifts curve to right) or at least have no effect on hardenability except Co (it decreases hardenability)

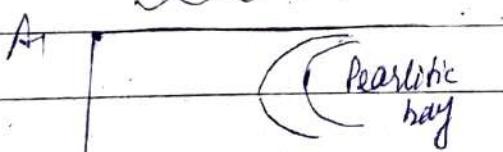
## Effect of alloying elements on TTT diagrams



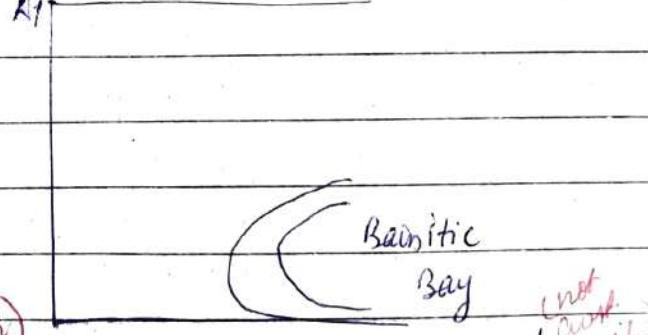
I low alloy steel

Special case

II low alloy steel



III high alloy steel (most stabilizer)



IV high alloy steel (not aust. stable)

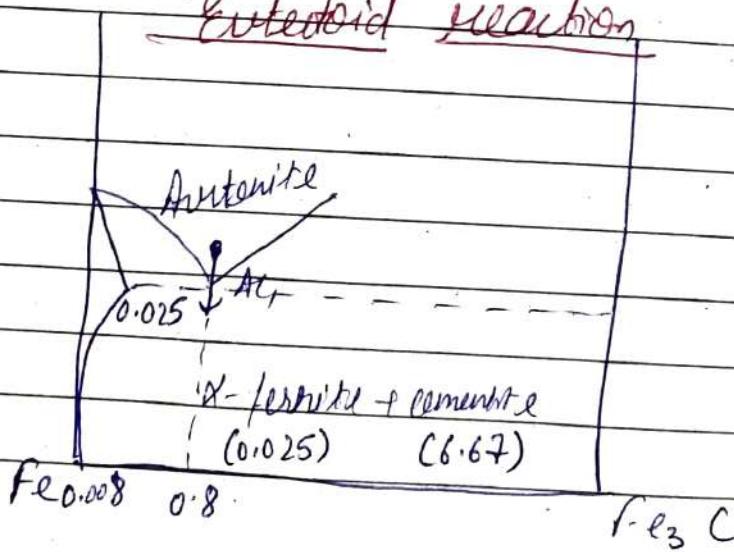
I. In case of general low alloy steel the diagram is very much similar to eutectoid steel.

II. In case of certain special steel, pearlite bay & bainitic bay are ~~not~~ separated i.e. it has shifted towards the extreme right. This kind of TTT diagram are useful in case of thermo-mechanical treatment.

III. In this case, alloying elements are austenite stabilizers which favour the transform to pearlite. These alloying elements also lowers the  $M_s$  temperature to subzero temperatures. Thus, the bainitic bay also shifts towards subzero temp. hence it is not indicated in the diagram.

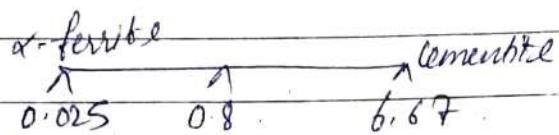
IV. Most of the alloying elements present are not austenite stabilizers hence pearlite transform is not favoured. Therefore, only the bainitic bay is indicated.

### Eutectoid reaction

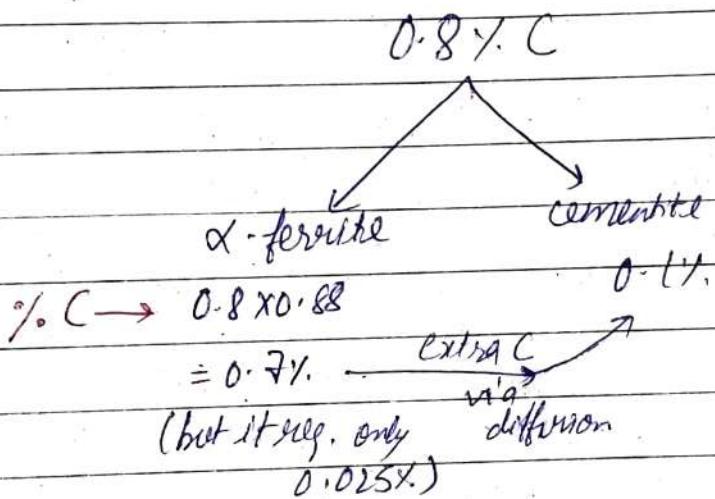


Let us consider an eutectoid steel

$$\begin{aligned} f_{\alpha\text{-ferrite}} & \text{ just below } 723^{\circ}\text{C} \text{ at } 0.8\% \text{ C} \\ & = 0.88 \\ & = 88\% \end{aligned}$$



$$f_{\text{cementite}} = 0.12$$

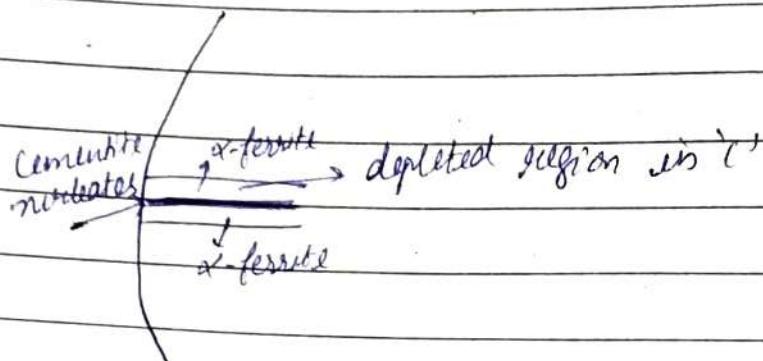


Annealing  $\rightarrow$  coarse pearlite

Normalizing  $\rightarrow$  fine pearlite

When no time is given, carbon gets no time, so carbon is enriched & hence C is more which is in case of tetragonal  $\alpha$  (BCT) hence it is of martensitic structure.

## Austenite to pearlite transform" mechanism.



Since density of  $\alpha$ -ferrite is less & cementite lamallae is similar & the fraction of  $\alpha$ -ferrite is 7 times more than cementite hence the width of  $\alpha$ -ferrite lamallae is almost 7 times than that of cementite.

Cementite nucleate first at Austenitic OB. As com. intakes more carbon, so neighbouring region gets depleted in carbon, which activates the process of nucleation & growth & thus favours the form of  $\alpha$ -ferrite.

### Limitation of Fe-Fe<sub>3</sub>C, TTT diagram

- Fe-Fe<sub>3</sub>C → doesn't show non-eq<sup>m</sup> cooling (applicable for slow undercooling which is not applicable for most cases)
- doesn't show about Bainite & Martonite
- unable to tell kinetics & phase transform.

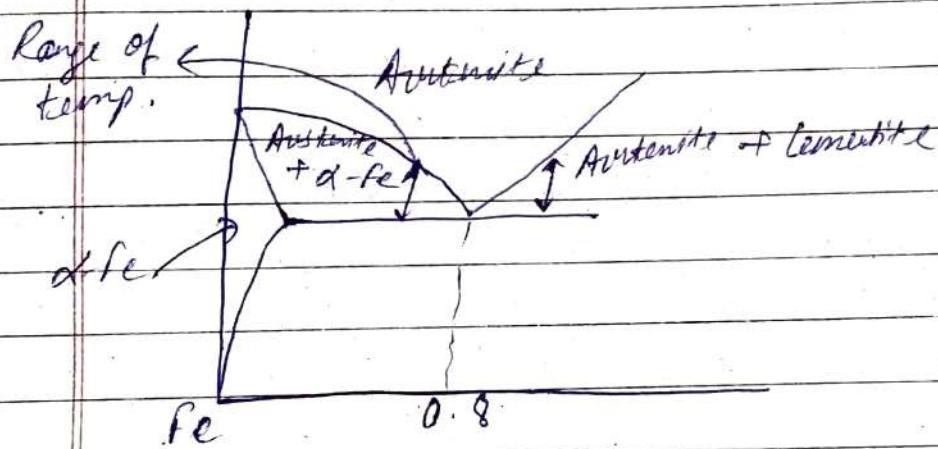
TTT → It is isothermal which is not practical in most of the cases. Since there is continuous cooling in most of the cases.

→ Eutectic means having lowest m.p. that is why it is named so.

Date \_\_\_\_\_  
Page 19

## Transform" to Austenite:

- Mechanical prop. depends upon microstructure.
- Mech. prop. can be modified by altering the morphology.
- Morphology → Shape  
Size  
Distrib'n of microconstituents
- Morphology also depends on whether austenite is of fine grain or coarse grain.



In case of eutectoid steel, transform" takes place at a single temp.

But in hypod hypers, it takes place at various range of T.

i. C is  $\alpha$ -Perlite  $\rightarrow 0.025$

ii. C is cementite  $\rightarrow 6.67$

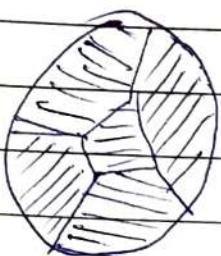
ii

Here carbon gradient is prevailing, but the microstructure is still same as at this temp.

difference of C is negligible. (Diffusion of C becomes substantial only around

$AC_3$  temp ( $713^\circ C$ )

Case 1: Eutectoid Steel



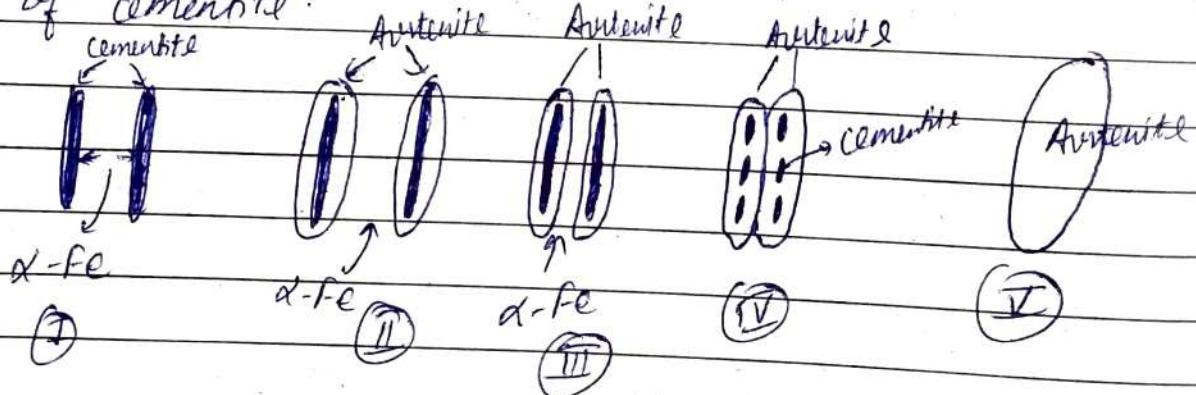
Cementite (Blue line)  
 $\alpha$ -Fe (Black Spots)

→ (Room T microstructure is 100% pearlite)

→ Orient' of lamellar structure is diff - as each grain is different.

$\alpha$ -Fe + cementite lamellar layers are in close contact with each other.

→ Density of both are same & fraction of  $\alpha$ -Fe  $\Rightarrow$   $\frac{1}{2}$  fraction of cementite.



→ From left to right dis' b/w two cementite plate decreases.

Stage I : (Room temp. stage)

Two cementites & b/w them  $\alpha$ -Fe is there width of  $\alpha$ -Fe  $\Rightarrow$   $\frac{1}{2}$  width of cementite -

Since cementite &  $\alpha$ -Fe lamellae are in close contact & surface of cementite is enriched in carbon. So, nucleation of austenite begins at interface b/w cementite & ferrite.

### Stage II

Austenite has started growing at interface close to cementite.

So, it is growing at the expense of  $\alpha$ -Fe that means  $\alpha$ -Fe is dissolving into austenite.

### Stage III

Austenite is growing at a very fast rate by dissolving  $\alpha$ -Fe.

Q.) Why austenite is growing at a fast rate?

Ans) i)  $\alpha$ -Fe is changing into  $\gamma$ -Fe above  $723^{\circ}\text{C}$ .

(Austenite) (as austenite is giving C to  $\alpha$ -ferrite which changes to austenite)

ii) Diffusion of carbon from austenite to  $\alpha$ -ferrite.

### Stage IV

Some streaks of cementite are still there.

→ Since cementite has more carbon & all the carbon must diffuse. That is why dissolution of cementite into austenite takes much longer time.

The austenite thus obtained (stage IV) at  $723^{\circ}\text{C}$  is not homogeneous in C content because the austenite which has formed adjacent to cementite has more C & austenite which has formed adjacent to  $\alpha$ -Fe has less carbon. Therefore to make austenite homogeneous, it is heated above  $A_1$ , temp. & also hold it is done for sufficient time so that austenite is homogeneous.

(Ans 2)

### Hypoeutectoid steel

Room temp. microstructure is proeutectoid  $\alpha$ -Fe + Pearlite.

Above  $723^\circ$   $\rightarrow$  <sup>Pearlite</sup> <sub>Austenite</sub> changes to <sup>Austenite</sup> Pearlite + pro-eutectoid  $\alpha$ -Fe continues dissolving into austenite.

Nucleation of austenite takes place at the interface of  $\alpha$ -Fe and cementite present in pearlite. As the T goes up more & more of austenite is nucleated & also growth takes place. As austenite grows it keeps on dissolving pro-eutectoid  $\alpha$ -ferrite.

The austenite obtained at  $Ac_3$  is not homogeneous. Hence the specimen is heated slightly above  $Ac_3$  to obtain homogeneous austenite.

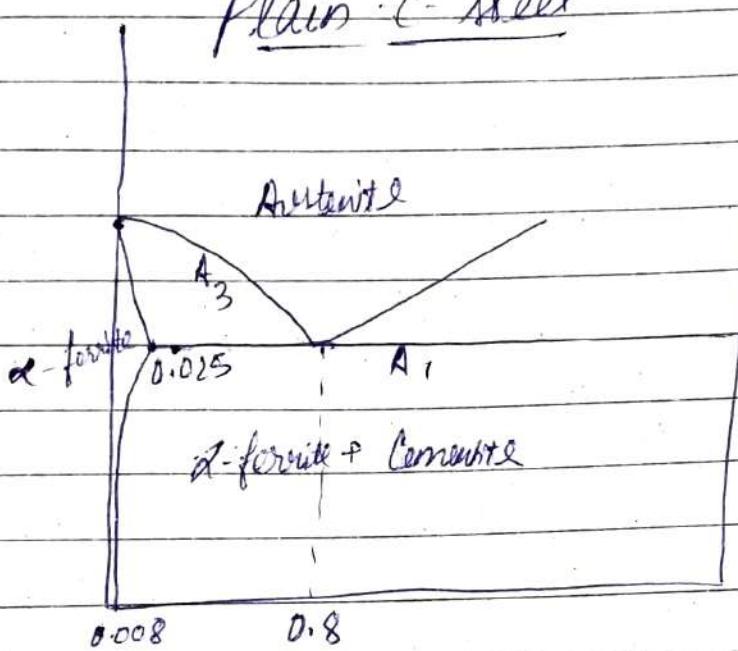
(Ans 3)

### Hyper-eutectoid steel

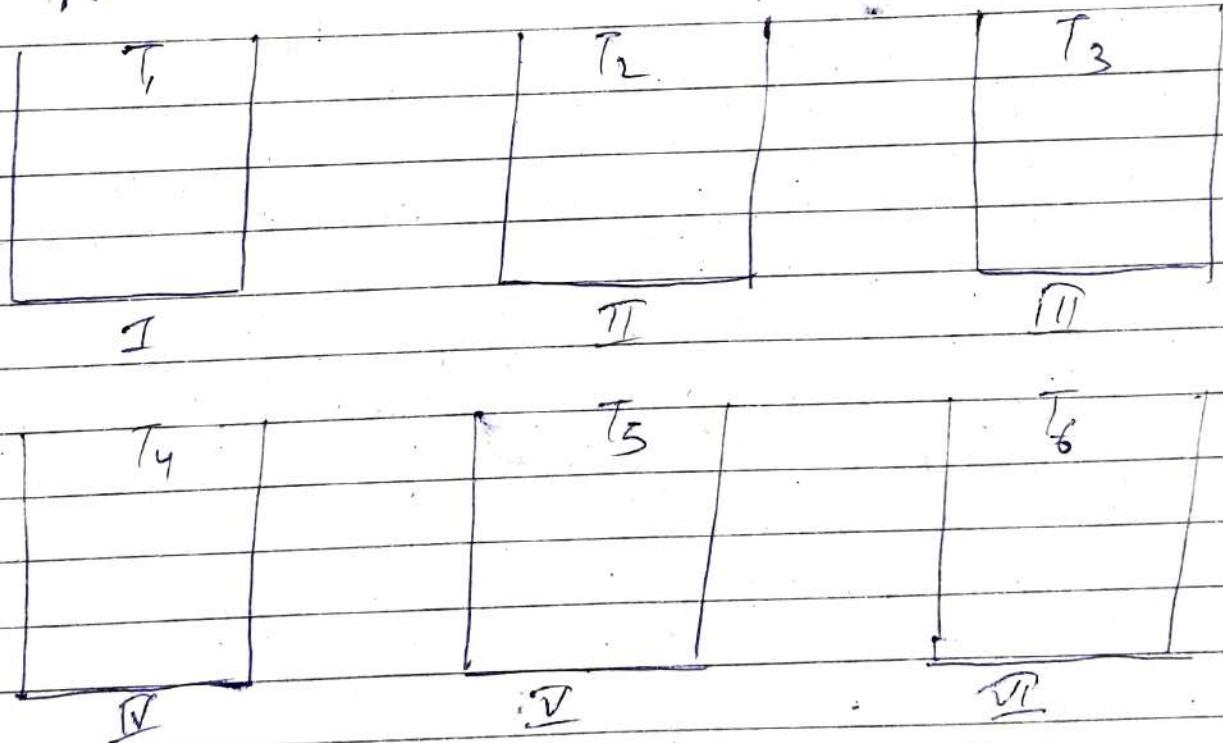
Room temp. microstructure is pro-eutectoid cementite & pearlite.

Austenite starts nucleating around  $A_1$  & grows with increase in temp. As austenite grows, it keeps on dissolving pro-eutectoid cementite. At  $Ac_m$  temp. the obtained austenite is not homogeneous. Therefore to obtain homogeneous austenite ( $\gamma$ ), the specimen is heated just above  $Ac_m$  temperature.

## Kinetics of Transformation (Pearlite to Plain C-Steel → Austenite)



### Experiments



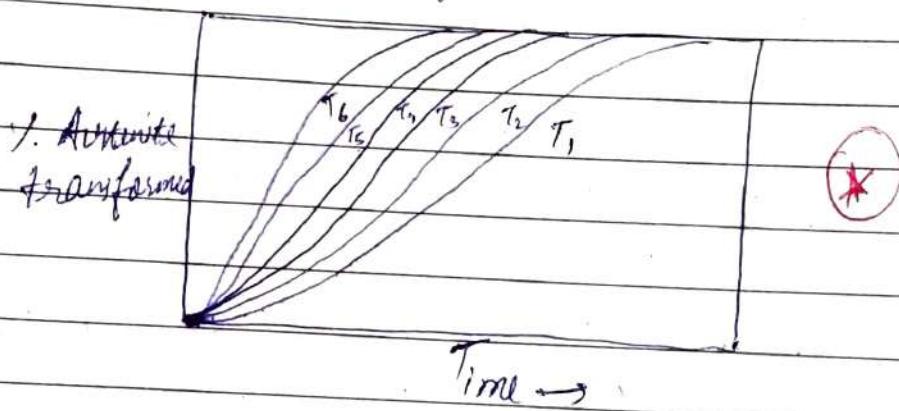
A large no. of samples taken so that  
There are bath maintained at diff. T. such

that

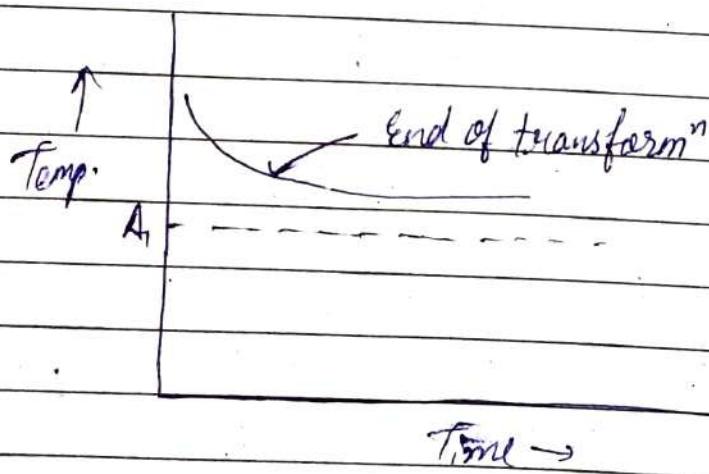
$$T_6 > T_5 > T_4 > T_3 > T_2 > T_1 > \text{AC}_1 (723)$$

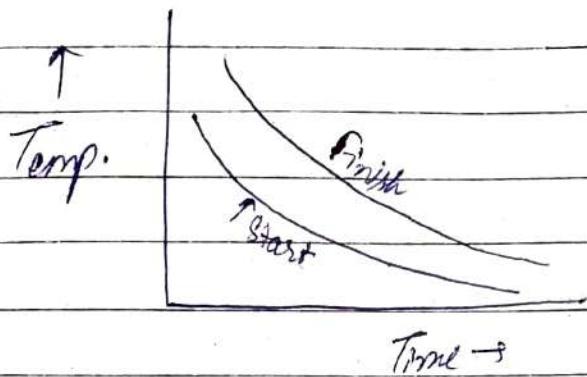
Specimens are dipped into the bath & taken out one by one & then quenched.

After quenching martensite will form & fraction of martensite depends upon fraction of austenite transformed.



$T_1$  is lowest temp., so it is taking most time





"Transform" will begin above  $A_c$ .

From all these plots we arrive at conclusion, transform to austenite depends upon holding temp. & holding time.

This plot does not give any inform' abt. the homogeneity of austenite.

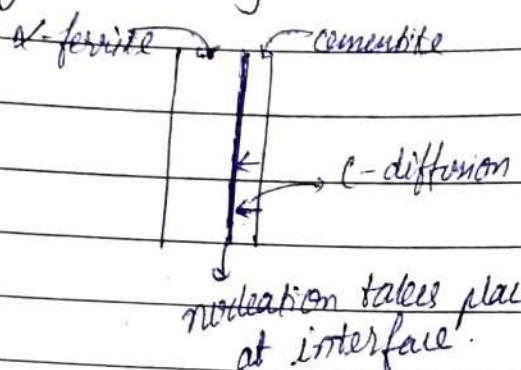
→ "Transform" to austenite takes place by nucleation & growth. So the factors which affect nucleation & growth of austenite will affect the kinetics of "transform".

(1) Nucleation takes place at the interface of  $\alpha$ -ferrite & cementite.

(2) Rate of nucleation thus can be increased by increasing the interface area.

Interface area can be increased by increasing the cementite content even at 0.8 v.c., it can be done by increasing C-content further. Thus, "transform" to austenite in case of high C steel is quicker than low-C steel.

2) By decreasing the interlamellar spacing.



If the interlamellar spacing is decreased, then C-atoms have to travel a smaller distance. This will result in faster nucleation and growth of austenite.

That is why, transform<sup>n</sup> to austenite in case of coarse pearlite is slower.

Transform<sup>n</sup> to austenite from granular cementite is slower (as interface area is less).

Globular cementite - Transform<sup>n</sup> to austenite in form of globules is also slower.

For Alloy Steel (Pearlite to Austenite)

Kinetics is greatly affected by nature of alloying elements. If the alloying elements are carbide formers no complex carbides should be formed (other than  $\text{Fe}_3\text{C}$ ).

These complex carbides do not dissolve easily into

• austenite, hence transform to austenite is delayed.  
 • To reduce the time, the holding temp. is raised. All carbide formers are mostly heavier than carbon iron atom, so there rate of diffusion is slower than Fe atoms. Hence the rate of dissolution of complex carbides is slower than  $Fe_3C$ . Hence to increase rate of diffusion of strong carbide forming elements the temperature is raised further.

\* Holding temp. in case of high speed steels is  $1050^{\circ}C$

### Importance of Austenitic Grain Size

1) Ductility & Strength

$$\sigma_0 = \sigma_i + k_y D^{-1/2}$$

2) Impact trans<sup>n</sup> temperature

3) Creep strength

Equistressure temp.

4.) Fatigue strength

5.) Hardenability

6.) Machinability

1)  $\Rightarrow$  Hall-petch eq<sup>n</sup>

$$\sigma_o = \sigma_i + k_y D^{-\frac{1}{2}}$$

$\sigma_o$  - YS

$\sigma_i$  - frictional stress which opposes movement  
of dislocations.

$k_y$  - extent of dislocation pile up at the GB.

D - Average diameter

Decrease in grain size, increase YS.

This criteria was used in development of  
NSLA steels

Microalloy  $\Rightarrow$  % alloying elements  $< 0.5\%$ .

$\rightarrow$  Microalloying increases the response to heat treatment

2)  $\Rightarrow$  Impact transition behaviour

(DBTT)

With decrease in grain size brittle to brittle trans<sup>n</sup> temp. (or impact trans<sup>n</sup> temp.) is lowered & vice versa.

Creep strength

3)  $\Rightarrow$  Although there is not any definite relationship correlating creep strength with grain size but it has been observed that creep strength is higher in case of worse grain size above equicohesive temp. but below equicohesive temp., creep strength is more in case of fine grain size.

Equicohesive temp.

It is the temp. at which coherency strength of CrBs is equal to ~~is~~ the strength of the interior of the crystal.

Fatigue strength

There is no definite reln b/w fatigue strength & grain size but it has been observed that FS is greater in case of small grain size.

Hardenability is higher in case of worse grain size.

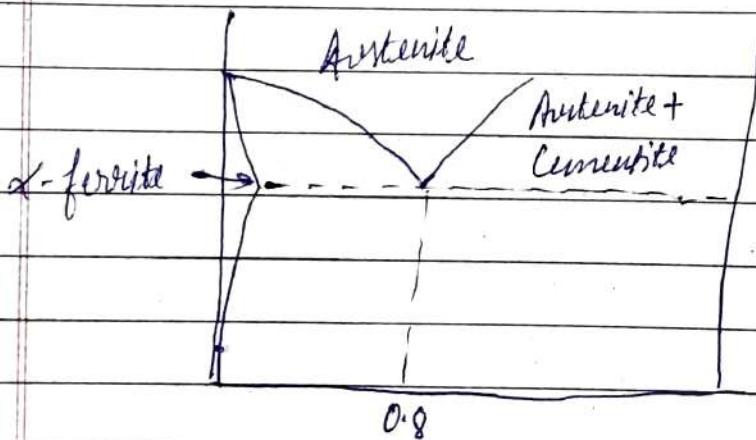
Nucleation of ~~without~~ pearlite takes place at austenitic grain boundary. So, nucleation & growth of pearlite will depend upon CrB area. If CrB <sup>area</sup> is large pearlite

"form" will be favoured but pearlite is a softer phase hence not desired. Therefore to suppress the tendency for "form" of pearlite the C<sub>3</sub>B area should be small. The coarse grains has less boundary area.

### ⇒ Machinability

Coarse grain size material has higher machinability as it comes out in the form of discontinuous chips.

### Austenitic Grain Size



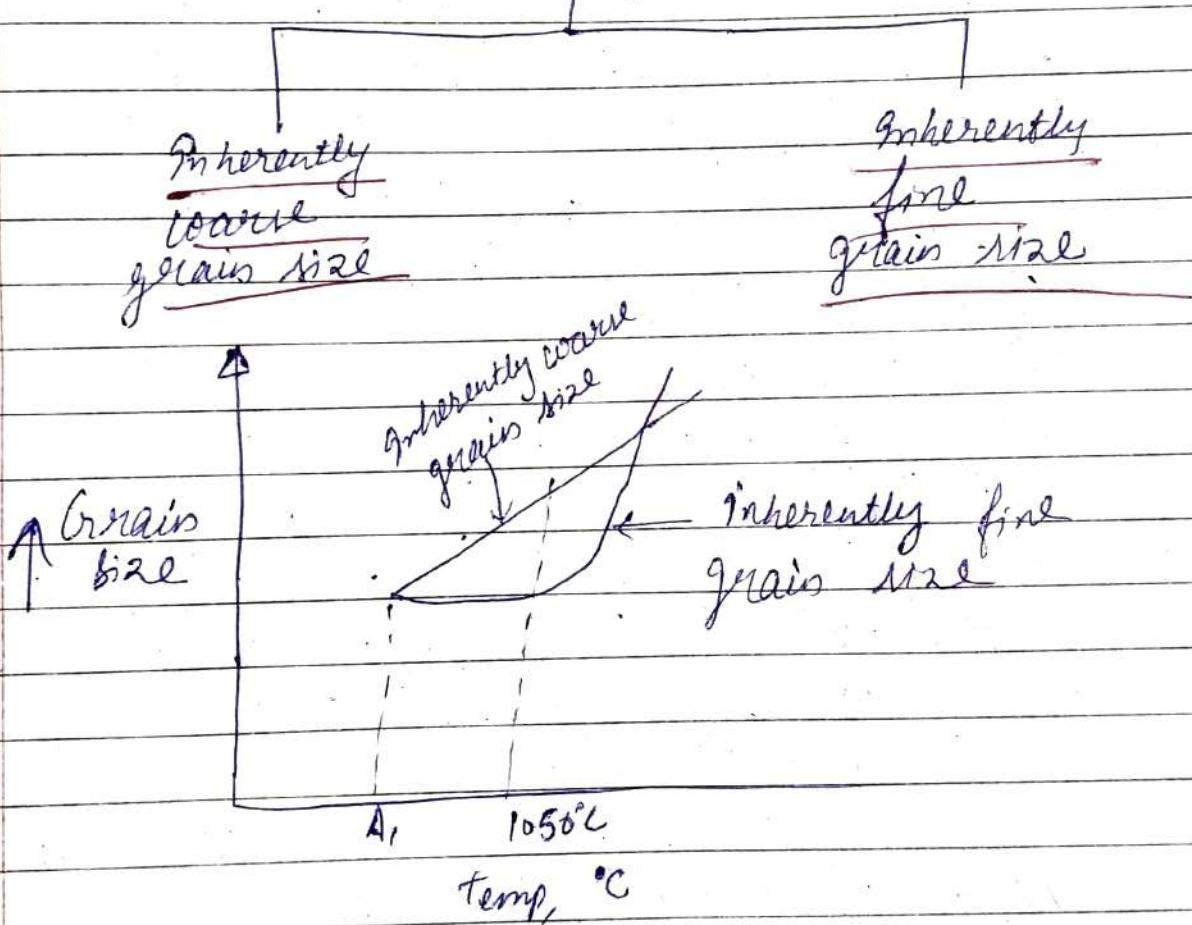
During slow heating of eutectoid steel to just above A<sub>1</sub>, it transforms to austenite which is in-homogeneous. (C-content is variable).

Size of austenitic grains, at this stage is known

As original austenitic grain size.

To make it homogeneous, the temperature needs to be raised further. This will cause a little grain coarsening. The grain size at this stage is known as actual austenitic grain size.

### Actual austenitic grain size



The inherently fine grain size nature is due to the presence of AlN, BN, TiN which are basically refractory materials. These compounds are formed when

Al, B or titanium are used as deoxidizers in steel making. These compounds segregate at the austenitic grain boundary & thus resist the growth of austenitic grains.

Beyond 1050 °C, these compounds start dissolving into the matrix & hence growth rate increases. Since, the austenitic grains now face no resistance the rate of growth is even faster than inherently coarse grain size.

### ASTM

#### Austenitic Grain Size

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

n - no. of grains per square inch when viewed at magnification of 100X.

N - Austenitic grain size number.

(\*)

## DBTT

(\*) Cottrell-Petch eqn

$$(\tau_i D)^{1/2} + \kappa' k' = C_s D_s \beta$$

$\tau_i$  = resistance force to dislocation movement

$\gamma_s$  = eff. surface energy.

$k'$  = parameter dictated to dislocation pile up.

$\beta$  = const. (ratio of shear stress to normal stress)

If  $D \downarrow$   $\tau_i \uparrow$  so  $T \downarrow$   
(DBTT)

i.e. for fine grain size DBTT is lowered.

If  $U_{IS} < R_{MS}$

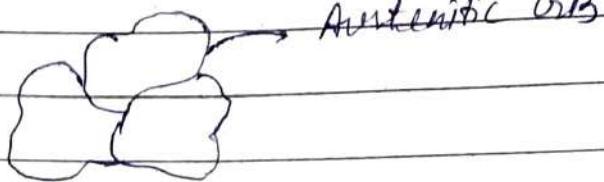
→ microcrack can be formed but cannot grow.

$U_{IS} > R_{MS}$

→ crack propagates into brittle fracture at a  
shear stress equal to  $\gamma_S$

## Measurement of Austenitic Grain Size

1) Revealing Austenitic grain Boundary by metallurgy



2 categories:-

- (a) Change in chemical compn is involved
- (b) No-change in chemical compn

(a) → Carburation resulting in chemical change  
 → Oxidation " "

Carburation process is suitable for low-C steels as extra C has to be diffused.

→ The sample is heated to a temperature of  $925^{\circ}\text{C}$  for 8 hours in a packed carburation bed (like breeze) & then it is allowed to cool in the packed bed itself. As a result of this treatment, the carbide gets precipitated along austenitic GrB. So, when the sample is etched austenitic GrB is revealed etc clearly. This test is known as Mc Quaid Ehn Test.

## Oxidation

The Specimen is heated into the austenitic range in an oxidizing atmosphere for a brief period of time & then it is cooled slowly to room temp. Since, austenitizing is carried out in oxidizing atmosphere, "grid" of the specimen will take place along ~~the~~ the austenitic GB.

[Heated for brief period]

Thus after etching austenitic GBs are revealed.

b) No. chemical change

→ Hypo-eutectoid steel

Separation of pro-eutectoid phase starts from austenitic grain boundary. The moment sep' of pro-eutectoid phase starts, the sample is quenched (or cooled rapidly) to room temperature. Thus the austenitic GB is revealed exactly from where the sep' of pro-eutectoid had started.

→ Hyper-eutectoid steel

Same technique is used in this case too

but here pro-eutectoid cementite is formed instead of pro-eutectoid  $\alpha$ -ferrite (as in case of hypo)

### $\rightarrow$ Eutectoid steel

In eutectoid steel there is no pro-eutectoid phase but with very controlled heat treatment nodules of cementite are formed at the austenitic grain boundary. Quick cooling to room temp. reveals austenitic CrB.

After cooling, the austenite may transform to pearlite but cementite (nodular) form at austenitic CrB, persists at the GB which can be revealed by etching.

### Methods of determination of Austenitic grain size

#### 1) By comparison with standard chart

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

ASTM E112-63  $\Rightarrow$  ASTM E112-1985  
Modified

$$C_2 = -2.9542 + 1.4427 \ln n_a$$

$$n_a = \text{no. of grains / mm}^2 \text{ at } 1x$$

In eyepiece - 8 glass discs are fitted which can be rotated.

Each disc is engraved with regular hexagons of different size ranging from 1 to 8.

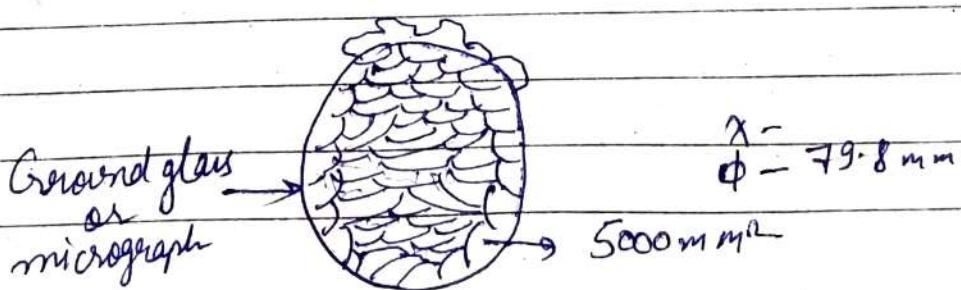
If grain size no. is less than 3, then it is treated as coarse grain size.

If ~~N > 3~~ (5 to 8), then it is treated as fine grain

But in case of high speed steel, the grain size is in the range 9-10. If ~~N~~ has been partially substituted by ~~N~~, then grain size no. is equal to 10 (very fine).

When austenitic grain boundary is observed under optical microscope, the glass discs are rotated to find the exact grain size.

(2) Jefferies Planometric method:- (suitable for equiaxed grains)



Micrograph  $\rightarrow$  image of microstructure

The magnification should be such that 50 grains should be present inside that iron-section area covered should be  $5000 \text{ mm}^2$

The grains falling inside the circle is taken as 1.  
" " which is intercepted is taken as  $\frac{1}{2}$ .

So,

Total no. of grains in  $5000 \text{ mm}^2$

$$n \Rightarrow n_i + \frac{n_c}{2}$$

$n_c \rightarrow$  no. of grains lying on circumference

$n_i \rightarrow$  no. of grains lying completely inside the circle/  
cross-section

Then

$$n_i \Rightarrow 2n \left(\frac{m}{100}\right)^2$$

$m \rightarrow$  linear magnification

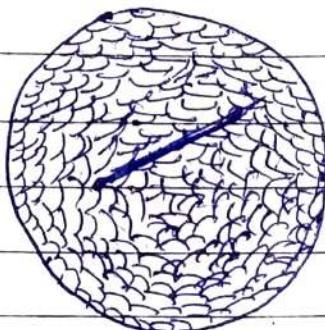
$n_i \rightarrow$  no. of austenite grain

So,

$$C_2 \Rightarrow -2.8542 + 1.4427 \ln n_i$$

$\rightarrow$  If we have mixed grain size then it is commonly expressed as %age of area occupied by each of the size.

3) Heyn's Intercept method. (Suitable for small grain size)



→ These days calibrated eyepieces are used.

An intercept is drawn of length 0.005 inch.

All the intercepted grains are counted as 1.

End pt grains are taken as  $\frac{1}{2}$ .

And magnificy is  $\times 1000$ .

Let the no. of grains intercepted by linear length of 0.005 inch at  $\times 1000 = I$

Then no. of grain per inch at  $\times 1000 \Rightarrow \frac{I}{0.005} = 200I$

No. of grains per inch at  $\times 100 \Rightarrow \frac{200I}{100} = 2I$

No. of grains per sq. inch =  $n = (2I)^2$

From ASTM grain size calculate

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

$$4I^2 = 2^{W-1}$$

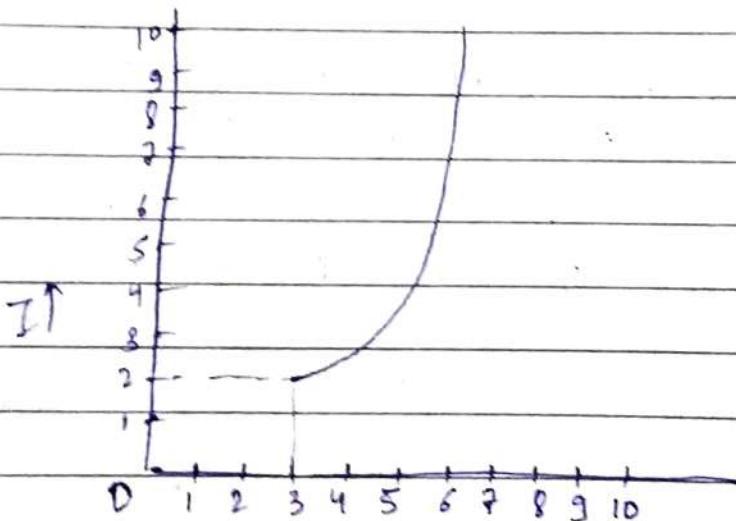
$$\log 4I^2 = (N-1) \log 2$$

$$\Rightarrow \frac{\log 4 + 2 \log I}{\log 2} = N-1$$

$$\Rightarrow \frac{\log 4}{\log 2} + \frac{2 \log I}{\log 2} = N-1$$

$$\Rightarrow 2 + \frac{2 \log I}{\log 2} = N-1$$

$$N = \frac{2 \log I}{\log 2} + 3$$



ASIM grain size  $\rightarrow$

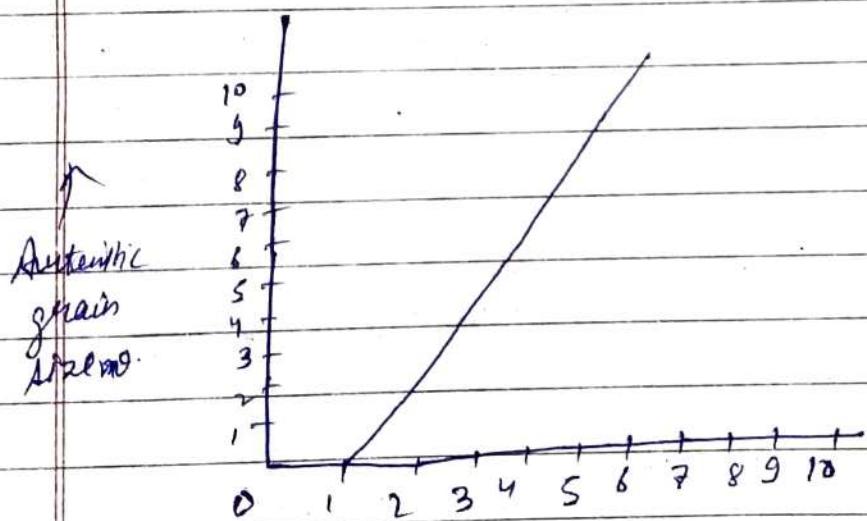
fig. 60-rel<sup>4</sup> by 2 grain size no. & Hegn's intercept (?)

## 4) Shephered fracture test -

→ Steel sample is heated to hardening temp. than it is quenched. So, the austenite grain size persists at room temp.

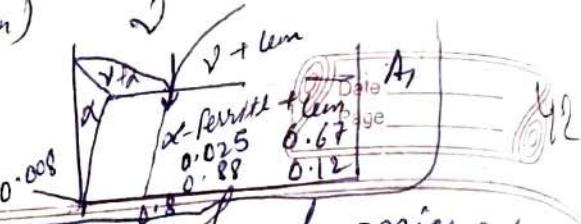
sample is fractured revealing grain size.

Prior to this standard test specimens are fractured & their grain size are numbered from 1 to 10. These no. are known as shepherd fracture test no. Now the grain size of the test specimen is compared with n value of standard test specimen.



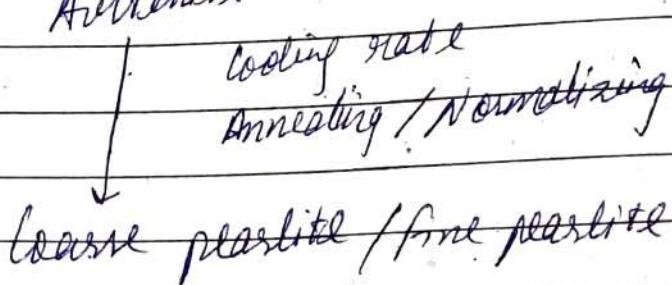
Shepherd fracture no. →

Austenite  $\rightarrow$  Pearlite (Mechanism)



When austenite is cooled the final microstructure depends on the cooling rate.

Austenite



Above A, Austenite has 0.8 atom% of C

$$\therefore \% \text{ C in } \alpha\text{-Fe} = (0.8 \times 0.88)\% = 0.71\%$$

$$\Rightarrow \% \text{ C in Cementite} = (0.8 - 0.71)\% = 0.1\%$$

So, there is a C gradient & there will be diffusion of C from α-Fe to cementite.

→ For form' of pearlite, the rate controlling step is rate of diffusion of 'C'

→ Also, pearlite is mechanical mixture of 2 phases  $\rightarrow$  α-ferrite + cementite

→ The nucleation of pearlite cannot start from inside the grain of austenite because the composition is homogeneous. Hence, nucleation of pearlite takes place at the austenite grain boundary (heterogeneous nucleation).

Nucleation may take place inside the grain in the presence of undissolved cementite

- Among the 2<sup>nd</sup> phase which nucleates first is called active nucleus
- A phase can be called active nucleus if it is present in the transformed microstructure & also it must have some "lattice orient" relationship with parent austenite



### Case I      Mehl's hypothesis

According to this hypothesis, cementite is active nucleus.

- The "orient" relationship of pearlitic ferrite & pro-eutectoid ferrite with parent austenite is different.
- The presence of undissolved cementite affects the transform to pearlite which  $\downarrow$  ferrite has no effect
- Pearlite cementite & pro-eutectoid cementite has certain "orient" relationship with parent austenite. Both are parallel to high index planes of parent austenite.



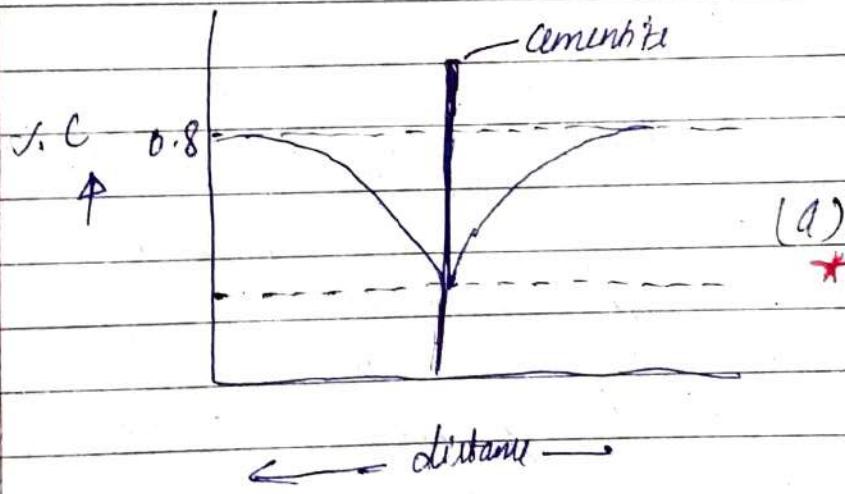
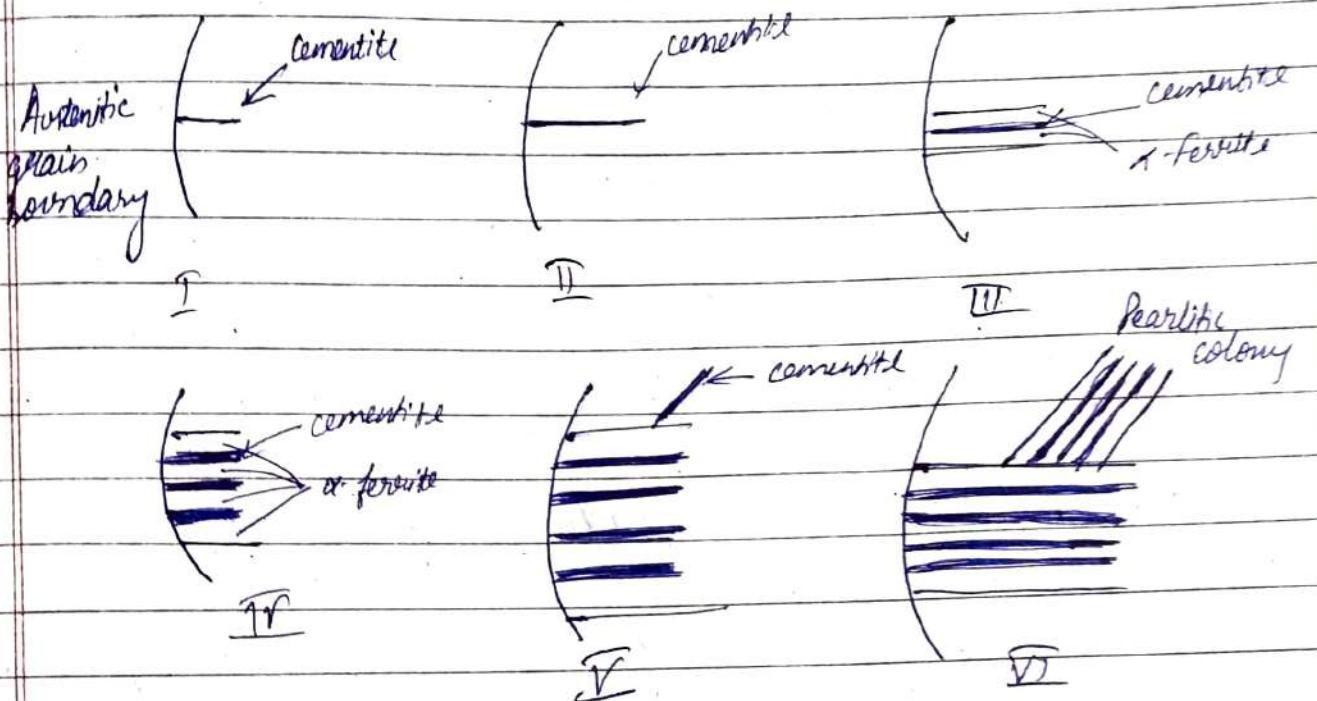
## Case 2: Smith's hypothesis

- Pearlitic ferrite & pearlitic cementite, both can be active nucleus it can have any orient<sup>s</sup> relationship with parent austenite except those which help us the form<sup>n</sup> of interfaces that are semi-coherent to parent austenite
- In general, in case of hypo-eutectoid steel  $\alpha$ -ferrite is active nucleus if in case of hyper-eutectoid steel, cementite is active nucleus

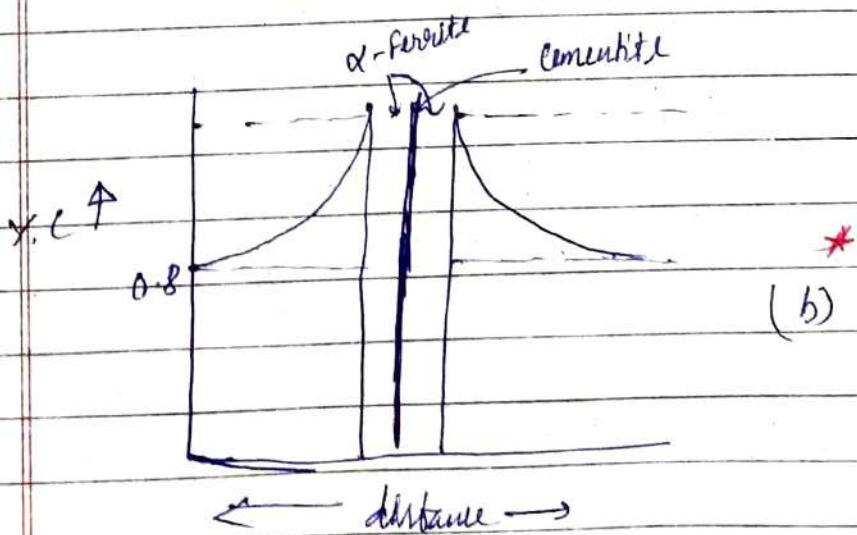
Coherent - If there is atom to atom matching b/w parent phase & the 2nd phase then the second phase is called coherent phase. If this is partial matching of atoms b/w parent phase & 2nd phase, then it is called semi-coherent phase.

And, if there is no matching at all, the 2nd phase is called incoherent phase.

## Hull-Mehl Model



Assumed level  
of ' $x_c$ ' for  
nucleation &  
growth of  $\alpha$ -ferrite



(b) Assumed level of  
' $x_c$ ' for nucleation  
& growth of  
cementite

Fig(a) & Fig(b)

Growing lamellae of  $\alpha$ -ferrite & cementite may nucleate each other.]

This model explains the form of lamellar pearlite.

~~Al to Melt - cem. is active model.~~

~~Al cem. grows from austenite orb.~~

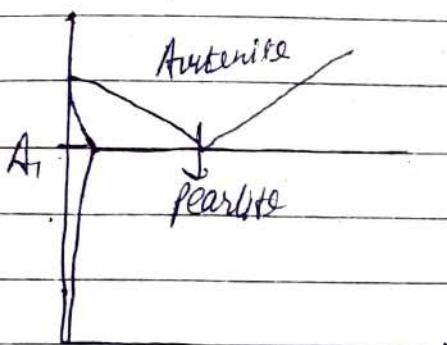
II: This is known as endwise growth of pearlite

sideways growth of pearlite or development of pearlite colonies.

The growth rate of pearlite lamellae is almost const., hence together, endwise & sideways (pearlite colony) is called pearlite nodules if spherical in shape. This process goes on till entire austenite is consumed.

When 2 pearlite colony meet each other, the growth is stopped & a boundary is formed.

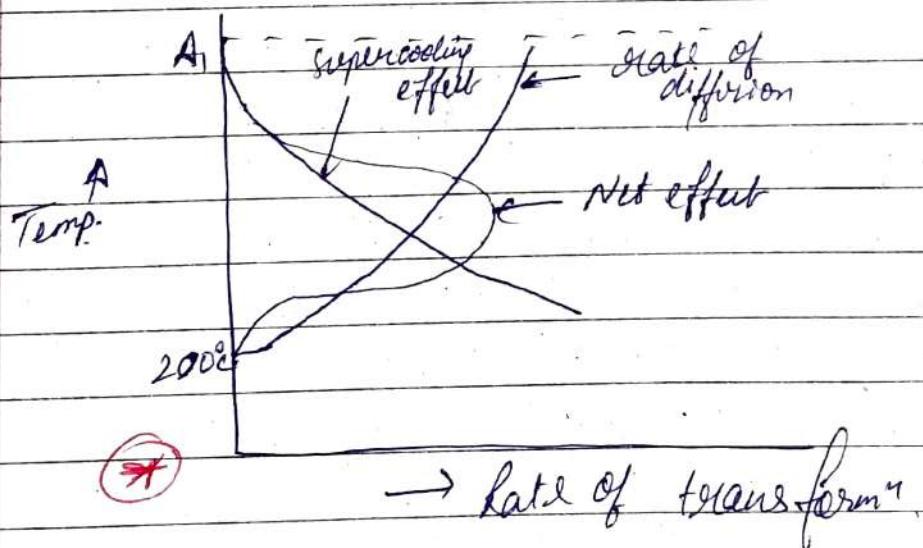
## Kinetics of Austenite - Pearlite transform



$$\Delta G = G_{\text{Pearlite}} - G_{\text{Austenite}} = 0$$

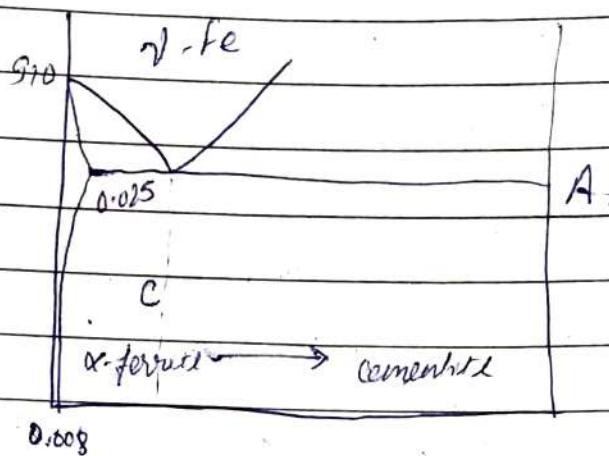
Transform will take place when  $\Delta G < 0$  i.e.  $G_{\text{Pearlite}} < G_{\text{Austenite}}$

Since pearlite is stable below  $A_1$ , therefore "transform" will take place at temperatures lower than  $A_1$ . The rate of "transform" of pearlite will depend upon degree of supercooling i.e. nucleation & growth of pearlite depends upon  $\Delta T$ .



At certain transform %, the rate of transform is max & then it will decrease & at around 200°C it is negligible.

## Martensitic Transform's -



Pearlite  
or  
Bainite

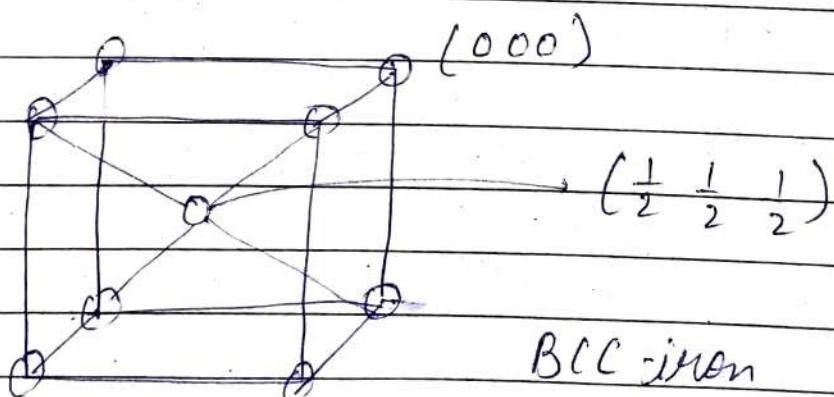
there is diff. of 'C' from  $\alpha$ -Fe to Cementite

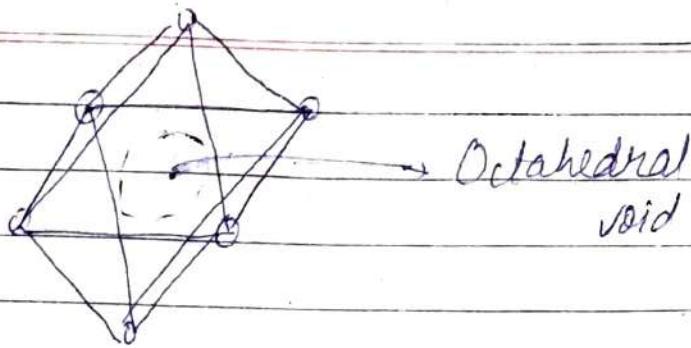
Solid state diffusion f(CT)

Austenite  $\xrightarrow{\text{quenched}}$   $c_{\text{in } \gamma\text{-Fe}}$   
 $c_{\text{in } \gamma\text{-Fe}}$   $\xrightarrow{\text{at RT}}$   $c_{\text{in } \alpha\text{-Fe}}$   
 Here

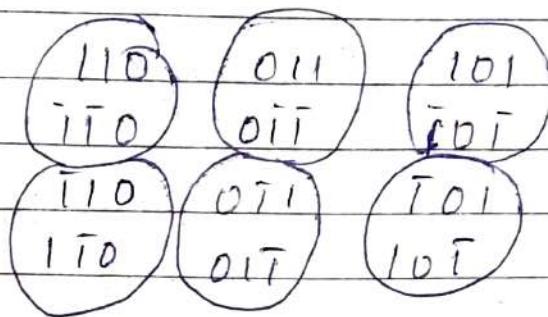
$$c_{\text{in } \gamma\text{-Fe}} \approx c_{\text{in } \alpha\text{-Fe}}$$

Martensite is supersaturated solid soln<sup>y</sup> of  
 'C' in  $\alpha$ -Fe as whatever 'C' is with  
 $\gamma$ -Fe it stays after quenching to RT.





BCC



$$\begin{aligned} & \langle 111 \rangle \\ & 6 \times 2 \\ & \text{planes} = 12 \\ & \text{directions} \end{aligned}$$

FCC

$$4 \times 3 = 12$$

$$\left. \begin{array}{l} \text{Planar size of Octahedral void} \\ = 0.414 \end{array} \right\}$$

$$T.V. = 0.225$$

Mechanism :-

P.t. Martensite	Interface parent phase (austenite)
--------------------	--

Driving force behind  $\gamma$ -Fe to Martensite transform

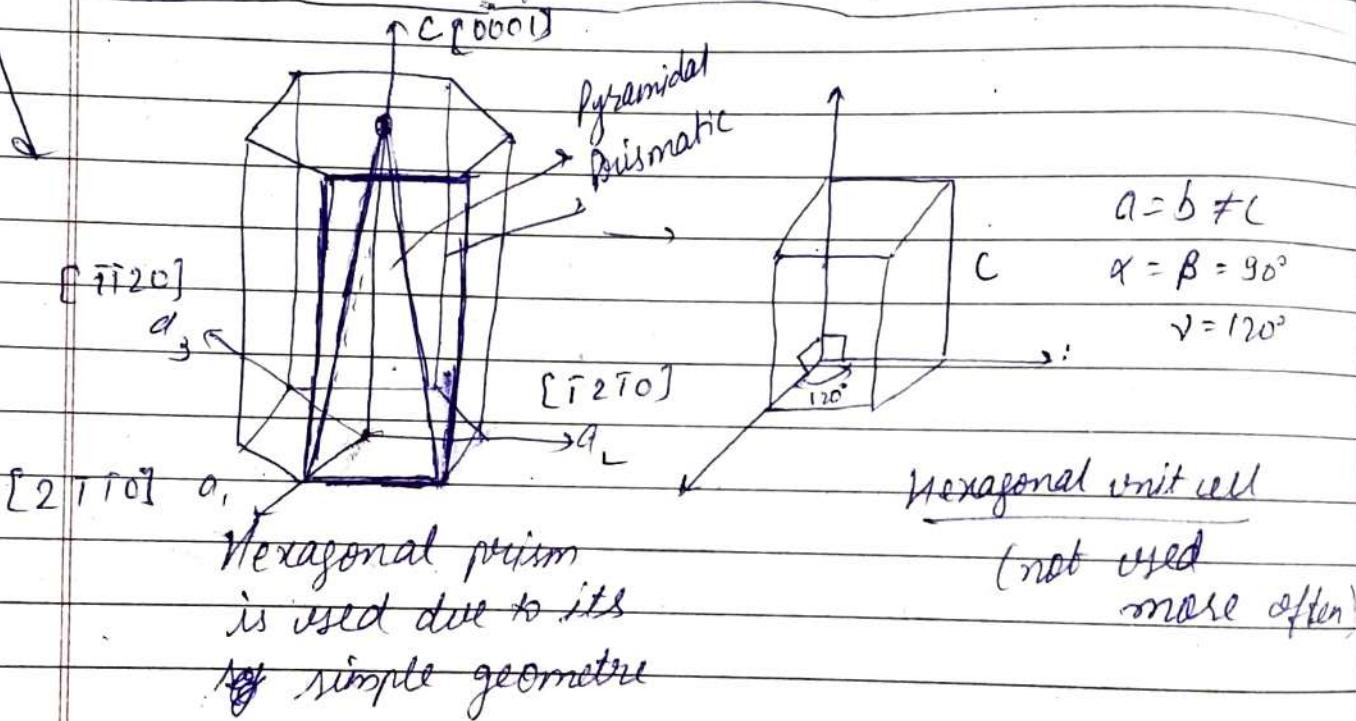
Driving force behind the transform is large free energy difference, which is negative.

Diffr is large as  $M_s$  is very low

HCP: -  $1 \times 3$  = 3 slip systems. But slip requires 6 systems.  
 Inside hexagonal prism so, turn takes place [largest possible plane direct]  
 Data \_\_\_\_\_  
 Page \_\_\_\_\_ So

There is a small movement of atoms.  
 This leads to

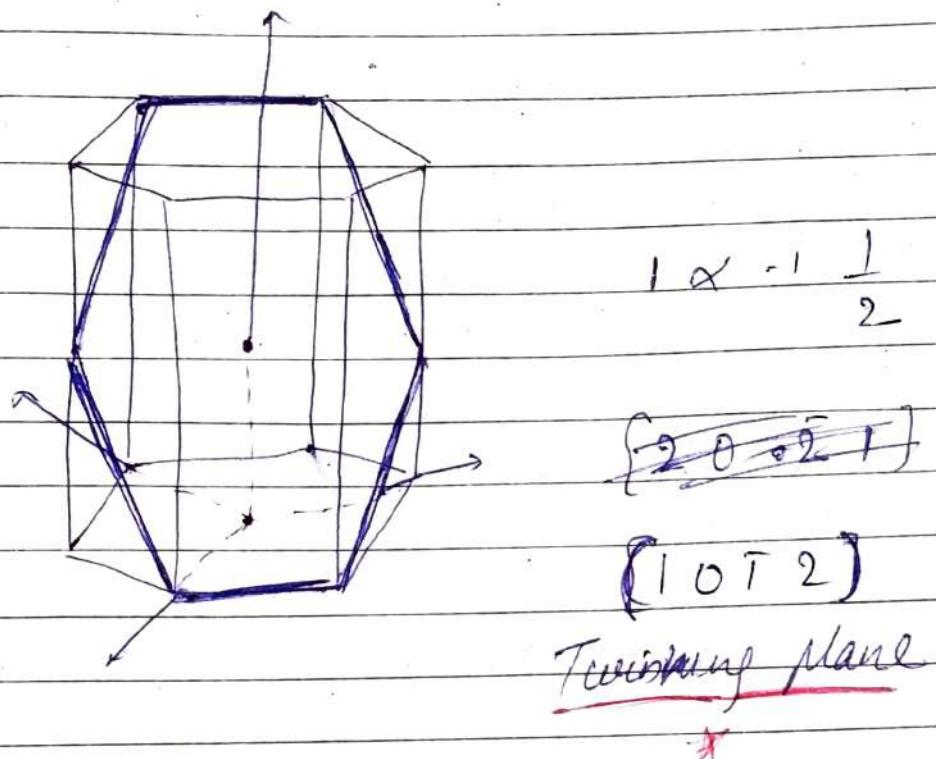
Habit planes are those planes on which martensite plates are developed. But the habit plane does not undergo any distortion similar to deformation twins.)



## Planes

- ↳ Basal plane  $(0001)$
- ↳ Prismatic plane  $(10\bar{1}0)$
- \* Pyramidal plane  $(10\bar{1}1)$

Largest possible plane inside HCP.



### M<sub>s</sub>-M<sub>f</sub> temperatures

$$\begin{aligned} M_s [^{\circ}\text{C}] = & \quad 561 - 474(\% \text{C}) - 33(\% \text{Mn}) \\ & - 17 (\% \text{Ni}) - 17 (\% \text{Cr}) \\ & - 21 (\% \text{Mo}) \end{aligned}$$

Y. C has a critical role in lowering M<sub>s</sub> temp.  
All other alloying elements also lowers M<sub>s</sub> temp. except Al & Co

Other factors which influence M<sub>s</sub> temp. -

- 1) Austenizing temp. - If austenizing temp. is high, more & more 'C' will dissolve into austenite. Hence M<sub>s</sub> temp. will be lowered.

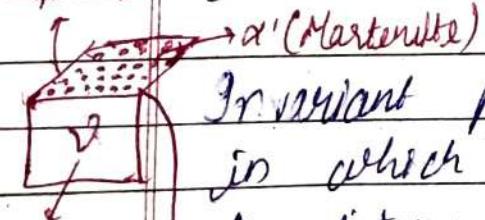
(A higher austenizing temp. results in grain coarsening & coarse grain in turn raises  $M_s$  temperature.)

2) Effect of stress - Martensitic transform<sup>n</sup> followed by plastic deform<sup>n</sup> raises the temp.

(If external stress favours the form<sup>n</sup> of martensitic plate then the temp. will be raised & vice-versa. But in reality,  $M_s$  temp. is not that affected because more than 1 habit plane is available for martensitic transform<sup>n</sup>.)

### \* Habit planes:

The basis of crystallographic phenomenological theory of martensite transformation is that there shall be an undistorted & unrotated interface b/w the martensite & the parent phase formed as a result of invariant plane strain.



Invariant plane strain is a homogeneous distort<sup>n</sup> in which displacement of atoms is proportional to distance from the invariant plane. This invariant plane is habit plane in case of low-carbon steel., habit plane is  $\{111\}$ , medium 'c' steel is

(displacement of atom is  $\propto$  to distance from habit plane)

(225) & high 'C' steel is (259)

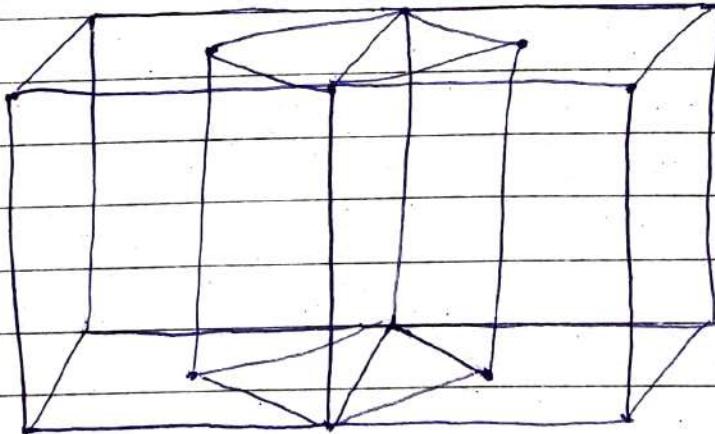
### Reversibility of Martenite

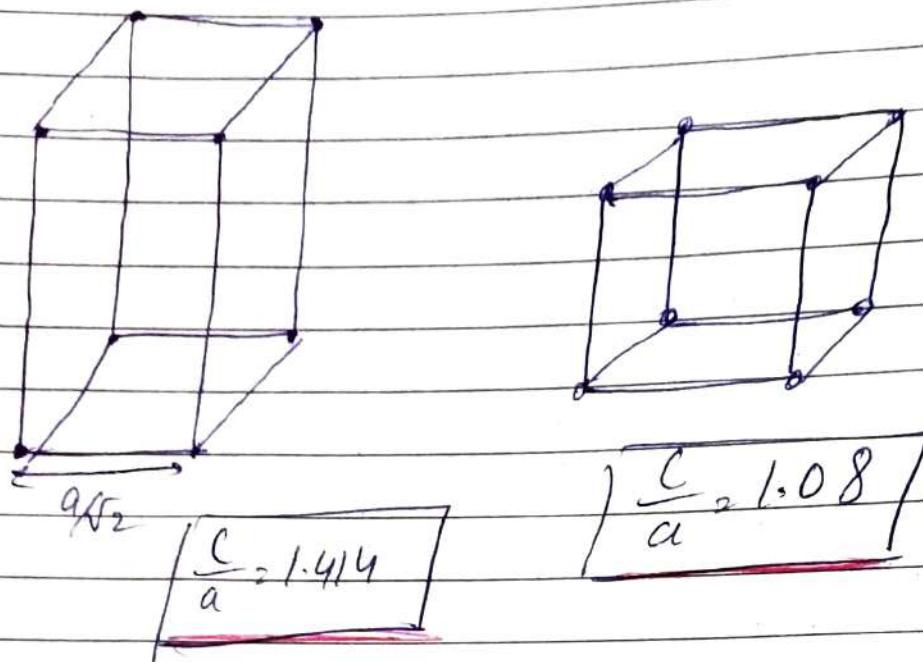
Martenite can be re-transformed into parent phase austenite, if it is heated above  $M_s$  temp. provided that there is no compositional change. But, since martenite is super-saturated with 'C', the diffusion of 'C' starts as it is heated above  $M_s$  temp.

Therefore, except in special cases, Martenite can't be re-transformed into austenite of same compns.

Exception case - Alloy carbide, sluggish rates of diffusion.

### Bain Distortion Model





This is Bain's distort<sup>n</sup> model which explain the movement of atoms in the transform<sup>n</sup> to austenite. According to Bain, the unit cell is compressed parallel to 'c' axis & extended. Also other 2 directions. In case of BCC,  $\frac{c}{a}$  is 1. Hence,  $\frac{c}{a}$  ratio of BCT martensite is nearer to BCC. Bain distort<sup>n</sup> model successfully explained the movement of atoms. However it fails to explain following.

- 1) It does not talk abt. shear deform<sup>n</sup>.
- 2) Since it assumes that all units cells are distorted, it fails to explain invariant plane strain.

## Hardness of Martensite

### Theories:

Hardness of martensite is due to the strains generated as it is a super-saturated phase.

Due to p.d. of parent austenite surrounding the martensitic plate.

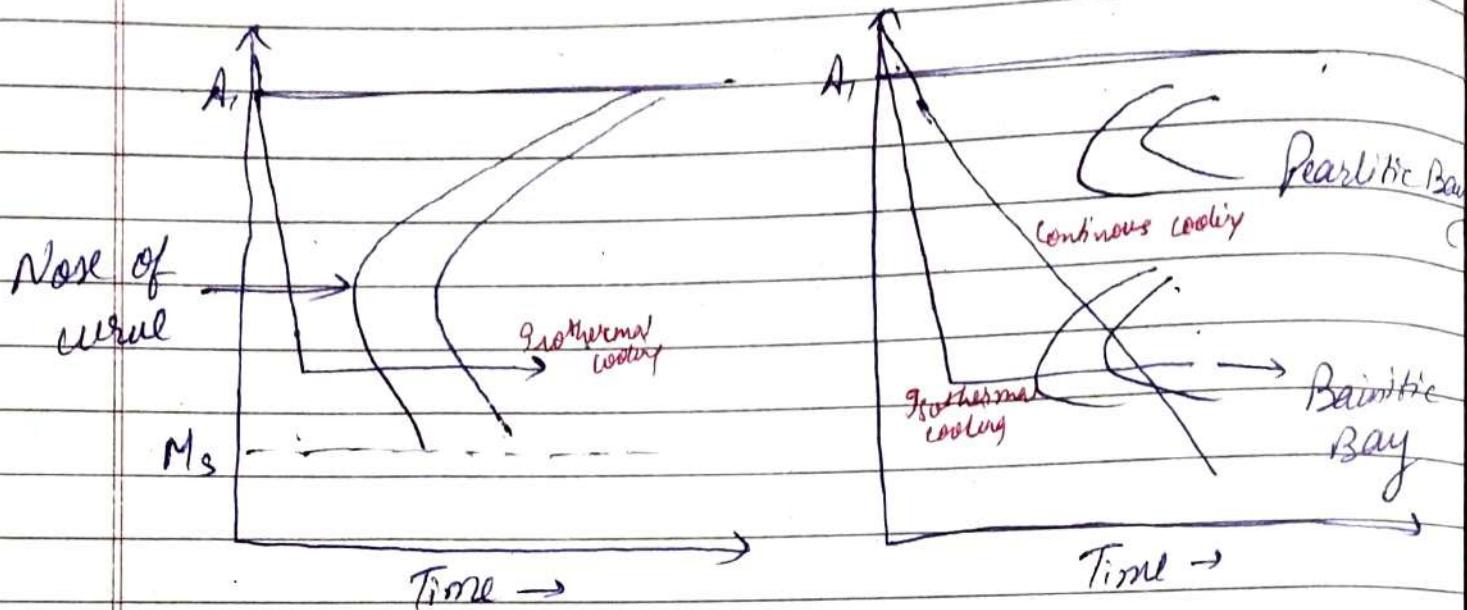
### Effect of 'C' content on hardness

A certain min<sup>m</sup> amt. of 'C' must be present for the form<sup>m</sup> of martensite in case of low 'C' steel, enough martensite is not formed hence hardness is low.

(In case of high 'C' steel, % of retained austenite ↑, which affects the hardness. As 'C' content increases,  $M_3$  temp. is lowered. This result is an ↑ in the retained austenite)

To ↓ retained austenite,  $M_3$  temp. may be raised. But if the  $M_3$  temp. is raised, the specimen may change undergo tempering which is called self-tempering which results in decrease in hardness.

## Bainitic Transform'



Bainite is the mechanical mixture of  $\alpha$ -ferrite + carbide + cementite.

### Difference -

- 1) Bainite normally forms just below ~~top~~ now of S<sub>E</sub> curve.
- 2) Bainite is not a lamellar structure.

Carbide is very finely dispersed in the  $\alpha$ -ferrite matrix. Hence, the microstructure can be observed only at higher magnific<sup>n</sup>.

If pearlitic bay & bainitic bay are distinct, then bainite can be formed by isothermal as well as continuous cooling.

But if 2 bays are not distinct, then bainite can be formed by isothermal cooling only.

Depending upon bainitic transform<sup>n</sup> temp. whether it is just below or just above  $M_s$  temp. it is classified as upper bainite when ~~above~~<sup>below</sup>  $M_s$  & when above  $M_s$ , lower bainite  
 (resembles pearlite)

Microstructure in upper bainite has feathery shape & lower bainite has circular shape  
 (resembles martensite)

Depending upon degree of dispersity of carbide in bainite it is classified as

- \* 1) Sorbite 2) Pearlite Troostite

### Mechanism

A large incubation period indicates that the bainitic transform<sup>n</sup> are dependent on rate of diffusion of 'C'. But, rate of diffusion of 'C' goes on ~~on~~<sup>with</sup> ↓ in temp. This means that some other mechanisms is also involved in transform<sup>n</sup>.

It has been observed that bainitic transform<sup>n</sup> are followed by surplus distort<sup>n</sup>. This means transform<sup>n</sup> also involves shear mechanism, thus, bainite transform<sup>n</sup> are bit complex.

18

## Austenite

Supercooled

Redistrib' of 'C'

\*

Low 'C' region

(different)

↓ by shear

High 'C' region

↓ ppt' of carbide

As a result,

Bainitic  $\leftarrow$  Ferrite

Ferrite

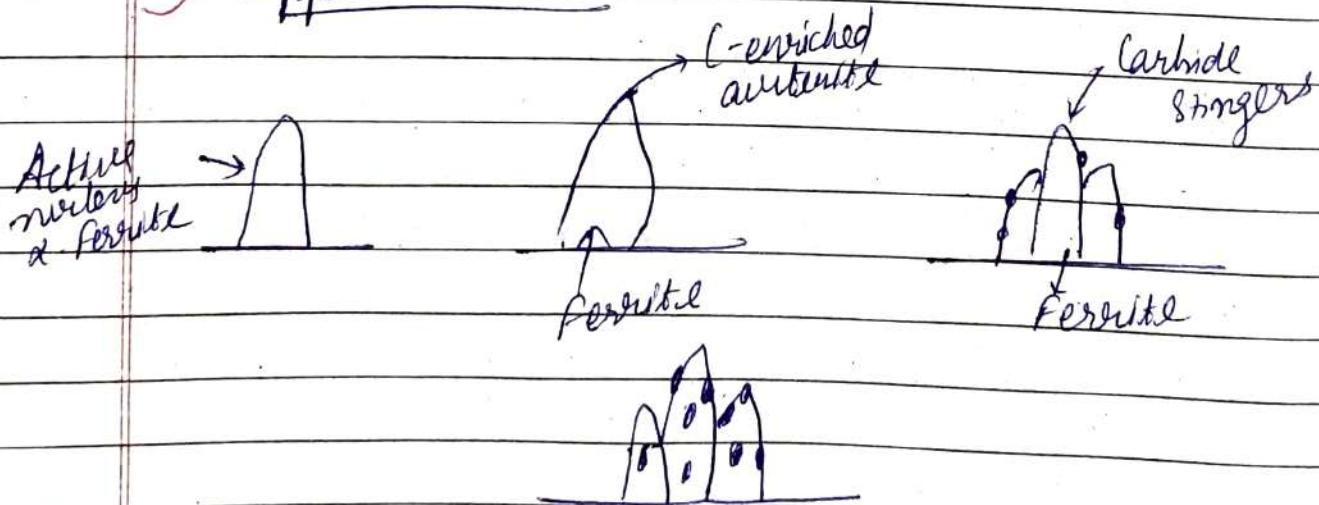
↓  
low 'C' austenite  
↓ by shear

Bainitic ferrite

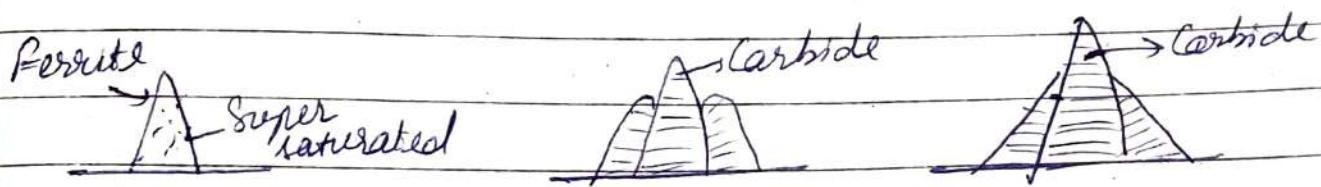
Since high 'C' region has more 'C', it rejects 'C' leads to the form' of ppt.

In case of alloy steels, carbide formed is known as epsilon ( $Fe_{2.4}C$ )

## Upper bainite



## Lower Bainite



## \* Upper bainite

I →  $\alpha$ -ferrite is active nucleus, well-established.

II → Interface b/w active nucleus & parent austenite consists of 'C' enriched. Diffusion of 'C' takes place from 'C' enriched austenite moving into 'apt' of 'C'. This diffusion of 'C' from 'C' enriched region is rate controlling step.

III → Carbides are precipitated at the interface in the form of stringers.

## Lower bainite

'Transform' takes place at lower temp. -

I.  $\alpha$ -ferrite is super-saturated with 'C' because of low rate of diffusion & low-temp.

II. Carbide is pted 'whiskers' within  $\alpha$ -ferrite

in the form of carbide stringers. The pvt' of stringers at angle from axis of bainitic ferrite.

Pvt' of carbide grows in low C' region which is transformed into bainitic ferrite by shear.

## Heat Treatment processes :-

### 1.) Stress relieving:-

- ↳ Internal stresses or residual stresses developed in the specimen as a result of
- \* Operation like hardening → residual stresses in castings (due to ~~non-uniform~~ cooling)
- \* Similarly during welding, (thermal & heat affect zone)
- \* During machining
- \* Shot-peening

### Problem due to it :-

- Internal or residual stresses may cause warping of the specimen.
- Internal stress along with corrosion may cause stress-corrosion cracking. SCC is

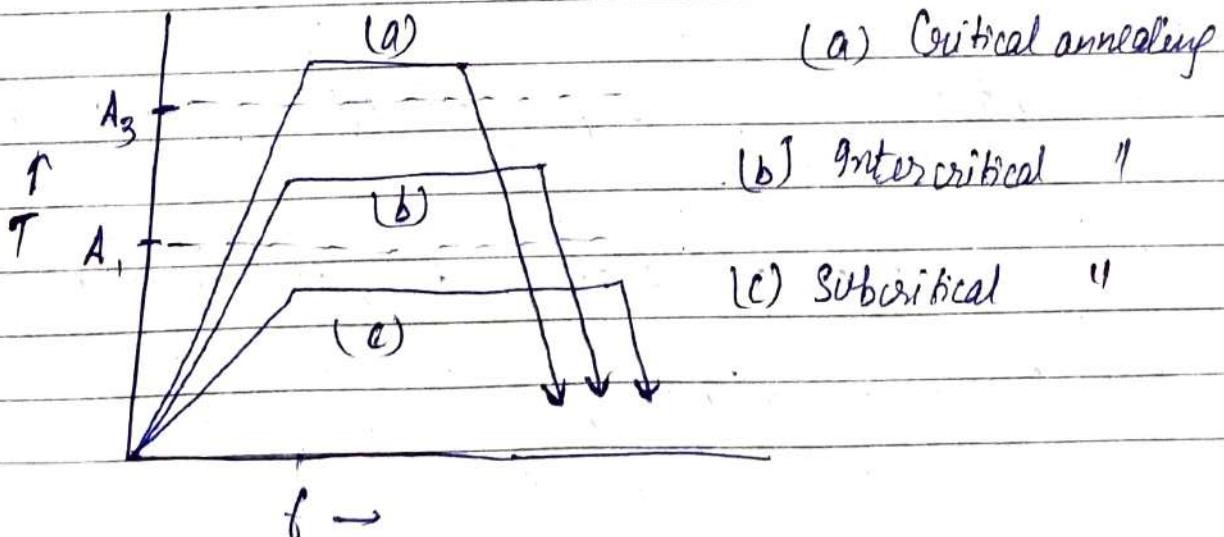
much faster compared to normal corrosion.

\* Stress relieving can be made by heating the specimen to a temperature well below  $A_1$ , i.e. around  $800^{\circ}\text{C}$ ). It is held for a certain period & then cooled at uniform rate.

Since heating is carried out well below  $A_1$ , so there is no microstructural change.

Cooling at uniform rate is very critical, since non-uniform may once again generate residual stresses.

2) Annealing: → Full annealing  
 Isothermal annealing  
 Diffusion annealing } Critical annealing  
 Partial annealing } Intercritical  
 Precise annealing  
 Recrystallisation annealing } Subcritical annealing  
 Spherodizing annealing.



## Annealing

Annealing is heating of the specimen above critical temperature holding for specified period of time and then cooling the specimen at a very - very slow rate.

Since the cooling rate is very very slow then the phases formed will be as per equilibrium phase diagrams.

### Purpose of annealing:

- Stress relieving
- Restoration of ductility & toughness
- Increasing machinability.
- Refinement of grain size
- " " interdendritic (columnar grains & dendrites are converted into equiaxed grains)
- Homogenization of composition
- Release of dissolved gases

Based upon this purpose of annealing, classification can be done -

Based upon temperature upto heating takes place:

- (a) Critical annealing : Above  $A_3$ .

- (i) Full annealing
- (ii) Isothermal "
- (iii) Diffusion "

(b) Intercritical annealing: Above  $A_1$  & below  $A_3$ .

~~\*)~~ → Partial annealing

(c) Subcritical annealing: Well below  $A_1$ ,

- (i) Process annealing
- (ii) Recrystallization "
- (iii) Spherodizing "

\* Full-annealing involves heating the specimen to a temp.  $30$  to  $50^\circ\text{C}$  above  $A_3$ .

or we are going higher than  $A_3$  just to homogenize the composition. We heat  $30$  to  $50^\circ\text{C}$  above  $A_1$  & ~~it is held for specified~~ period of time (depending on size shape & section thickness) & then it is cooled very very slowly. So, following advantages

- Stress relieving
- Return of toughness
- More importantly increase in machinability.

### ↑ Problems

- ⇒ Process is highly time consuming
- ⇒ kind of annealing we described is

for hypoeutectoid steel.

In case of eutectoid steel, it is heated 30 to 50°C above  $A_1$ .

### Hypereutectoid steel

Full annealing is not employed for hypereutectoid steels.

#### Reasons:

To obtain full homogeneous austenite, specimen should be heated 30° to 50°C above  $A_{cm}$  temp.

The temp. thus will be quite high & hence certain coarsening may take place. After cooling to room temperature, the microstructure will consist of coarse pearlite surrounded by continuous network of pro-eutectoid cementite & both are not desirable.

### (\*) Isothermal annealing

\* The process involves heating the specimen 30 to 50°C above  $A_3$ , holding for specified period of time & then superseding the specimen to a temperature below  $A_1$  (700 to 600°C) & then holding the specimen at this temperature till the transformation to



pearlite is complete. After that it is air-cooled to room temperature.

~~700°, 600°, 500°, 400°~~ In the temperature 700-600, austenite is highly unstable. The result obtained are similar to full annealing but takes much less time.

### Limitation of this process:

⇒ The process is suitable only for small size specimens since homogenization of temp. may not occur during isothermal holding for large castings.

### Diffusion annealing

This involves heating the specimen to a temperature 1000-1200°C & is held for 10 to 20 hrs at that temp. & it is cooled very slowly.

#### Advantage:

At high T,

⇒ Rate of diffusion of elements will be faster, segregation will be minimized, as a result homogenization of composition occurs.

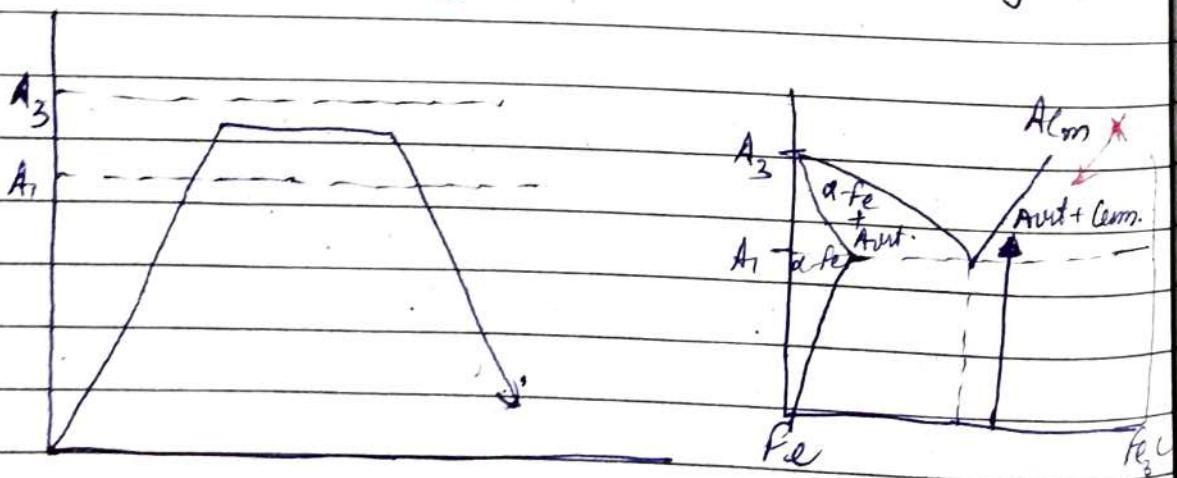
- ⇒ Dissolved gases are released.
- ⇒ Columnar grains & dendrites are converted into equiaxed grains

### Limitations

- ⇒ Massive plane grains coarsening
- Surface oxidation (high T), it may result in loss of yield.
- Correction of grain coarsening may require a second heat treatment. It is very costly process.



### Partial annealing: (Interstitial annealing)



This process involves heating the specimen above  $A_1$  but below  $A_3$ , holding for specified period of time & then cooling it slowly to room temp. The process is suited for

## hyper eutectoid steel

(Not suitable for hypo- as softer phase  $\alpha$  or  $\alpha$ -Fe are formed which is not desirable).



## Recrystallization annealing:

The temperature at which new strain free grains are nucleated is known as recrystallization temperature. The temperature is not fixed & depends upon following :

- (i) Chemical composition
- (ii) Degree of prior deformation
- (iii) Holding time
- (iv) Original grain size.

A certain min<sup>m</sup> amount of deform<sup>n</sup> is needed for recrystalliz<sup>n</sup> to occur -

Coldworking produces a lot of lattice defects on which strain free grains are preferentially nucleated.

If prior deform<sup>n</sup> is in excess, recrystalliz<sup>n</sup> temp. will be lowered, but a higher temperature is preferred so as to minimize holding time. Hence, the process involves heating the specimen below A, holding it

\* For specified period of time & cooling it to room temp.

(This heat treatment is suitable for refining the grain size. This heat treatment process is known as 'in-process' annealing.)

During cold rolling after a certain thickness reduction, it is not possible to reduce the thickness further due to work hardening (due to enlargement of grains). Therefore it is necessary to produce once again strain free grains. For that recrystallization annealing is done (that's why called in-process).

### ① Process annealing

Process involves heating the specimen ~~just~~ below A<sub>1</sub> holding for specified period of time & cooling to RT. The holding temp. in case of process annealing is slightly below recrystallization annealing. Therefore recrystallization may or may not take place. In the process annealing stress-relief & recrystallization may occur. Since heat

time heating T is lower in this case, it is cheaper than recrystallization annealing.

## (\*) Spherodizing annealing

The process is employed to convert lamellar cementite of hypo-eutectoid steel & cementite or lamellar cementite of hyper-eutectoid steel.

This process employed to convert lamellar cementite into spheroidal or globular form. This change in shape increases the machinability of steel. The process can be carried out in many ways -

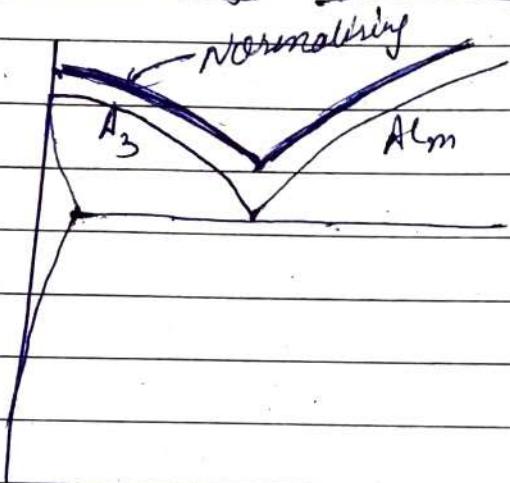
- (i) Specimen is heated just below A<sub>1</sub> & is held at that time for very long period till cementite globules are formed & then it is cooled to RT.
- (ii) In this process specimen is heated ~~at~~<sup>just</sup> above A<sub>1</sub> followed by just below A<sub>1</sub>. The process is repeated many times till cementite globules are formed.
- (iii) Specimen is heated just above A<sub>1</sub> & then quickly superseded to a temperature just below A<sub>1</sub> & is held at this temperature for quite long time till cementite globules are formed.

This process is not suitable for hypo-

\* - electrode steels because microstructure consists of ferrite which is softer & sticky & hence difficult to machine.



### Normalizing: ~~Annealing~~



The process involves heating the specimen to a temp. 40 to 50°C above  $A_3$  or 40 - 50°C above  $Ac_m$  holding for specified period of time & then cooling in air. Microstructure will consist of fine pearlite. Thus, it has higher strength compared to full annealing.

### Air cooling:

2 types :

→ Static air

→ Agitated air: Cooling faster, finer pearlite

→ But in case of air-hardening alloy steels, martensite will be formed.  
 (When  $Mn$ ,  $Ni$  are in abundance,  
 shifting of TTT diagram towards right)

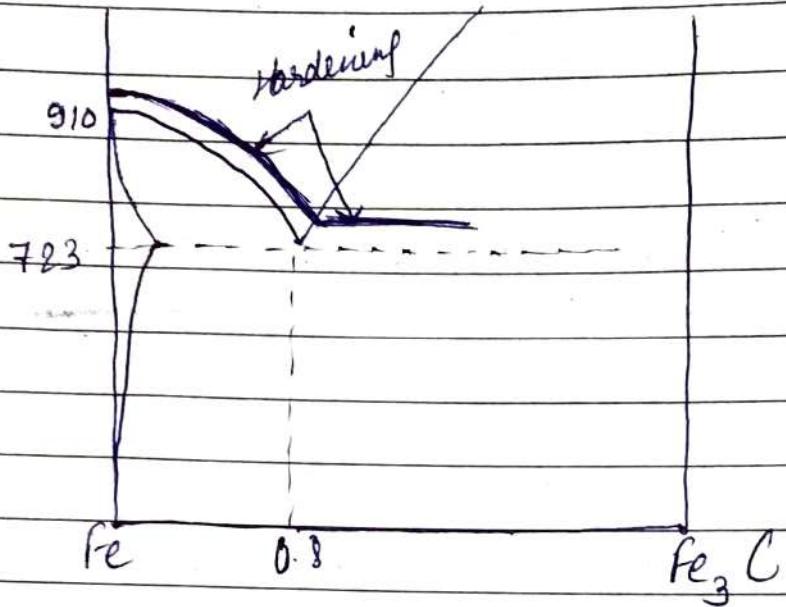
\* In case of annealing If we go above  $AC_m$ ,  
 the main problem is, a continuous network  
 of cementite is formed + ~~surrounds~~  
 surrounds pearlite grains which is not  
 desirable.

\* In the case of normalizing continuous network  
 of cem. is not formed as rate of  
cooling is faster as compared to full  
 annealing.

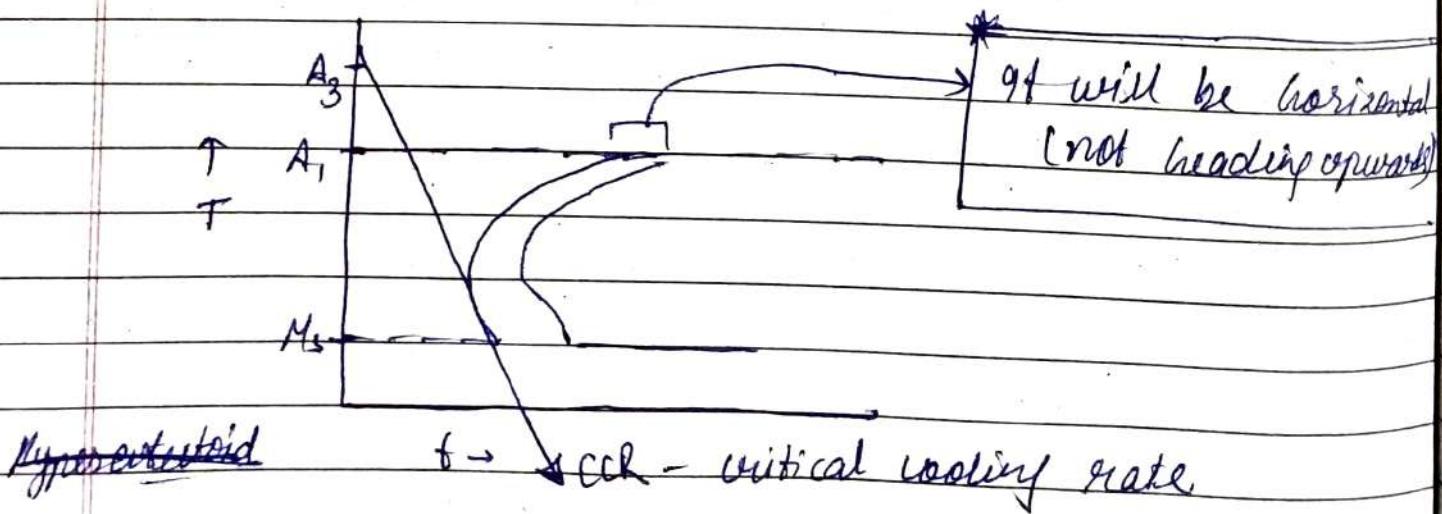
( $40-50^{\circ}C$ )

Holding temp. in case of normalization is higher  
 compared to full annealing. This done to  
obtain greater ( $30-40^{\circ}C$ ) homogeneity  
of austenite. The more homogenized  
austenite results in better dispersion  
or in other word, finer microconstituent  
is the end product. Thus, strength is  
increased)

# Hardening



\* Hardening is a process of heating the specimen to a temperature 30-50°C above A<sub>3</sub> in case of hypoeutectoid steel & 30-50°C above A<sub>1</sub> in case of hypereutectoid steel, holding for specified period of time & then cooling it at a rate more than the critical cooling rate to room temperature.)



→ Cooling rate  $\geq$  CCR, otherwise Pearlite may form.

## Quenching medium or Quenchants:

Quenchant

Severity of quench

1. Ideal quenching med.

$\infty$

### \* → Synthetic quenchants

- Agitated → Brine  
→ Water  
→ Fused salt  
→ Oil  
→ Air

[for shiver  
~~quench~~]

The vapour film forms on the surface as an insulator & thus reduces the cooling rate.

### Brine

(10-15% NaCl in water).

When brine water comes in contact with hot surface, salt particles are deposited on the hot surface. Since, the surface is very hot thus salt particles start jumping & thus the vapour film is broken. Problems for this are:

- Shiver quench: lot of internal stress may develop  
→ Corrosive action on the container

Synthetic quenchants: There are basically organic ~~salt~~ based heat water soluble solution. The vapours film which is formed on the surface goes back into the solution thus rate of cooling is faster. No pollution or corrosion problem.

Fused Salt: Potassium nitrate & Sodium nitrate molten salt. \*

Oil: Heavy oil

Quenching is much milder is above 2 bars.

Air: Air is used in case of air hardenable alloys.

~~In case of hypereutectoid steel, if we go above  $A_{cm}$ , then chances of grain coarsening (coarse acicular martensite) which is not desirable.~~

There is chance of surface ox'd.

→ If heated to the  $A_1$  to  $A_3$  (just above  $A_1$ ), ~~decarburization~~

Austenitic grains will be finer, that will result in fine ~~perlite~~ austenite martenite.

The other constituent is cementite which is a hard constituent & also has good wear resistance.

~~→~~ If in case of hypoeutectoid steel we heat the specimen above A<sub>1</sub> but below A<sub>3</sub>, the end microstructure will consist of ferrite + martenite. Ferrite is a softer phase & hence not desirable.

Hardening is done to obtain very high hardness level.

### \* factors affecting hardening process :

(i) Chemical composition: If it consists austenite stabilizers, the proportion of retained austenite will be more which is not desired (softer).

~~(ii)~~ Complex carbide formers is in abundance, then wear resistance is increased.  
In case of tool steels, cutting ability & thermal stability increases.

(vii) ~~Alloying elements which increase hardness~~  
~~like Cr, Mn etc. increase hardness. In~~  
~~presence of these elements, the TTT curve~~  
~~shifts towards right & thus martensite~~  
~~can be obtained even with milder~~  
~~quenching rates.~~

(viii) Homogeneity of Austenite & grain size

→ Homogeneous austenite ensures a finer  
martensite → Coarse grain size favors  
hardenability.

(ix) Size & shape of specimen

In case of large size, the surface & core  
will cool at different rates, thus forming  
different phases. Similarly with complex  
shapes, variable thickness of section &  
sharp corners will cool at different rates,  
thus generating a lot of internal  
stresses which may cause growth cracks  
or warpage.

(x) Hardenning cycle:

Hardenning cycle consist of heating rate,  
holding temp., holding time & quenching  
rate.

dependent on

- \* Heating rate  $\rightarrow$  size & shape
- holding T  $\rightarrow$  x. age of C
- " f  $\rightarrow$  size, section thickness
- Quenching rate  $\rightarrow$  final prop. desired

### (iii) Surface condition of specimens

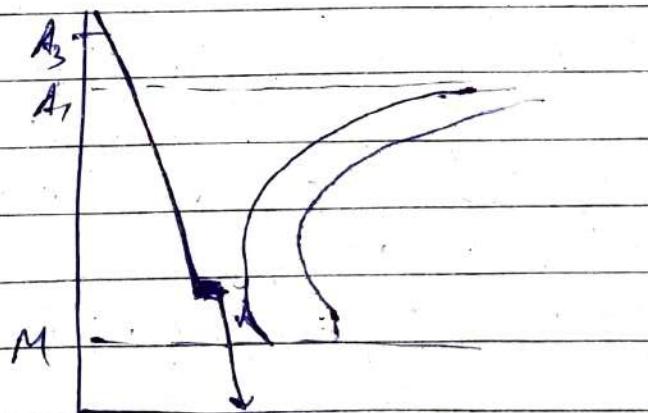
The presence of dirt, grease, oil or oxide layer affect the heat transfer during quenching. Therefore the surface must be cleaned of all these.

### \* Hardening methods

#### (i) Direct quench

This is most common method but it results in excessive generation of internal stresses.

#### (ii) Step quenching



The specimen is super-cooled to a temp. where beyond pearlite & bainite region it is held in a oil bath or salt bath for sometime & then it is cooled in air. This ensures a smaller magnitude of internal stresses.

### (ii) Spray quenching

This method is employed when selective hardening is desired. Spray of mostly water is made is used on the portion of the specimen where hardening is desired. Hard



### Hardening with self-tempering

The specimen is super-cooled to a temperature above  $M_3$  & is held for a very specific time & then is cooled in air. Since the specimen is held in the quenching medium for a very brief time the surface hardens but the core which is still very hot self-temperes resulting into the formation of fine pearlite. Thus the specimen has hard surface but tough core.

## Tempering :-

Tempering always follows hardening process.

\* Why?

- A lot of internal stresses generated after hardening which must be removed.
- Microconstituents: micro-constituents after hardening are martensite & retained austenite.  
Martensite is not an eq<sup>m</sup> phase as RT therefore with ageing excess carbon may slowly diffuse out, thus causing dimensional changes

Retained austenite <sup>(RA)</sup> is also not stable at RT (metastable) hence RA must be stabilized

Tempering involves reheating quenched sample to a temperature below A<sub>1</sub>, holding for specified period of time & then cooling in air. Process may be repeated for multiple time (multi-stage tempering).

Tempering (to obtain optimum level of hardness & toughness) results in loss of hardness & wear resistance to some extent but on the other hand

toughness & durability increases. Thus tempering is carried out to have a optimum comb' of hardness, wear resistance & durability, toughness.)

Depending upon holding T of tempering, tempering can be classified into 3 categories:-

- |      |                        |             |
|------|------------------------|-------------|
| I.   | 1st stage (low temp.)  | upto 250°C  |
| II.  | 2nd stage (med. temp.) | 250 - 500°C |
| III. | 3rd stage (high temp.) | 500 - 650°C |

### \* 1st stage

changes involved:

As the temperature goes up, carbon atom being smaller in size start diffusing out of the matrix. This results in the form of low - c - martensite / tempered martensite & carbide  $\epsilon$ -carbides.  $\epsilon$ -carbide is different from  $Fe_3C$  (orthorhombic) as it has HCP structure & also it consists of more carbon ( $Fe_{2.4}C$ ) than  $Fe_3C$ .

### \* 2<sup>nd</sup> stage

Retained austenite transforms to bainite but this bainite is different because it consists of  $\text{E}$ -carbide.

### \* 3<sup>rd</sup> stage

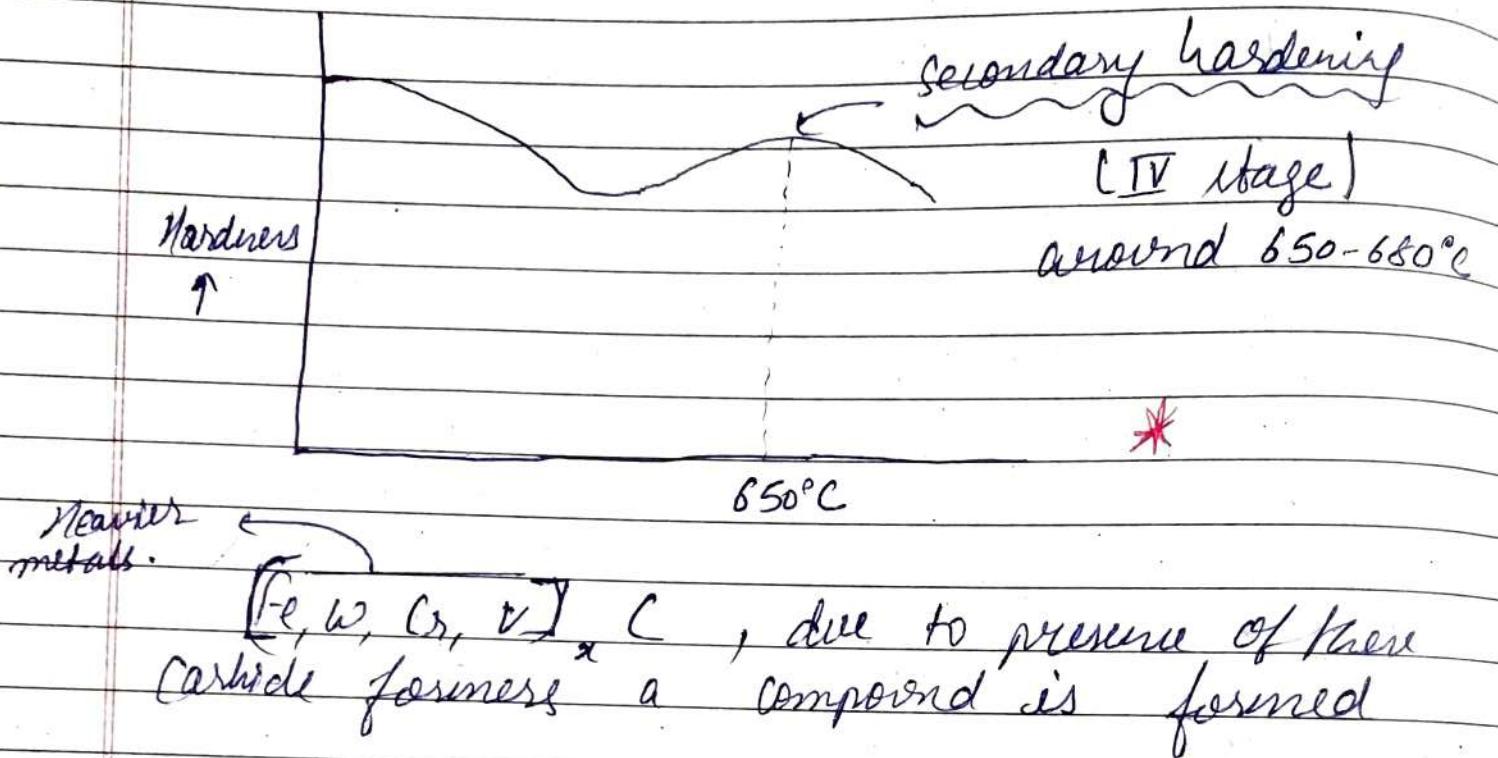
Low C-martensite transforms into ferrite & rejects excess carbon. The excess carbon combines with  $\text{E}$ -carbide & forms  $\text{Fe}_3\text{C}$ . Thus the microstructure consists of ferrite & cementite.

\* (As we go to further stages, loss of hardness & wear resistance.)

### \* 4<sup>th</sup> stage (Alloy steels)

The alloying elements are ferrite stabilizer & aust. stabilizers, then they do not make much difference, because ferrite stabilizers will merge into ferrite phase & aust. stabilizers will merge into austenite phase. But in case of carbide formers, complex carbides are formed which do not dissolve easily in austenite matrix during holding period. Hence a temperature more than

1000°C is needed for the diss' of complex carbides.



High speed steel: 18:4:1 O.7% C  
W or V

when tempering is carried out initially hardness keeps on decreasing but above 600°C once again hardness starts increasing. The phenomenon is known as secondary hardening.

- \* The complex carbide consist of heavier elements like Fe, W, Cr, V. The diffusion of which is substantial only above 600°C. As a result complex carbides are precipitated & dispersed uniformly in the matrix causing dispersion hardening.)

## Temper embrittleness

\* This problem is not caused in plain-C-steel but mostly in alloy steel.

650°C  
\* ↓ while cooling slowly is 350°C this range or prolonged holding in this range causes loss of toughness known as "temper brittleness".

⇒ Hardness, tensile strength, YS, ductility

\* Problem can be corrected by heating or cooling 650°C → 350°C at a higher rate.

\* → This problem is present due to tramp elements. (Pb, Sn, As, Sb)

\* → To suppress the effect of these tramp elements, adding of Ti, Zr, Mo is made. It has also been found that Ni, Mn, Cr, Si have also effect on the temper embrittleness.

## Temper colour

\* Change of colour during tempering.

250°C - Pale yellow

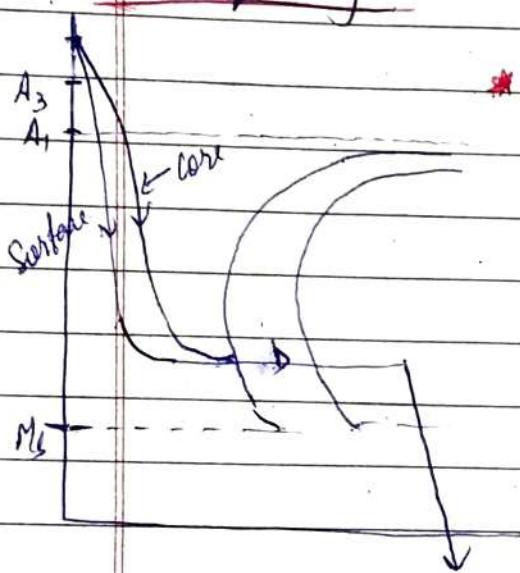
400°C - Purple

} depend on  
} thickness of oxide layer

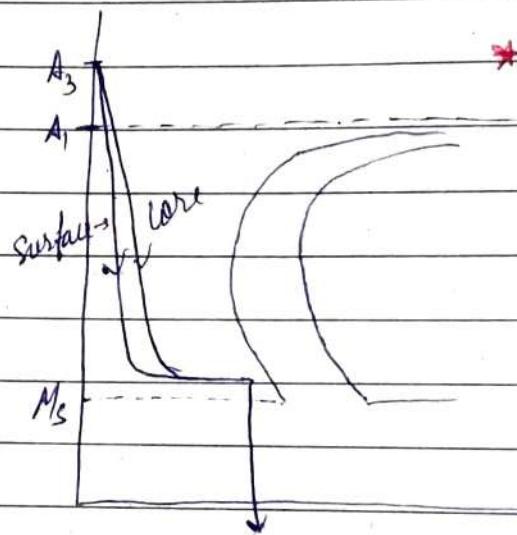
Temper colour depends on thickness of oxide layer which is formed during the oxidising atmosphere.

{ Lower T → Pale yellow  
Higher T → Dull grey

### Austempering



### Martempering



Tempering is carried out during hardening process in both process.

⇒ Surface will cool at faster rate  
) Core " " " " " " " .

Austempering & Martempering, both are suitable for small size components

In both cases, incubation period should be sufficient so that homogenisation of T is complete before transformation begins.

## Austempering

In this case, <sup>specimen</sup> it is reheated to a temp.  $400^{\circ}\text{C}$  -  $200^{\circ}\text{C}$  in the bainitic range. The specimen is held at that temperature till homogenization of temp. is complete.

Once temp. is held, it will transform to bainite & once transform is complete then it can be cooled in air.

## Advantage.

- Mech. properties obtained in case of austempering are better than conventional route (hardening + tempering)

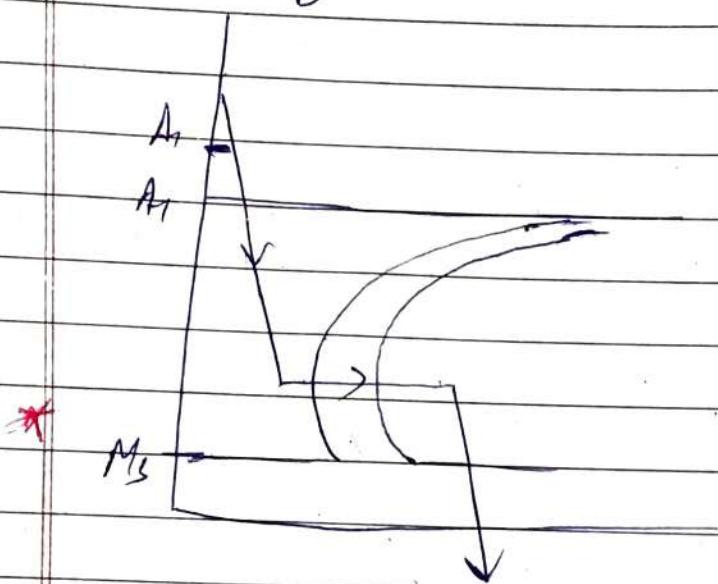
## Martempering

In this case isothermal T of holding is kept above  $M_s$ , hence it is called martempering.

Once T is homogenized (isothermal period has to be large for this) after this it is cooled. Martemtic transform takes place during air cooling, thus internal stresses generated will be not high. This case is not very useful as to obtain better mechanical

prop. a second tempering process is required.

## Patenting



} for medium C-steel,  
high C-steel,  
low alloy steel

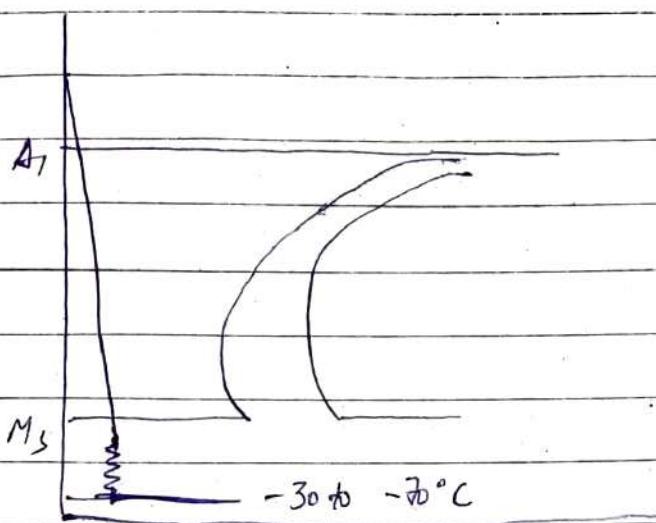
(Not for low C-steel  
(can be done by annealing.) )

\* Patenting is done for drawing wires, ropes, springs.

Specimen is supercooled to a  $T$  around the nose of C-curve. (Thus depending upon % of C temp. may vary from  $550 - 450^{\circ}\text{C}$ )

Then 'transform' is carried out at this  $T$  to obtain a microstructure consisting of fine pearlite.

## Subzero treatment



Subzero treatment



Retained austenite —

→ visible only when  $> 20\%$ .

→ depends on Y.C : RA  $\uparrow$  as Y.C  $\uparrow$

→ alloying element :

(Particularly Austenite stabilizers)  $\uparrow$  R.A.  $\uparrow$

RA is not an  $ep^m$  phase, so dimensional changes may occur & hence it is necessary to stabilize it.

It is necessary to carry out subzero treatment immediately after hardening, otherwise RA may stabilize itself.

For steel:

Subzero temp. range



-30 to -70 °C

These T are well below  $M_f$  temperature

These orange of T are obtained by using dry ice or liquid nitrogen.

## Care hardening

Care hardening is employed to those components where there is need of harder wear resistance surface & tough core.

For e.g. Ball bearing, gears.



## Care hardening

(1) Thermochemical treatment

(2) Surface hardening

(1) → Chemical of core & care are different.

(2) → Chemical compo<sup>n</sup> is not altered during treatment.

### Thermochemical treatment

Care carburizing

Vacuum carburizing

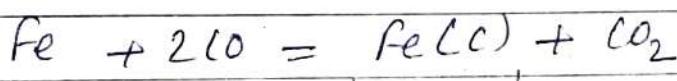
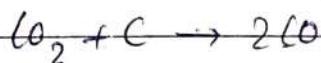
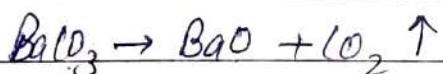
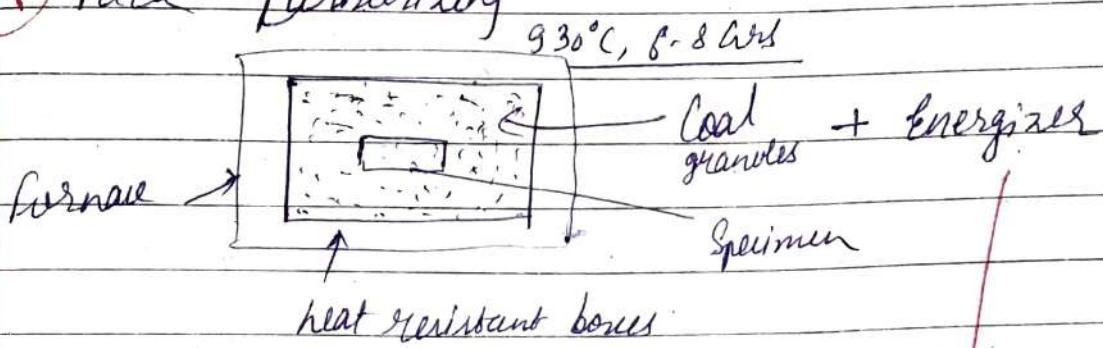
Solid Liquid Gas

Post carburizing treatments

I

## Case carburizing (Solid)

### (1) ~~A~~ Pack carburizing



BaCO<sub>3</sub> as energizer

Suitable for low - C - steel.

Carburizing treatment is done for low - C - steels in the range 0.1 - 0.25.

Diffusion of C will depend on T & t.

Case depth in this case is 1-2 mm

$$C(x, t) = A + B \exp\left(\frac{x}{2\sqrt{Dt}}\right) *$$

↓      ↓      ↓  
Carbon case time  
depth

A & B are constants.

Value of each will be found by applying

boundary condition.

erf - error function

$(x, t) \rightarrow$  Carbon com<sup>n</sup> as a func<sup>n</sup> of case depth & time.

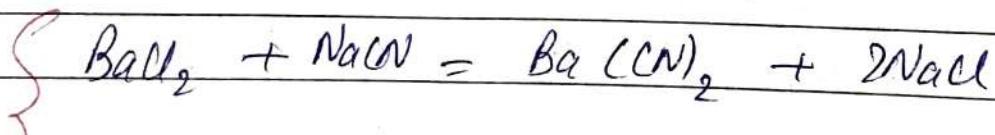
(Liquid)

In case of lig. carburizing, rate of etc<sup>n</sup> will be faster. Temp. is in the range 870 - 980 °C.

Carburizing med. is  $\text{NaCN}$  &  $\text{KCN}$ . It have to be handled very carefully, thus usage is difficult.

$\text{BaCl}_2$

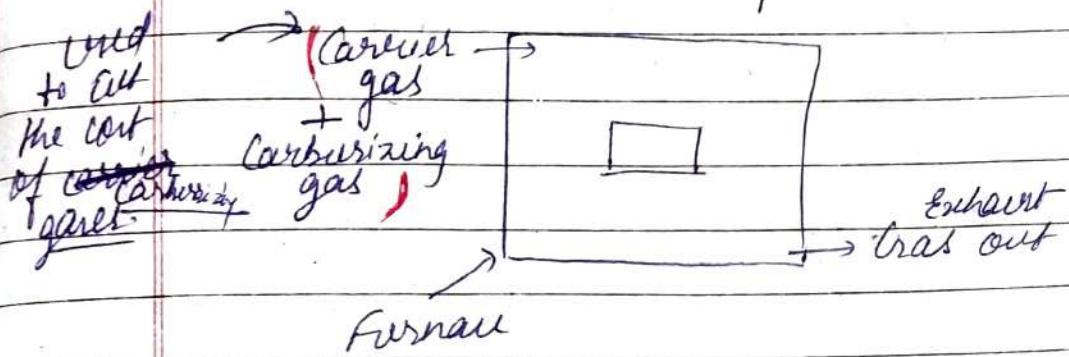
$\text{Ba}(\text{CN})_2$  is used as an energizer



C diffusing into Fe.

(Gas)

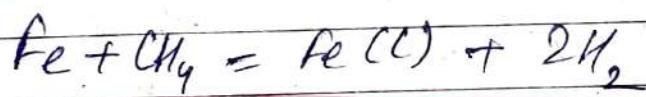
gaseous carburizing (most common)



These days, in bigger industry  $N_2$  is used as carrier gas & carburizing gas is normally natural gas ( $> 80\% \text{ CH}_4$ ) methane

Temp. is in the range  $870 - 950^\circ\text{C}$ .

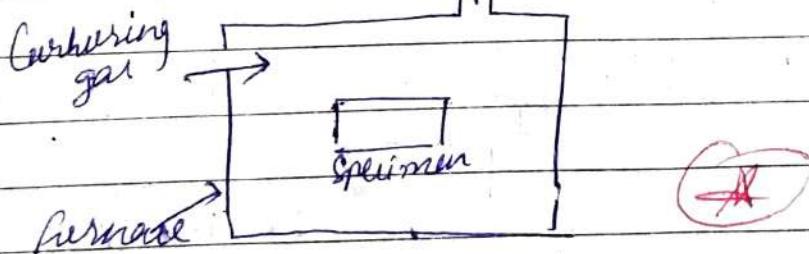
Rk's taking care:



II.

Vacuum Carburizing

↑ connected to vacuum pump.



- When we need a quick carburizing.
- Cost will be more as vacuum has to be created in furnace.

Volume of furnace have to be limited.

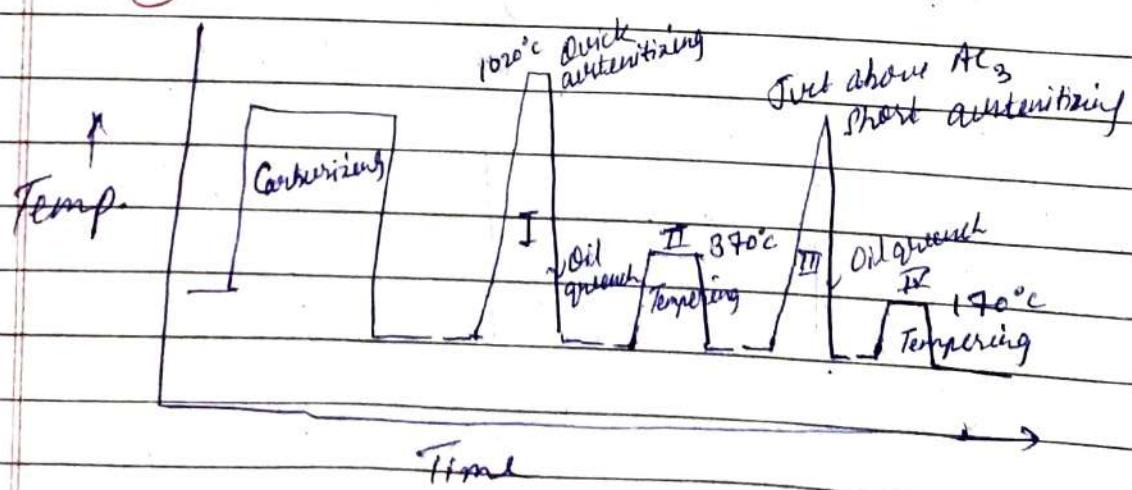
Only for small sample testing treatment.

- Furnace is evacuated to a certain level
- Then Specimen is heated to the desired T.
- Once desired T is reached, carburizing gas is introduced.

(Case depth will depend upon the time up to which the specimen is exposed to the carburizing gas.)

After a specified period vacuum is applied once again & carburizing gas is taken out.

### Post-carburizing Treatment



## Problems after carburizing

- ① Since the specimen is heated at the carburizing T for prolonged period, there is appreciable grain coarsening
- ② Since the carburized case has higher carbon content, the room temp. structure consists of continuous network of cementite around pearlite grains. This continuous network of cementite is brittle & hence not desired.

(I) : First treatment involves breaking of cementite network by dissolving it completely into austenite at a higher T  $1020^{\circ}\text{C}$  for a short time. Then it is oil quenched.

(II) : Tempering is done at a temp of  $350^{\circ}\text{C}$  during which retained austenite transforms into bainite.

(III) Specimen is quickly heated to a T just above  $\text{A}_{\text{1}}$  & then oil quenched. This step is basically to refine the grains

(IV)

Tempering is done to a T of  $170^{\circ}\text{C}$ .  
This is mainly for stress relieving.

### Surface hardening

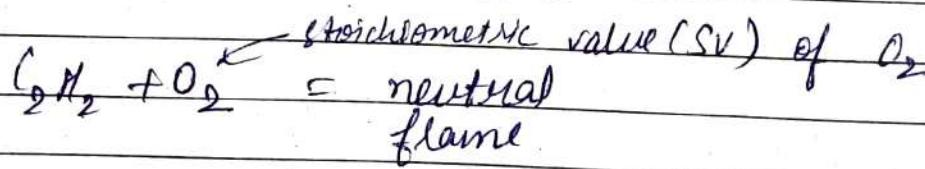
\* No change in the chemistry of hardened case.

- (i) Flame hardening
- (ii) Induction hardening
- (iii) Electron beam hardening
- (iv) Laser beam hardening

} more costly

### Flame hardening

#### Acetylene gas torch



< SV. = reducing flame

> SV. = oxidising flame

(Also known as Oxy acetylene hardening.  
The flame is kept slightly ~~mildly~~ oxidising.

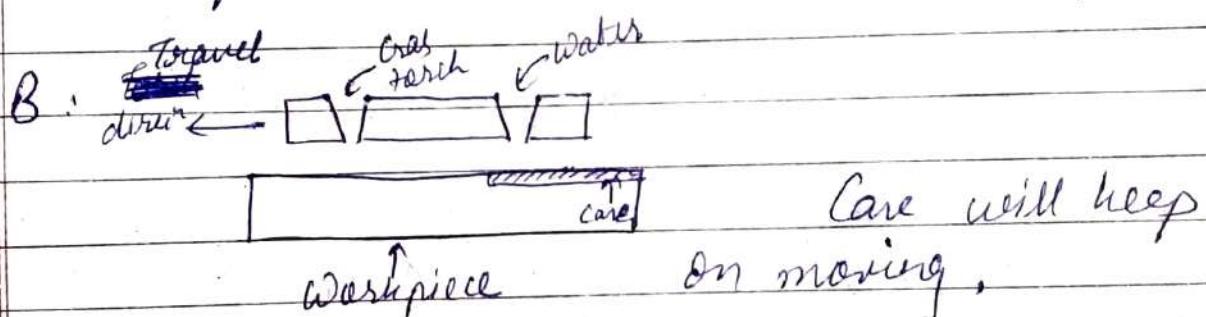
This process is suitable for very large work pieces. Y. age of cut is the

0.3 to 0.6)

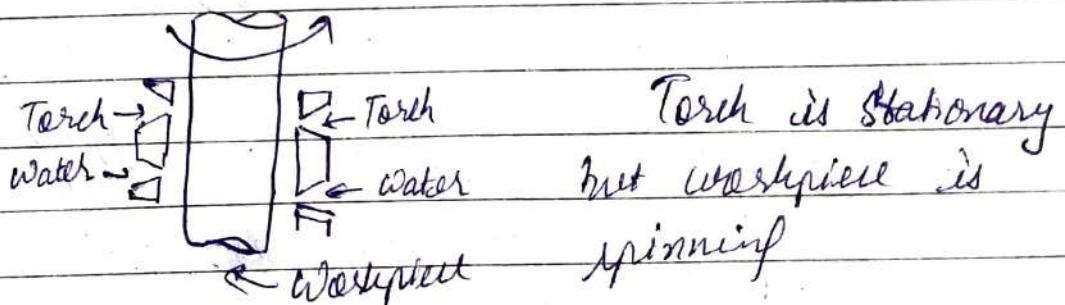
\* Within this, there are 4 types :

- A. Stationary
- B. Progressive
- C. Spinning
- D. Progressive spinning.

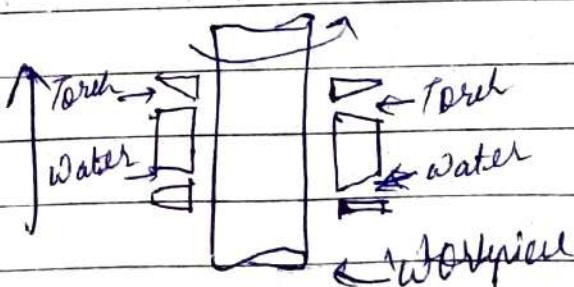
A: When workpiece & oxyacetylene is stationary. Once sufficient heating is done nozzle is removed & it is quenched with  $N_2O$ .



C.



D.



Advantage of this process:

- Cheap
- Convenient for large work pieces

Limitation

- Surface and
- Brain warming
- Decarburization

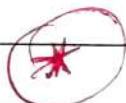
But,

Depending upon size it is followed by annealing.

## (ii) Induction hardening

It is very quick process. (heating is quick).

$$\delta = \sqrt{\frac{f}{\pi \mu f}}$$



( $\delta$  - resistivity of charge)

$\mu$  - magnetic permeability of the medium

$f$  - frequency of power supply.)

So for small case depth (skin effect):

→ frequency of supply should be high.

Medium range of  $f$ : klo Hz  
High " " : Mega Hz

~~Ans~~  
Once again this process is also used for large work piece like hardening of gear teeth.

(iii)

Electron beam hardening. This process is suitable for those where flame & induction hardening ~~can~~ cannot be carried out.

In this case technique a defocused electron beam is made to fall on the specimen surface.

Initially the energy needed is more which can be reduced slowly.

Limitation:

Equipment cost is high.

(iv)

Laser beam hardening:

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



$\gamma$  - case depth (in mm)

P - laser power (Watt)

$D_b$  - Diameter of incident laser beam (mm)

V - Traverse speed (mm/s)

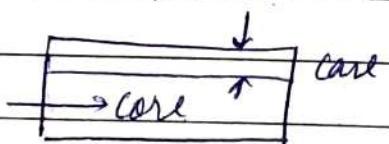
## Advantage

- Quick process
- Better properties compared to first two.  
(Flame & induction)
- Suitable for low-C steels
- Suitable for cast irons (Graphite in spheroid form)

## Limit

- Not suitable for large soaking time  
(thus not for large workpieces).

## Measurement of Case depth



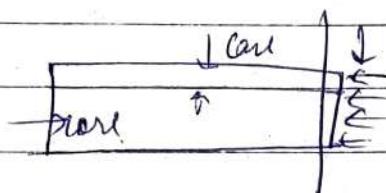
As moving towards core from case there is:

- Change in hardness
- Change in chemical compn' (may or may not be)
- Change in microstructure.

## A) Measurement of Hardness.

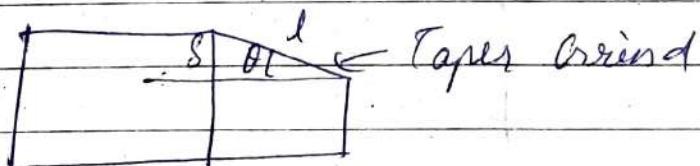
### Method 1) Cross section method

A depth is cut 1" to case while cutting. Utmost care should be exercised so as to prevent tempering.



Now we start measuring hardness from outside. Now, there will be abrupt change in hardness. That pt. gives the depth of case.

### Method 2) Taper grind Method



While grinding, utmost care should be exercised to prevent overheating of surface otherwise it can lead to tempering.

We start measuring hardness at diff. pts. So, wherever there is abrupt change in hardness. Hardness measure is stopped.

\* Case depth is generally 1-2 mm or even less than 1 mm

Date 10/10  
Page 6

Now:  $\sin \theta = \frac{s}{l}$

$\Rightarrow s = l \sin \theta$

$l \rightarrow$  length of tapered surface

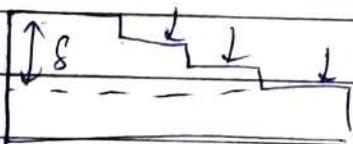
$s \rightarrow$  case depth.

### Advantages:

- Quick process
- Better properties compared to flame induced hardening
- Suitable for low C steels
- " Cast iron (SG)

### Limits:

### Method 3): Step grind method



Steps are made by grinding & hardness of each step is measured. The change in hardness value indicates case depth.

### B) Chemical control

This method is suitable for carburizing

1) carbonitriding.

The material is drilled out & its composition is found out. Again this process is done until a homogeneous composition is found out.

### C) Change in microstructure.

A vertical section is made  $1^{\text{m}}$  to core depth. (microst. of core - fine pearlite)

Then it is viewed from the side where it is cut & by microstructure analysis results are obtained.

### Thermo mechanical Treatment:

Until now, the processes discussed are:-

- A) Add<sup>n</sup> of alloying elements
- B) Mechanical working
- C) Heat treatment
- D) grain size control

In view of increasing demand of HSLA steel better mechanical properties out of these, ~~one~~ single treatment is not enough. So it was thought to combine 2 processes so as to get better mech. properties as per demand of the customer.

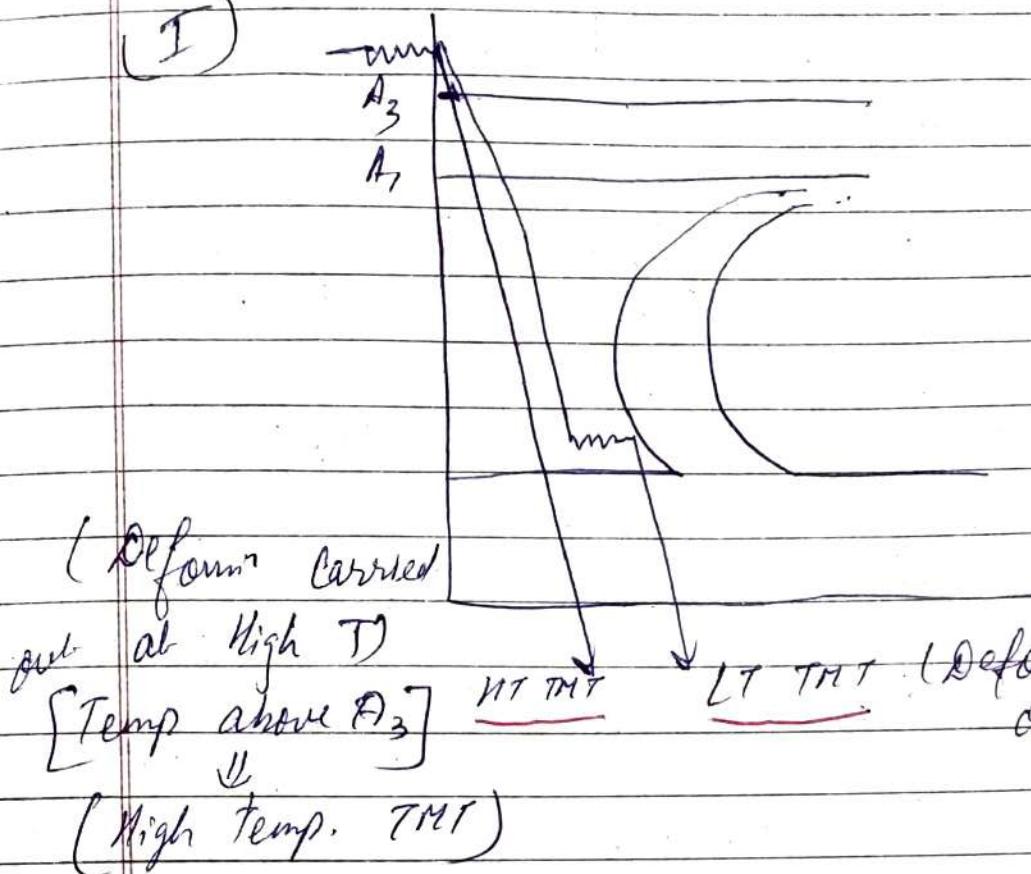
\* So, thermo mechanical treatment is basically a comb<sup>n</sup> of heat treatment & mech. working principle.

(Any comb<sup>n</sup> of heat treatment & mech. working can't be called a thermo-mechanical treatment. The essential cond<sup>n</sup> is that mech. working must alter the kinetics of process as well as morphology of final constituent. In other words, the mech. working (plastic deform<sup>n</sup>) must affect the phase transform<sup>n</sup>)

(A substantial amt of plasti. deform<sup>n</sup> may create vacancies, dislo<sup>n</sup>s, sub-grain boundaries (i.e. grain boundary outside gr.) & change in S.F.E.

If vacancies are created, rate<sup>n</sup> of diffusion will increase. This will affect kinetics of process. Other defects provide add<sup>n</sup>al nucleating sites. This will affect the morphology of final polt -)

(I)



- II) a) Super critical TMT (above  $A_3$ )  
 b) Inter " " (b/w  $A_1$  &  $A_3$ )  
 c) Sub " " (below  $A_1$ )

### \* High Temp. TMT

→ It is carried out above recrystalliz" temp. Since recrystalliz" temp. ~~is~~ it compensates work hardening. Therefore the hardness, tensile strength will be less but the ductility will be more. Since large plastic deform' is of bio-help due to recrystalliz", therefore mechanical deform' is limited up to 20-30%.

## Low - Temperature T<sub>0.7</sub> \*

→ It is carried out at low temp. which is much below recrystallization temp. Since recrystallization doesn't take place, the value of hardness & tensile strength will be much higher as compared to high temp T<sub>0.7</sub>. Therefore a plastic deformation up to 90% is carried out. There shouldn't be any phase transformation during plastic deform., so, the strain period should be sufficiently large.

- 1) Controlled rolling
- 2) AUS-forming
- 3) Iso-forming
- 4) Crys. forming
- 5) Thermo-mechanical annealing

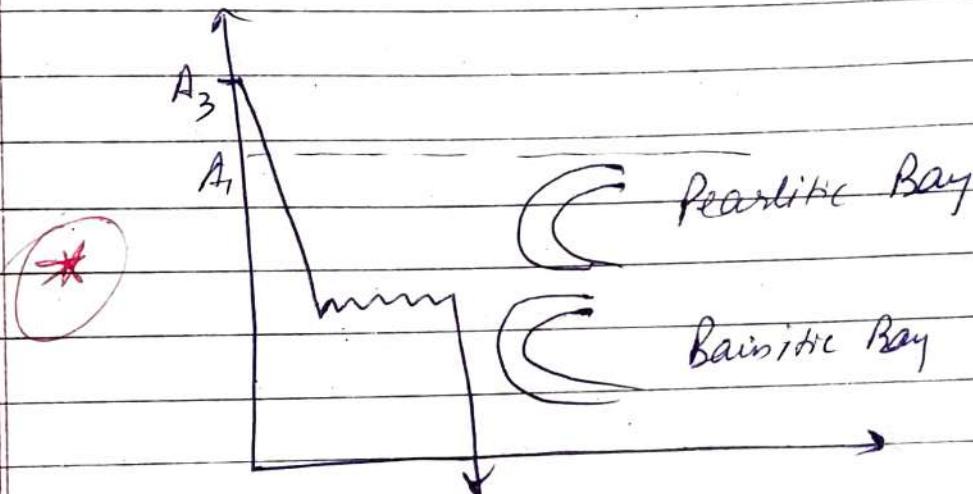
### X) Controlled rolling

The specimen is heated above  $A_3$  temp to convert it completely with aust. Now mech. deform. (rolling) is carried out at that T. in a controlled manner such that austenitic grain remain fine. This can be ensured

- (i) by having proper rolling parameters
- (ii) presence of complex carbide hinder grain growth.

(The temp. of rolling must be below  $1050^{\circ}\text{C}$  otherwise complex carbide will dissolve & grain growth will be faster. After air cooling, the phase/ microst. consists of ferrite carbide.)

## 2) Ausforming



In this, specimen is heated just below  $A_3$ , to obtain metastable Austenite. Then it is supercooled to a temperature in the gap b/w pearlite & bainitic bay followed by mechanical working & finally quenched in air.

(The microstructure will consist of martensite - since the transform. T is much higher no internal stresses set up will be less.)

## \* Pre-condition

- There should be large incubation period
- " " " sufficient gap b/w pearlite & bainitic bay.

## Advantages

→ Properties, tensile strength is much higher as compared to conventional process (quenching + tempering)

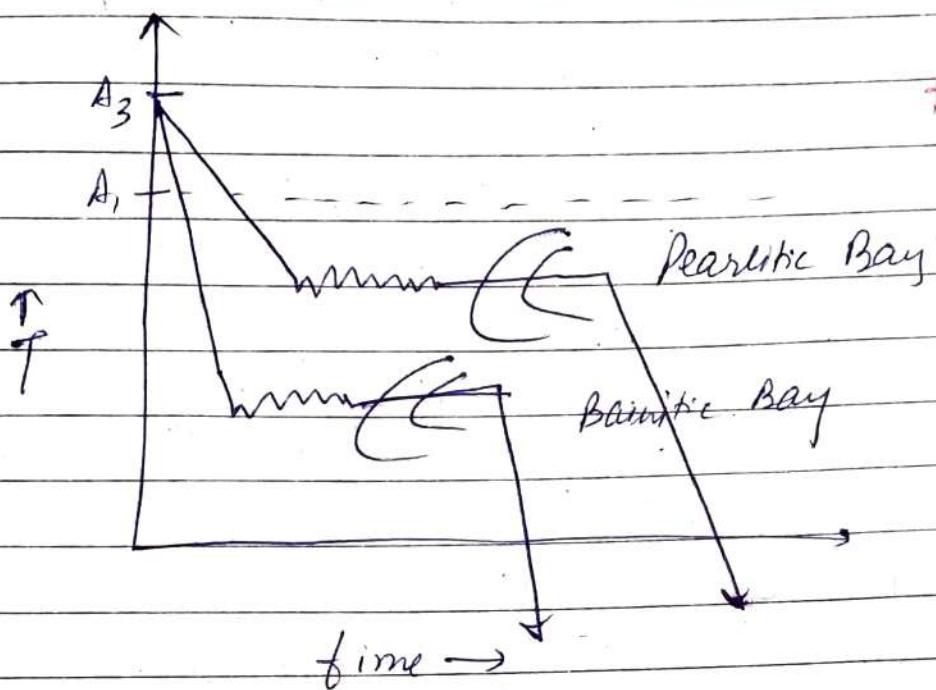
→ Suitable for MS IA steel

→ A min<sup>m</sup> amt. of C → 0.1% should be present  
 → Those alloying elements which have S.P.G. reduces tensile strength. For ex. Ni.  
 → Those alloying elements which lower S.P.F. raises tensile strength. e.g. Mn.

This is due to the reason that alloying elements which lowers the S.P.F. & raises the rate of strain hardening

Alloying elements shift curve to right & their carbides doesn't softening during tempering

3) Isoforming (Forming takes place at const. T)



→ Specimen is heated at temp. just below  $A_3$  to obtain metastable austenite.  
Now:-

Case 1:

Specimen is supercooled to a temp. in the fine pearlite's range followed by mechanical working at const. T & then the transform<sup>n</sup> is allowed to complete. Then it is air cooled. So, the microstr. will consist of fine pearlite.

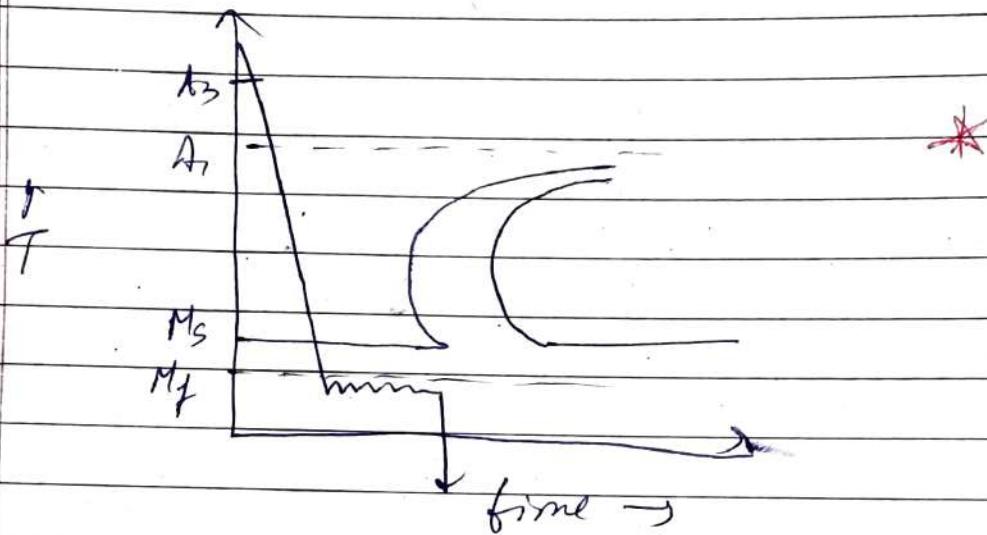
Case 2:

Specimen is supercooled to a temp. in the lower bainit. range followed by mech. working at const. T & then transform<sup>n</sup>

is allowed to complete. Then it is air cooled. So, the microstr. will consist of lower bainite.

4)

### Cryo-forming

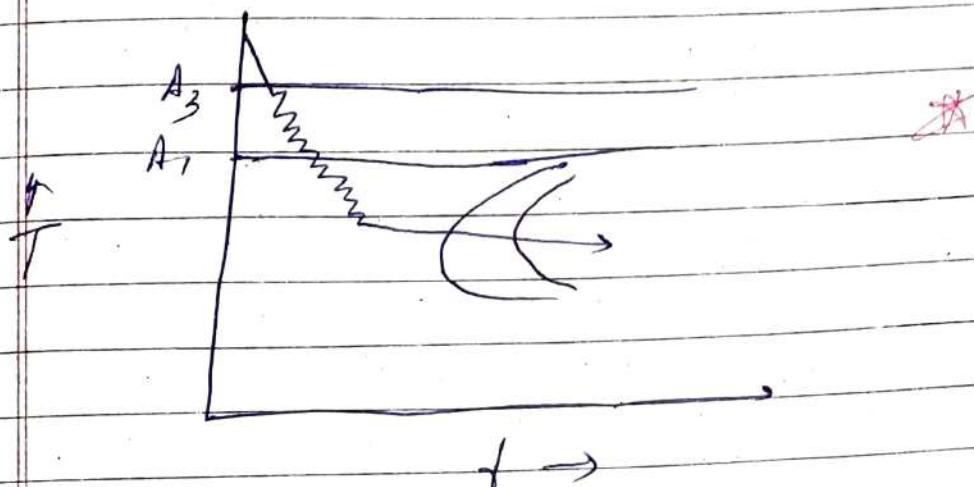


(This process is suitable for those steels for which cold working can't be adopted.)

The process involves heating specimen above  $A_3$  to obtain homogeneous austenite. Then it is quenched to a temp. around  $M_f$  followed by mech. working. In this process, phase transfer immediately follows mech. working to produce martensite.

During the process some austenite is stabilized which doesn't service appl<sup>n</sup> transforms into martensite which is brittle & hence not desired.

## 8) Thermo-mechanical annealing



The process is a comb<sup>n</sup> of thermo-mechanical treatment + annealing. The process involves heating the specimen above A<sub>3</sub> to obtain homogeneous austenite & then while cooling, the mech. working is carried out & the transform. is allowed to complete in pearlite range.

The microstr. consists of ferrite + carbide in globular form. The process is similar to spheroidising but is much quicker.

### White Cast Iron

C → 1.8 - 3 %

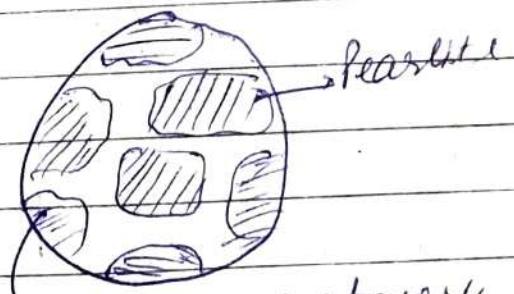
Mn → 0.6 - 1.5%

Si → 0.6 - 1.5%

P → 0.1 - 0.4%

S → 0.15

Hard, wear resistant



continuous network  
(make it of cementite  
machinability brittle, has poor

## Limited appl's

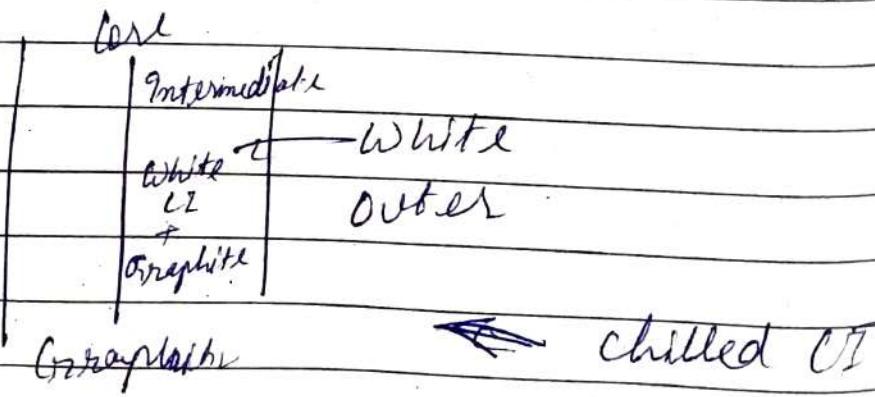
- Grinding media (in ball mills)
- diners of cement mixers

for the pd<sup>n</sup> of malleable CI, white CI, is first / raw material.

The heat treatment process through which it is obtained is called "malleabilizing" or graphitizing annealing.

If outer layer is white CI, core is graphitic carbon & intermediate layer consist of both of these. Then such cast iron are known as chilled CI. This type of CI are produced by pouring white CI into metal mould. When poured, as a result of metal mould, outer layer will chill.

If combined C & free C are present in CI, then it is called mottled CI.



Lend's

for white CI to be sturdy material  
for malleable CI, temper is -

$$C \rightarrow 1.8 - 3\%$$

$$Si \rightarrow 0.6 - 1.5\%$$

$$Mn = 0.6 - 1.5\%$$

$$P \rightarrow < 0.18\%$$

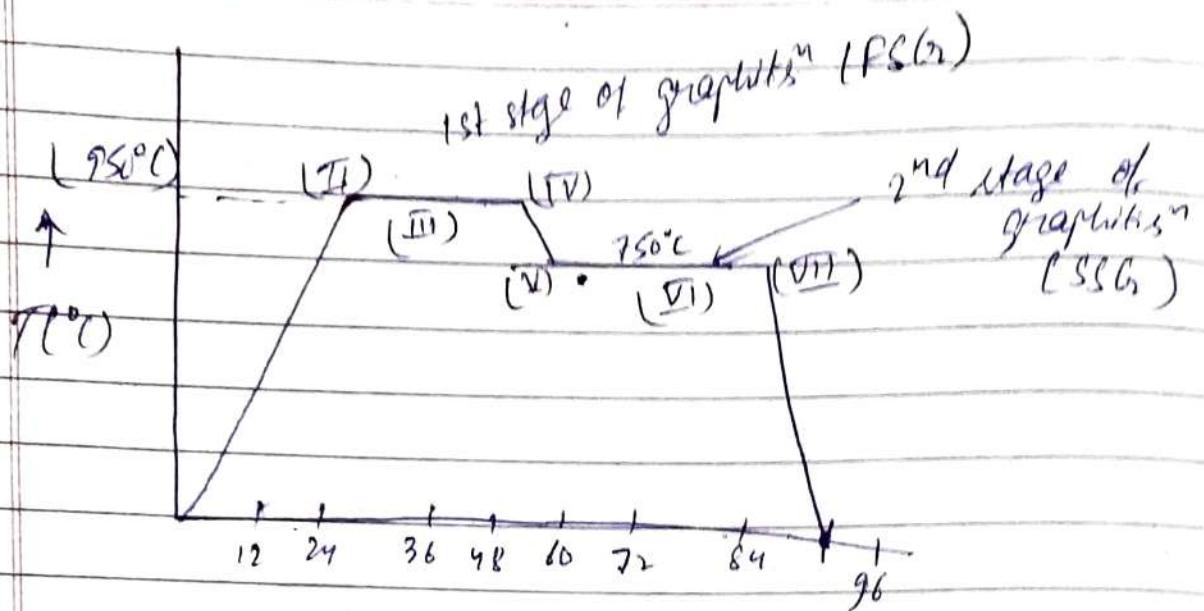
$$S \rightarrow < 0.05$$

The essential reqd' is that all the C should be in combined form i.e. there shouldn't be any free C or graphite otherwise the resultant CI will be a mottled CI which is not desired.

Malleability → It is ability of a material to deform under compressive loading.

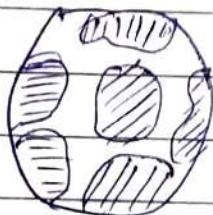
Heat treatment of white CI → malleable CI

- i) ductile
- ii) good machinability.

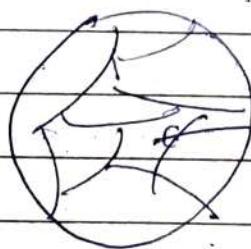


Time, hr →

I) →



(II) → At beginning, microstr. consist of austenite grains.

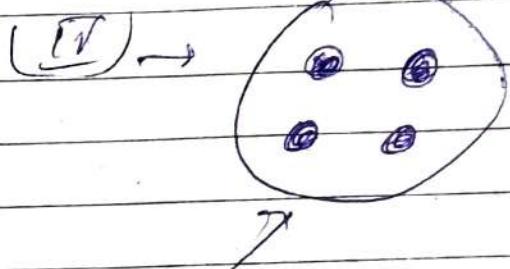
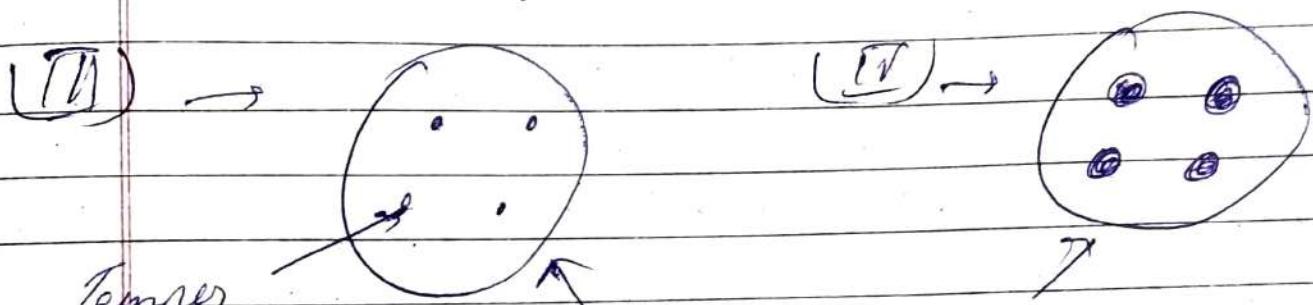


Austenite grains.

As holding starts, cementite will start dissolving into austenite. Since temp - is high solubility of cementite in austenite T<sub>et</sub>. This will result in nucleation of graphite.

Now austenite is depleted in C & hence it dissolves some more cementite. This growth is former deposit of graphite on

already nucleated graphite. Thus, growth of graphite nuclei takes place. This graphite is known as temper carbon. Since graphite grows with the same rate in all directions, it is in shape of spheroid. This stage is known as first stage of graphitization. (Nucleation of graphite takes place at austenite + carbon interface)



Austenite boundaries are not indicated as they are not visible at that magnification.

### Second stage of graphitization

Now the specimen is cooled slowly ( $\approx$  about 0.6 hrs) to around  $750^{\circ}\text{C}$  (just above  $A_1$ ). In the FCA, all the cementite was dissolved in austenite. So, in this stage the holding time is quite large to ensure diffusion of carbon out from the austenite phase which results in

G.C.I. + Mg/CC  $\rightarrow$  SC. (2020)

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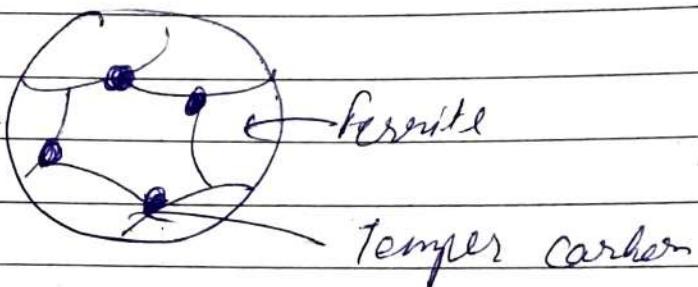
114

Growth of temper carbon. Once the graphitization is complete, it is cooled in air.

(V)

$\rightarrow$  Austenite + Temper carbon

Room T microst.  $\rightarrow$  ferrite + Temper C.



These type of malleable CI are known as black heart malleable CI.

In this process the specimen is kept inside heat resistance boxes & is filled with sand. Thus the atmosphere is mildly reducing. The fractured surface of black heart CI is black.

If the same heat treatment is carried out in deoxygenating atmosphere, then the fractured surface will have white appearance. Hence known as white heart malleable CI.

## White heart m.c.t.

If C-content of white GT. is 3% or more & less Si content i.e.

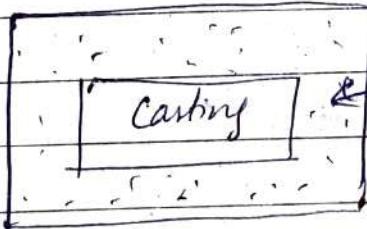
White heart means

In this process, decarburization is carried out of the surface layers. So, fractured surface has white appearance.

If specimen is thin decarburization may take place to the core.

In the both cases microstr. is same ferrite + tempered C but fractured surface will be different.

To obtain this is done to obtain greater durability & machinability.



air / iron oxide /  $\text{CO}_2$

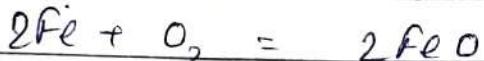
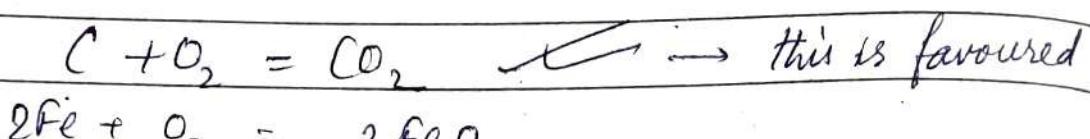
Black heart

So it is no contact with air or iron oxide or  $\text{CO}_2$ . Temp. is around  $950^\circ\text{C}$

The oxygen potential (in case of air / iron oxide)

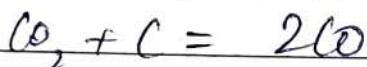
Oxidising potential -  $p_{O_2}$

is adjusted in such a manner that decarburization is preferred over surface oxyd<sup>ation</sup>.

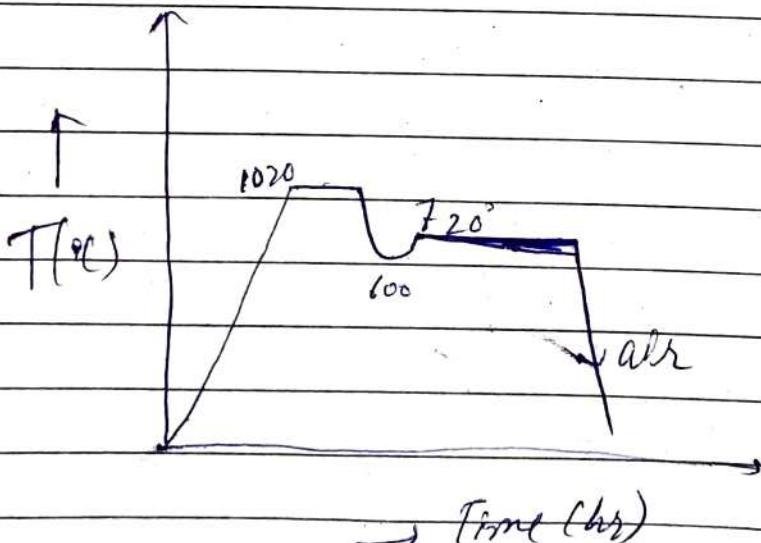


So compared to scale form<sup>s</sup>, decarburiz<sup>n</sup> is favoured.

If  $CO_2$  is used, decarburiz<sup>n</sup> will take place in



Decarburiz<sup>n</sup> of surface layers depends upon holding time at  $950^\circ C$ . The core has a microstr. consisting of lamellar pearlite which has poor properties. The cementite must be transformed to globular cementite to have greater mafinability.



If it is heated to a temp. of  $1020^\circ C$  for

very short period & supercooled to  $600^{\circ}\text{C}$  &  
then reheated to  $720^{\circ}\text{C}$  hold for very long time & air  
cooled.  
Transform to globular cementite tubes  
plus.

### Pearlitic malleable Cast Iron

In the case of black heart/ white heart  
microstr. consist ferrite + temper carbon

Since the matrix <sup>consist of</sup> is ferrite, therefore  
the durability is quite high & wear  
resistance is not so high. In the case  
of pearlitic malleable C.I., the  
matrix is pearlite + temper C. This  
is done to increase wear resistance at  
the cost of decreased durability. This is  
<sup>now</sup> <sup>pearlite</sup> → done by controlled heat treatment process  
in which certain amt. of combined  
C is knowingly left.

### Heat treatment process

Process is similar upto FSC (first stage  
of graphitization) as in case of malleability  
of cast iron. After FSC, the  
casting is supercooled to a temp.  $600^{\circ}\text{C}$   
& then again heated in the range

870 - 930°C to take back cementite  
once again into austenite, and then it  
is air cooled - this way Abt. 0.7% C  
can be kept in the combined form. Thus  
the microstr. consists of perlite +  
tempered C (from PSR).

S.G. iron → Spheroidal graphite.  
 Ce or  
 0.01 - 0.06% Mg (1-2% Ni-Mg)  
 Mg is abt 20%.

In the molten bath of grey C.I.  
 Mg & Ce are added. Mg content is high  
 0.01 - 0.06%. Mg is added in form of alloy  
 Ni-Mg (1-2%), Mg content in Ni-Mg alloy is  
 20% (Since Mg is light material)  
 Ni acts as graphitiser, thus Mg is alloyed  
 with it for addn.

Mg lower the surface tension of  
 molten surface of bath &  
 graphite flakes are transformed into ferrite.  
 Ferrite consist of ferrite + spheroids of  
 graphite. This is done to increase machinability.

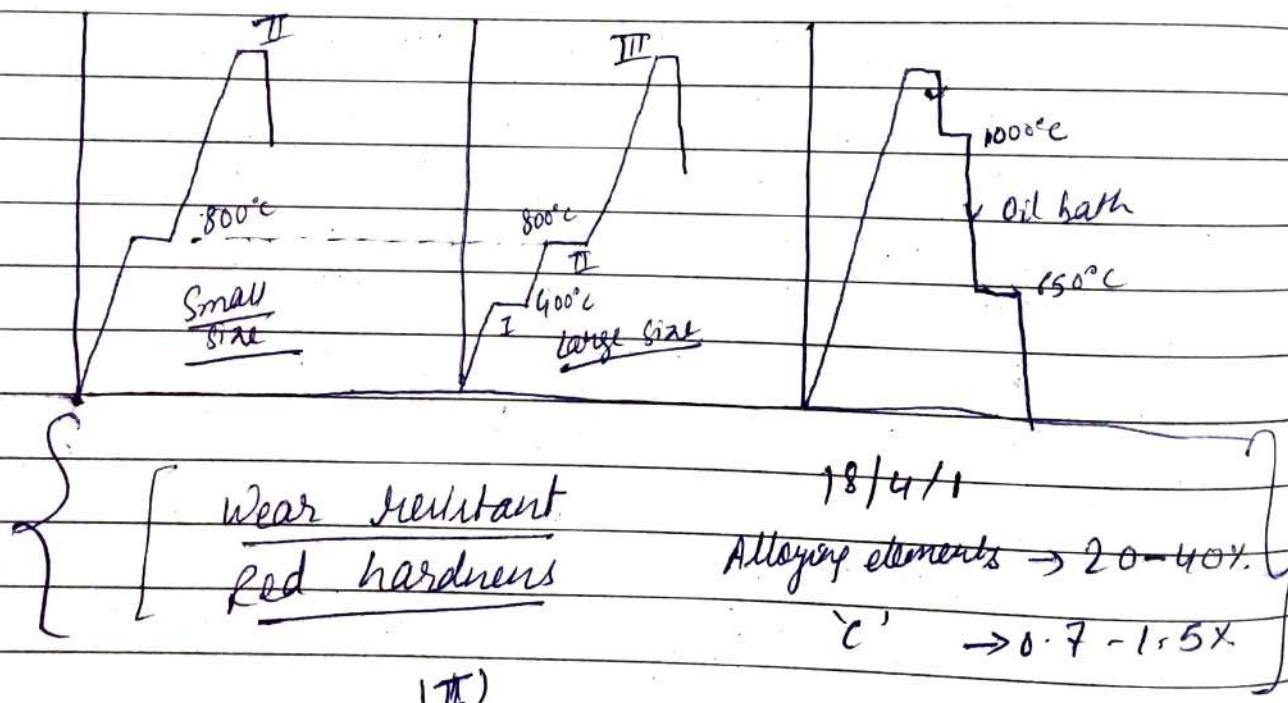
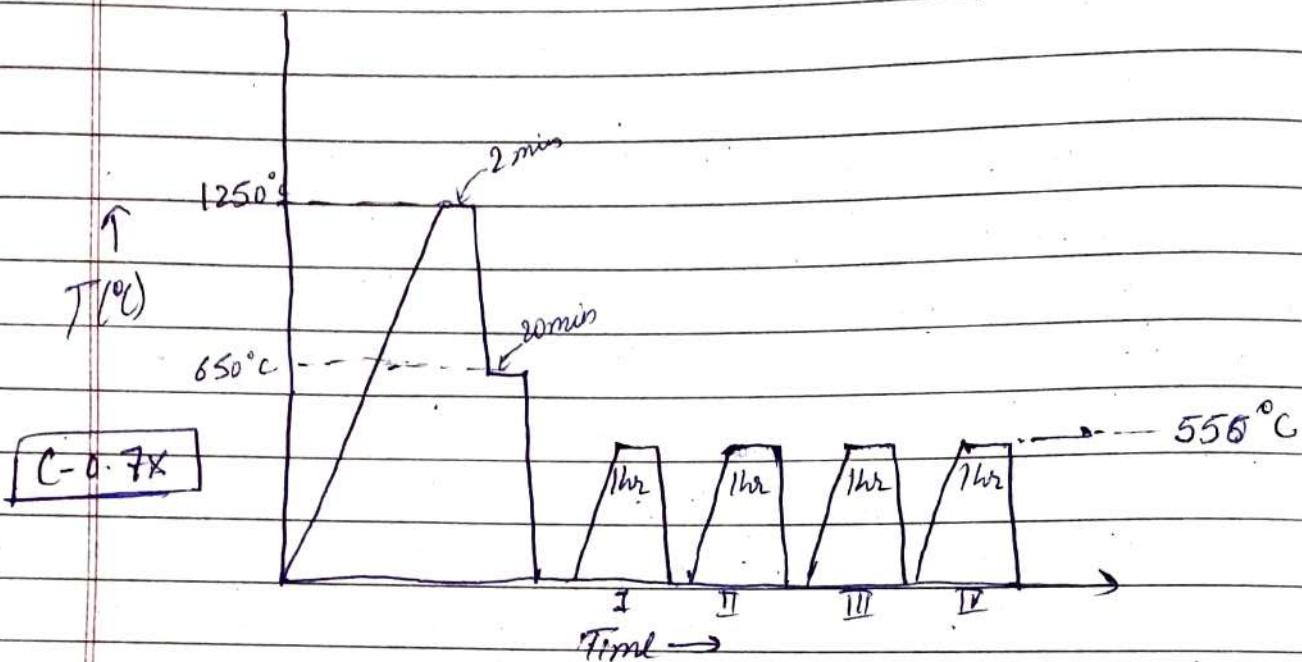
## Austempered ductile Iron

Austempering of SC iron is carried out by heating the casting to a temperature - e.g. to  $950^{\circ}\text{C}$ . It is kept at this temp. for sufficient amt. of time, then it is supercooled to a temp. in range  $425 - 235^{\circ}\text{C}$  & then transform. is allowed to take place at this temperature.

Microstr. consist of hainite (matrix) & graphite)

This will increase the tensile strength as well as wear resistance.

## Heat Treatment of High Speed Steel



Small size - 2 stage heating [holding  $T = 1250^{\circ}\text{C}$ ]

Large size - 3 stage " [holding  $T = 400^{\circ}\text{C}$ ,  $800^{\circ}\text{C}$ ]

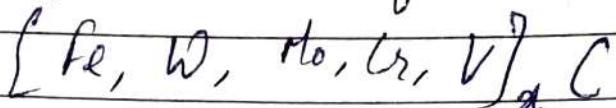
- In case of oil bath, 2 stage quenching
- In case of salt bath, single stage ".
- Tempering cycle here is multi-stage (at  $550^{\circ}\text{C}$ )
- Holding T is  $1250^{\circ}\text{C}$ , thus following problems
  - \* Grain coarsening
  - \* Surface oxid'
  - \* Decarburization
- This holding time is kept low
- It is known as high speed as it can cut at high speed, it retains its cutting in red hot state. This is thus known as red hardness prop.
- To maintain wear resistance
- $\sim 18\text{Cr}1\text{WV}$  - W, Cr, V, these are all strong carbide formers. W is very costly thus forms lcase. It is partially substituted by Mo. (At least 7% Mo).

Alloying elements must vary b/w  $20-40\%$ .  
 % C is also kept <sup>high</sup> <sub>to</sub> that sufficient carbides are formed [ $0.7-1.5\%$ ].

In this case intergranular corrosion

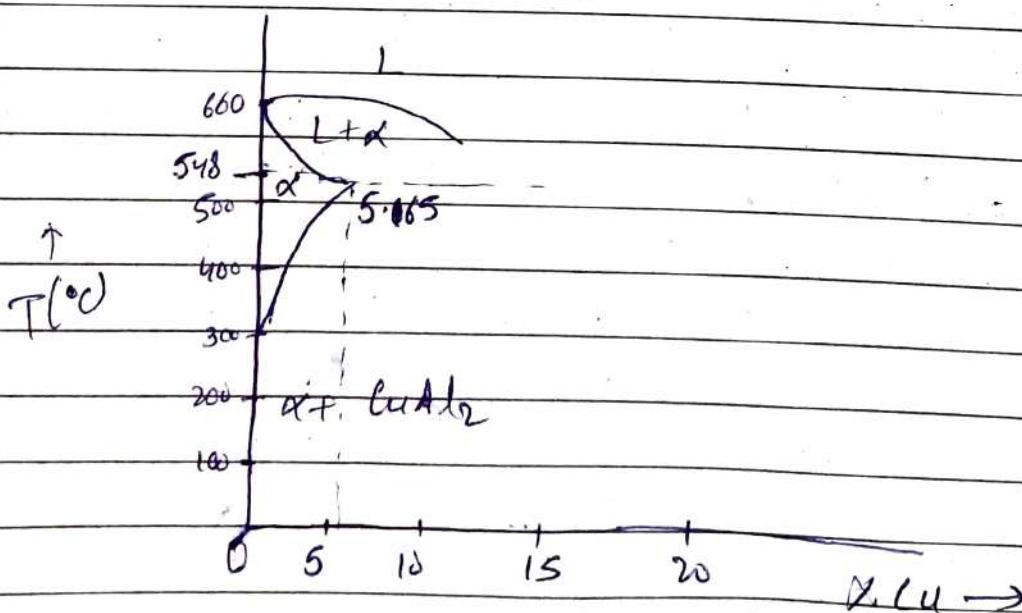
takes place, so strong carbide formers are added (so that Cr do not form at the  $\alpha\beta$ )

Complex carbide formed:

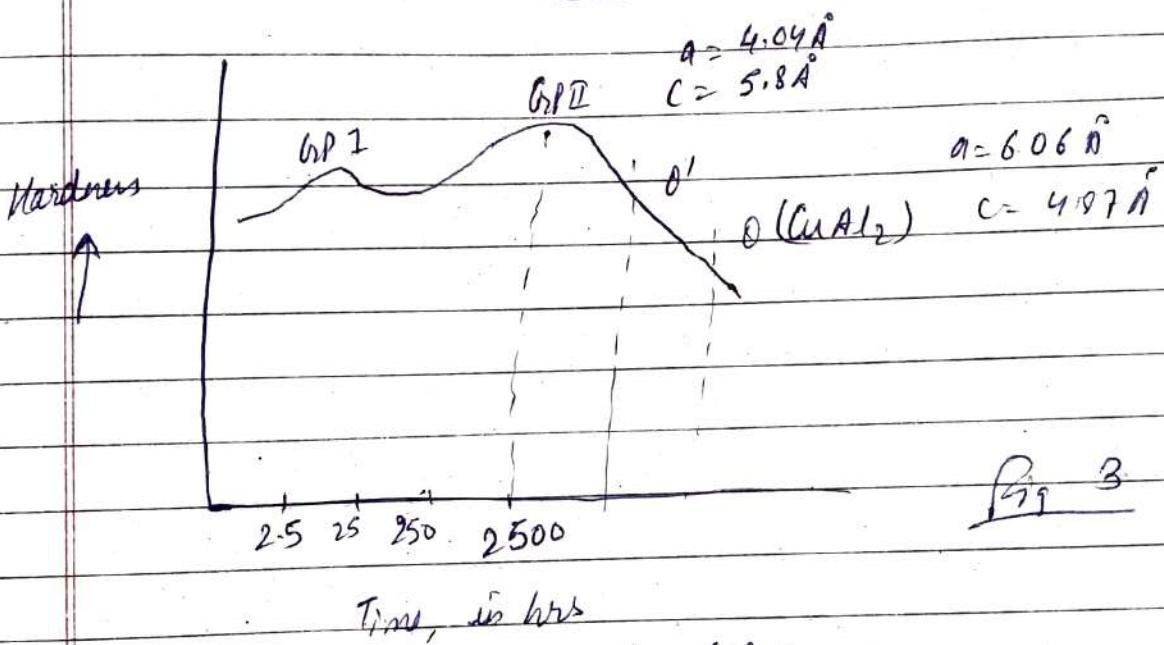
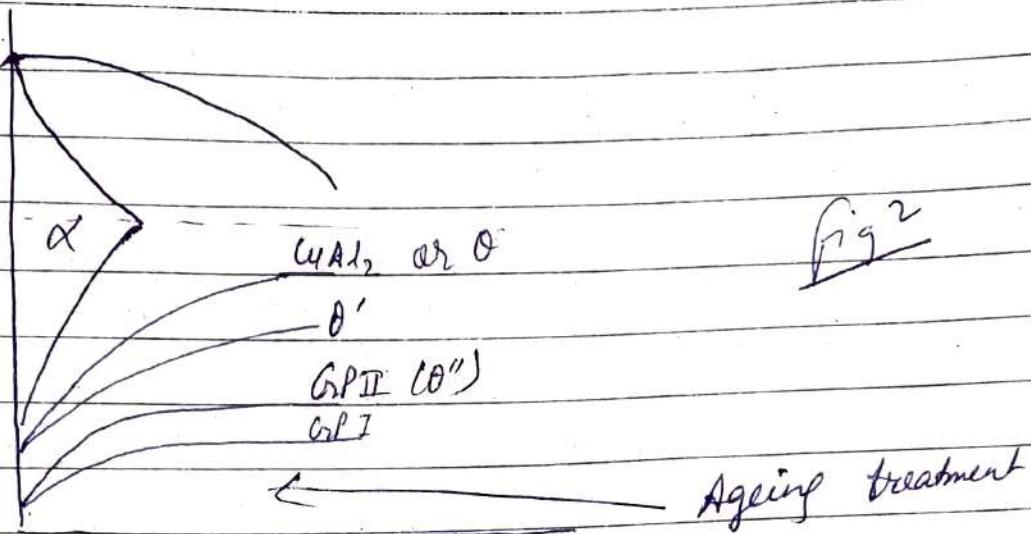


All alloying elements are heavier elements thus they diffuse out only at high T. So complex carbides ppt. but only at high T & then disperse into the matrix. This happens during tempering (multiple tempering). It is repeated many times all complex carbide ppt. out & disperse out ~~from~~ in the matrix, thus raising hardness.

### Heat Treatment of Duralumin (Al-4%Cu)



Al-Cu phase diagram



Hardness Peaks for GP I & GP II

### Durability

Strength ratio is very high.  
Weight

Relevant portion is upto 5.165 % Cu.

$\text{CuAl}_2$  - Tetragonal structure.

## Steps

I. 1st step is the heat treatment is known as 101<sup>o</sup>C heat treatment

The process involves heating the specimen in the single phase region to a temp of abt. 500°C & it helps for sufficient length of time so that a single phase is available (α)

II. Specimen is now quenched in water

Pdt. phase Specimen is now supersaturated with CuAl<sub>2</sub>. All the CuAl remains with Al.

III. If specimen is left at RT for long time we call it natural ageing.

If the ageing is carried out at higher T, we call it artificial ageing

IV. Form<sup>n</sup> of GP I zone

Guinier Prestige zone.

When the ageing is carried out at a temp. of 130°C, Cu-rich clusters of the dimension 100 Å in dia & abt 3 atomic depth thickness are formed. These Cu-rich clusters are known as GP I Zone. These clusters

are completely coherent with the parent matrix but since atomic size of Al & Cu are different, elastic strains are developed.

~~Fig 3~~ <sup>hardness</sup> The 1st peak corresponds to formation of GP zone.

### (ii) formation of GP II zones

If the ageing is carried out at around  $180^{\circ}\text{C}$ , formation of GP II zones take place. Here the Cu clusters growth is size i.e.  $\phi$  around  $1500\text{\AA}$  & thickness  $150\text{\AA}$ .

GP II zones are semi-coherent. There is matching along A & B axis but there is mismatch along C, as a result compressive strains are developed along thickness.

GP II zones are coherent along the  $\phi$  but the coherency is lost along the thickness so GP zone ( $\phi''$ ) are tetragonal.

$$a = 4.04 \text{\AA}$$

$$c = 5.8 \text{\AA}$$

Second peak in hardness is ~~at high form~~<sup>corresponds to</sup> of GP II zone

(vi) As the temp. is raised beyond  $200^{\circ}\text{C}$ , GP II zones are dissolved which is known as reversion. Therefore app<sup>n</sup> temp. of ppt<sup>n</sup> hardened disaluminis is limited to  $200^{\circ}\text{C}$ .

(vii) If the aging T is raised further, coherency is slowly lost, (as a result of increase in tetragonality) & thus hardness values are decreased.

(viii) If the aging T is raised further coherency is completely lost &  $\text{CuAl}_2$  (D) is formed.  $\text{CuAl}_2$  is tetragonal with

$$a = 6.06 \text{ \AA}$$

$$c = 4.87 \text{ \AA}$$

### Mechanism of ppt<sup>n</sup> hardening

The mechanism was explained by Orowan mechanism.

(i)



(ii)



(III)



→ (I) If the  $\text{pt}$  is very fine, then the disloc<sup>n</sup> can cut through it.

→ (II) If the  $\text{pt}$  particle are very fine but larger than  $\text{pt}$  can then the disloc<sup>n</sup> can pass in the gap b/w the two.

→ (III) The disloc<sup>n</sup> forms a loop (bending) to move through as the size of rotated particle grow. These disloc<sup>n</sup> loops interact with adjacent disloc<sup>n</sup> & cancel each other (annihilation). As a result a closed loop is formed around the rotated particle similar to annihilation in case of ESR-Red source. This form of close loop creates more problem for the dis loc<sup>n</sup> loops as they have to bend more.

The increase in strength / of hardness is due to obstacle created by rotated finer particles

(III) results in increase in hardness ~~of~~

[Or II]

(IV) results in increase in " " <sup>of</sup>  
[Or I]