UNIT - II

Contents

- **Pearlitic transformation:** Mechanism of transformation, Kinetics of transformation, Hull-Mehl model of pearlitic transformation, Effect of alloying elements on transformation, Interlameller spacing,
- **Bainitic transformation:** Characteristics, Mechanism of transformation, Bainitic structure.
- **Martensitic transformation:**

Diffusionless transformation, Mechanism of transformation, Kinetics of transformation, M_s - M_f temperatures, Athermal and isothermal martensites, Effect of applied stress on transformation, Habit planes, Bain distortion model / crystallographic theory of martensitic transformation, Tempered Martensite, Retained austenite, Martensitic transformation in non-ferrous systems such as Fe-Ni and Cu-Al systems.

Pearlitic Transformation

- At eutectoid composition (0.77% C)

  Fe_3C – 11.28 % α-Ferrite- 88.72%

  Density =7.70 g/cc density = 7.87 g/cc

- Decomposition of austentie to pealite is
  - Diffusion controlled process
  - Nucleation and growth
  - Interlamellar spacing depends on transformation temp.

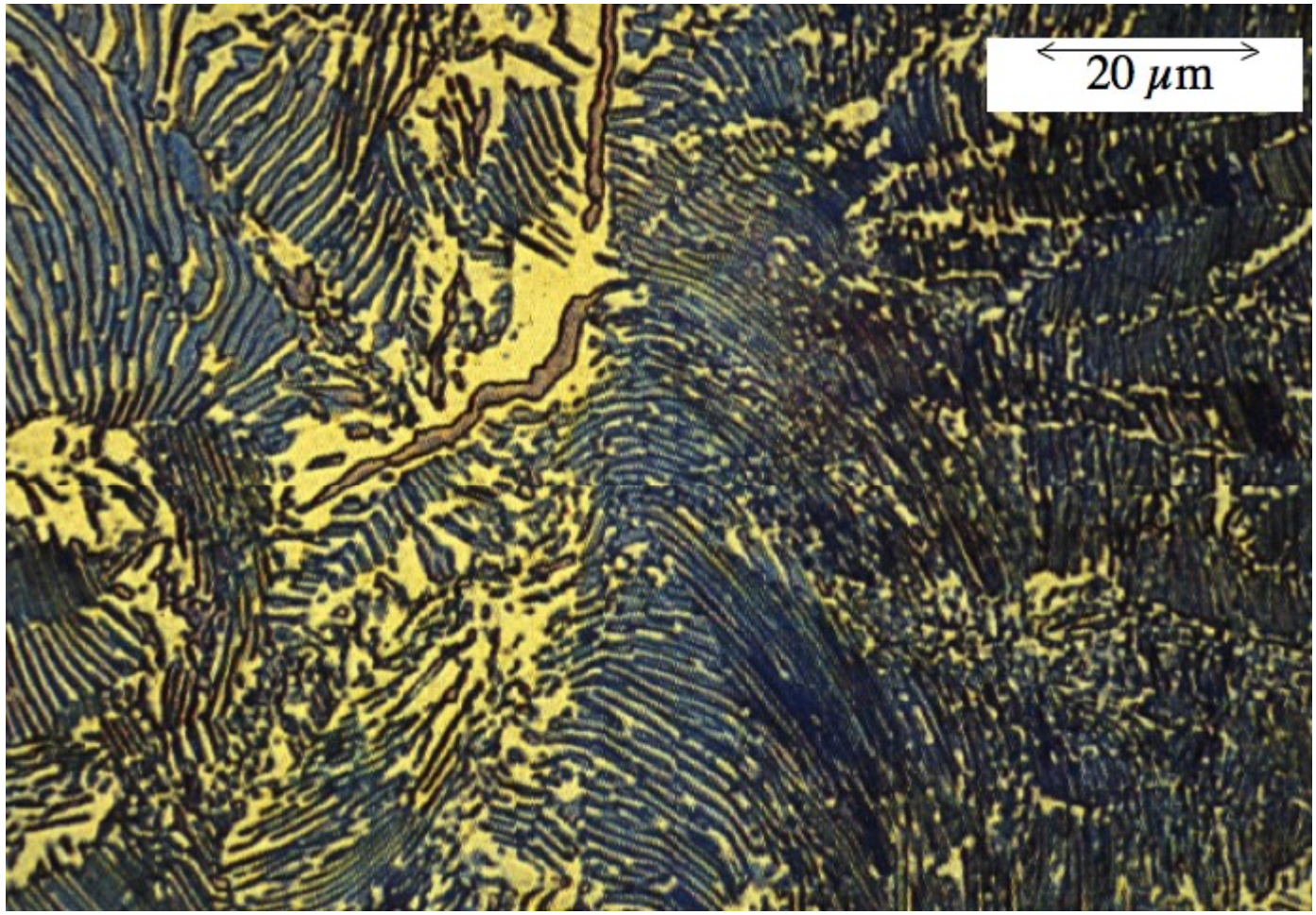


Figure : The appearance of a (coarse and fine) pearlitic microstructure under optical microscope.

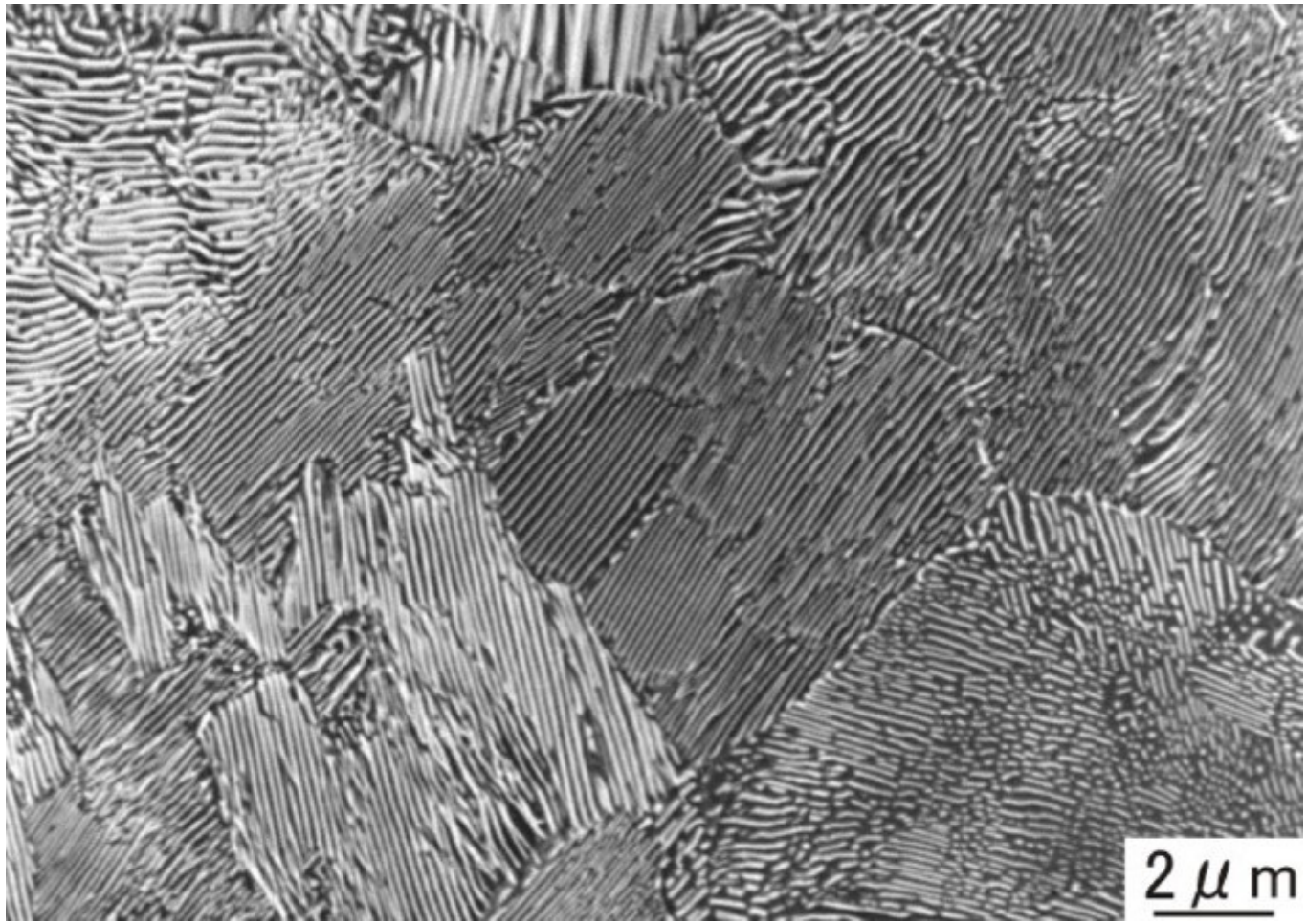


Figure: Optical micrograph showing colonies of pearlite

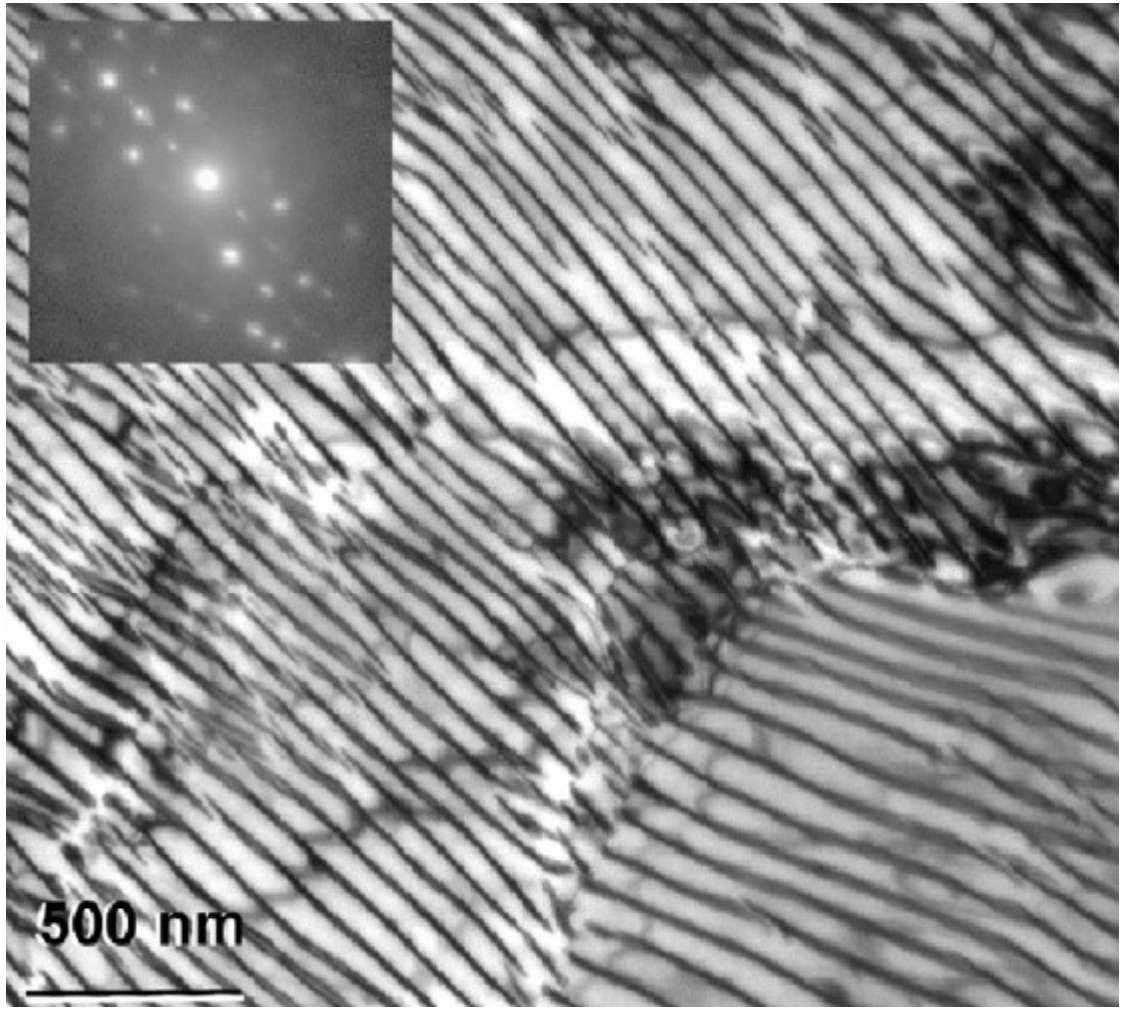


Figure: Transmission electron micrograph of extremely fine pearlite.

Hull-Mehl model

Nucleation and growth of pearlite

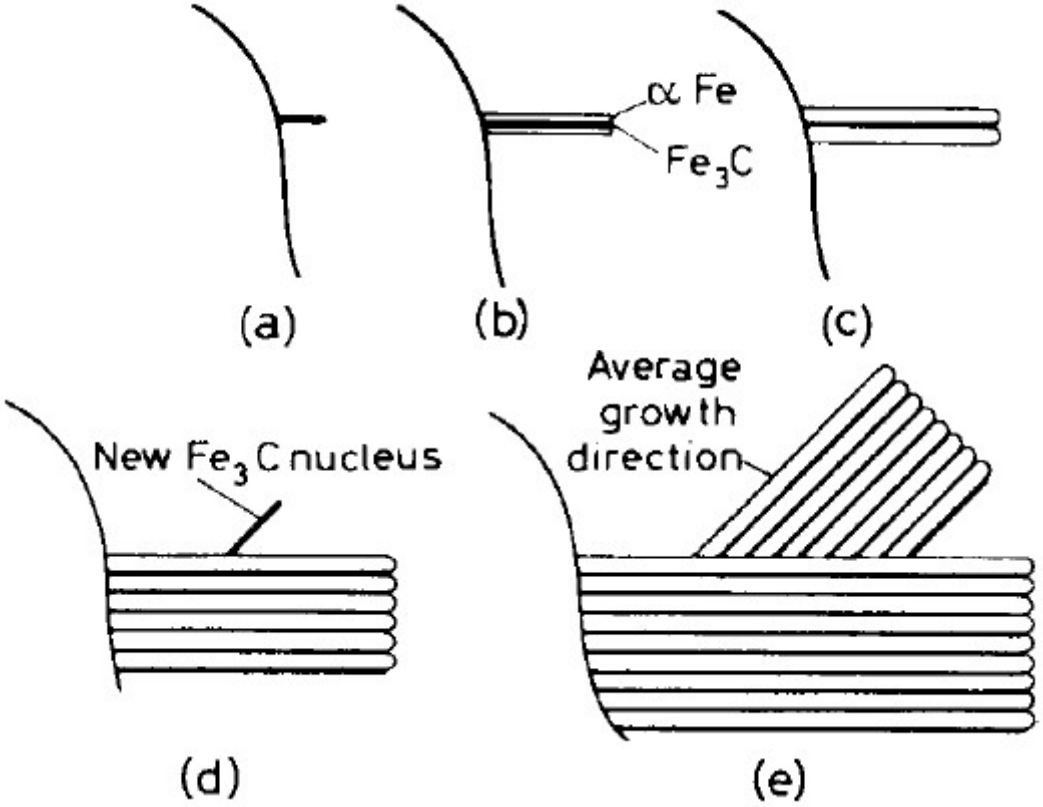
(a) Initial Fe_3C nucleus;

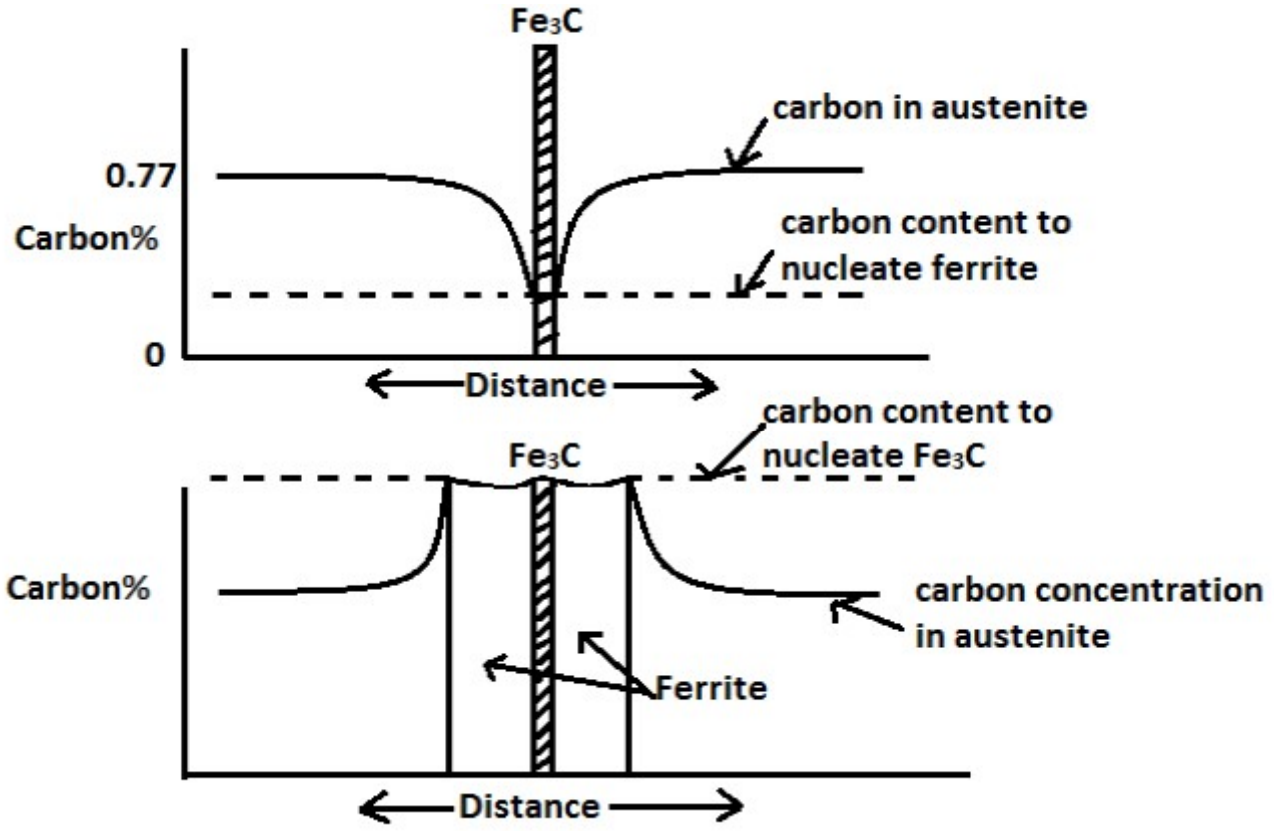
(b) Fe_3C plate full grown, α-Fe now nucleated;

(c) α-Fe plates now full grown, new Fe_3C plates nucleated;

(d) Fe_3C nucleus of different orientation forms and original colony grows;

(e) New colony at advanced stage of growth




Fe3C
carbon in austenite
0.77
Carbon%
carbon content to
nucleate ferrite
0
Distance
carbon content to
nucleate Fe3C
Fe3C
Carbon%
carbon concentration
in austenite
Ferrite
Distance

Transformation of Austenite to Pearlite

- The decomposition of austenite into pearlite by diffusion controlled process. i.e. Diffusion of C. It can be explained by Thermodynamics and Kinetics
- There are two steps involved in diffusion controlled process
  - Nucleation
  - Growth
- The rate of transformation is governed by both.
- Rate of nucleation and growth is zero at A_1 temperature
- Rate of diffusion of C atoms is negligible below 200˚C.

Kinetic of transformation:

At Ac_1, G(pearlite) = G(austenite) → No transformation

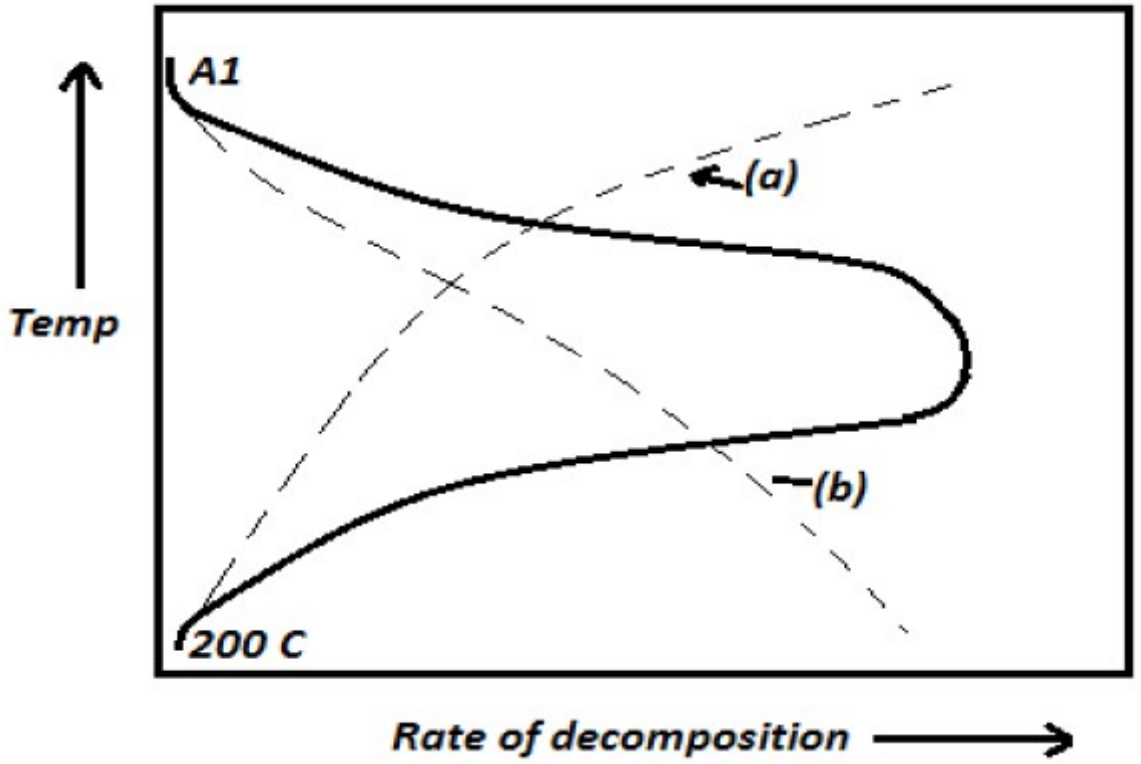
$<Ac_1$, G(pearlite) < G(austenite)

austenite ⟹ pearlite

$<< Ac_1$, stability of pearlite increases

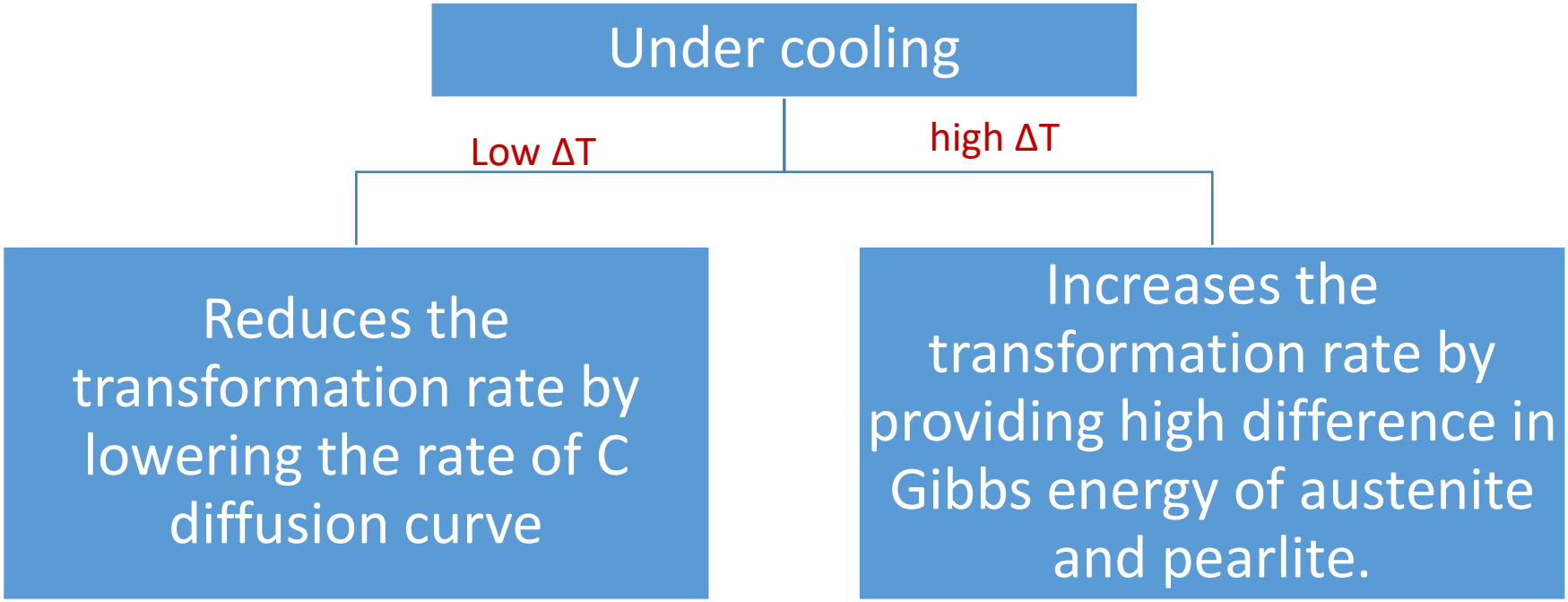
Rate of austenite to pearlite transformation increases with lowering / undercooling transformation temperature

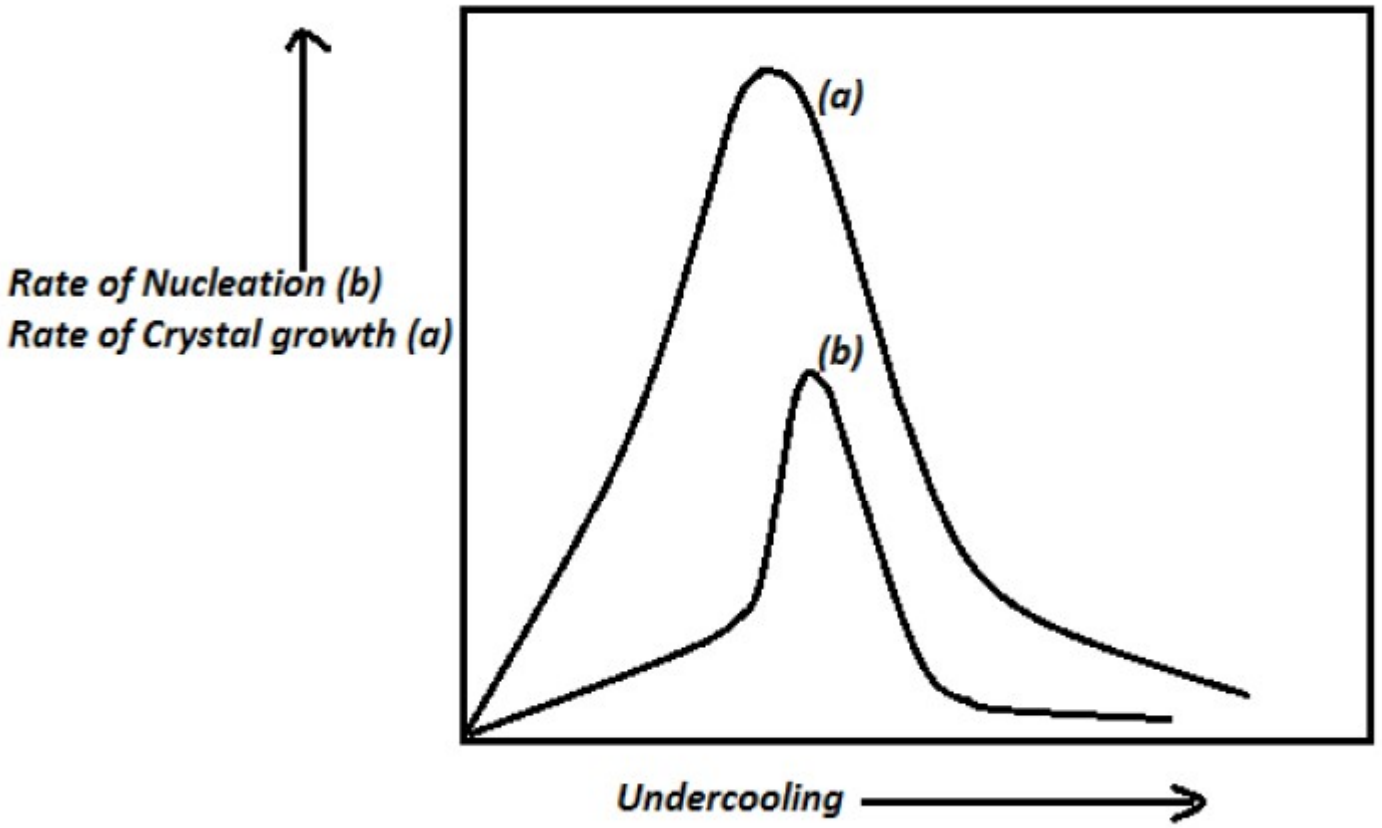
Rate of diffusion of carbon decreases exponent with decreasing temperature



a) Rate of crystal growth b) Rate of nucleation

- Under cooling affect the rate of transformations.





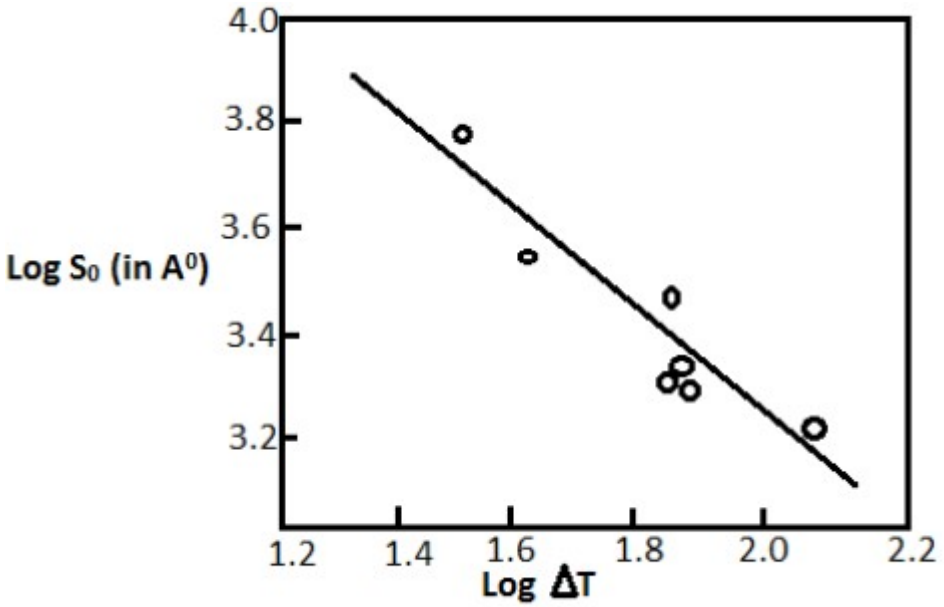
The rate of nucleation and growth with respect to under cooling

Interlamellar spacing:

- Zener has shown that

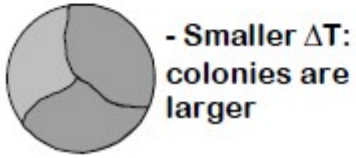
$$S_o = \frac{4\gamma T_m}{\Delta H \Delta T}$$

Where γ – specific surface energy,
T_m- transformation temperature,
ΔH – enthalpy of transformation
ΔT- amount of under cooling .



- Depends on function of transformation temperature.
- Lower the transformation temp., smaller is the interlamellar spacing.
- Hardness and strength increases when So is decreases.

- Alloying elements, except Co, increase the interlamellar spacing due to slow diffusion of alloying elements.
- Interlamellar spacing is structure insenstivie. i.e. independent of austenitic grain size and degree of homogeneity of austenite



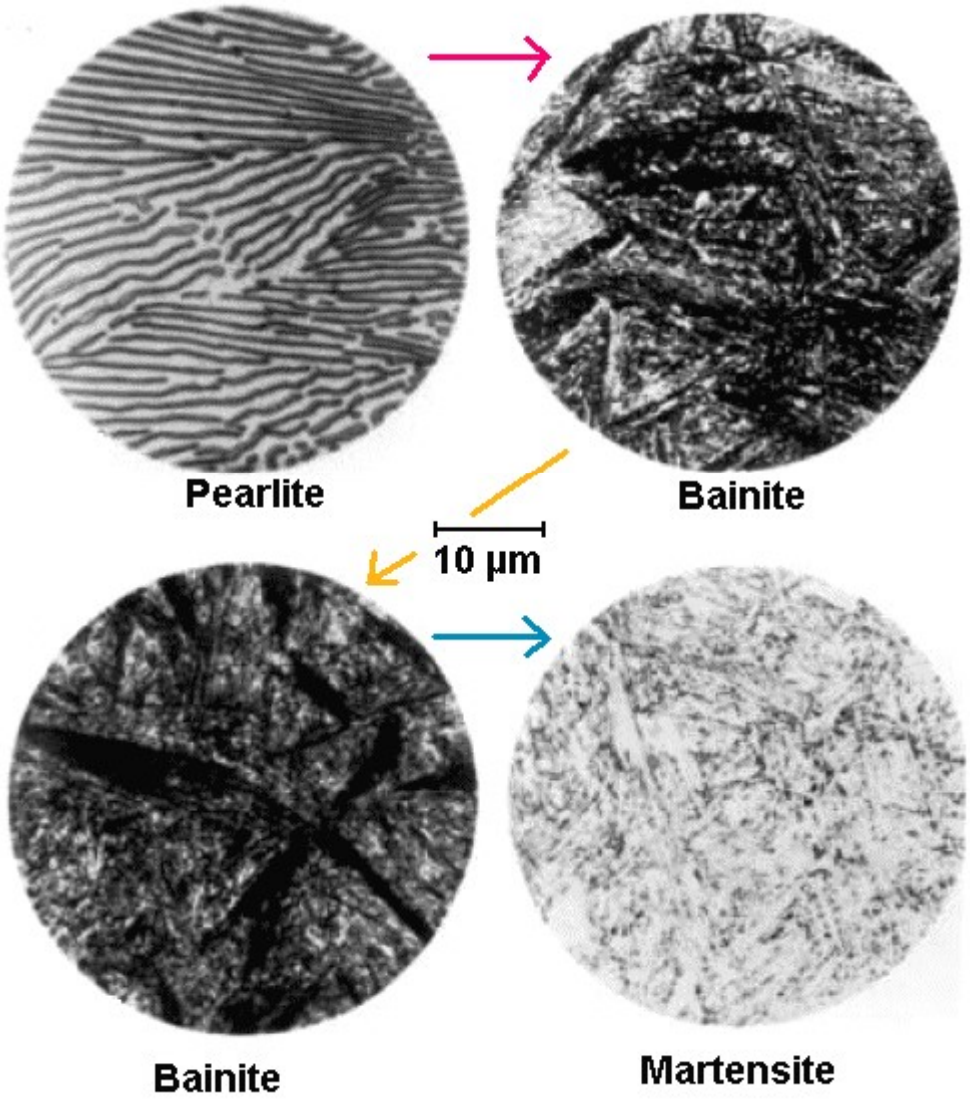
- Smaller ΔT: colonies are larger

- Larger ΔT: colonies are smaller

- Effect of alloying elements:

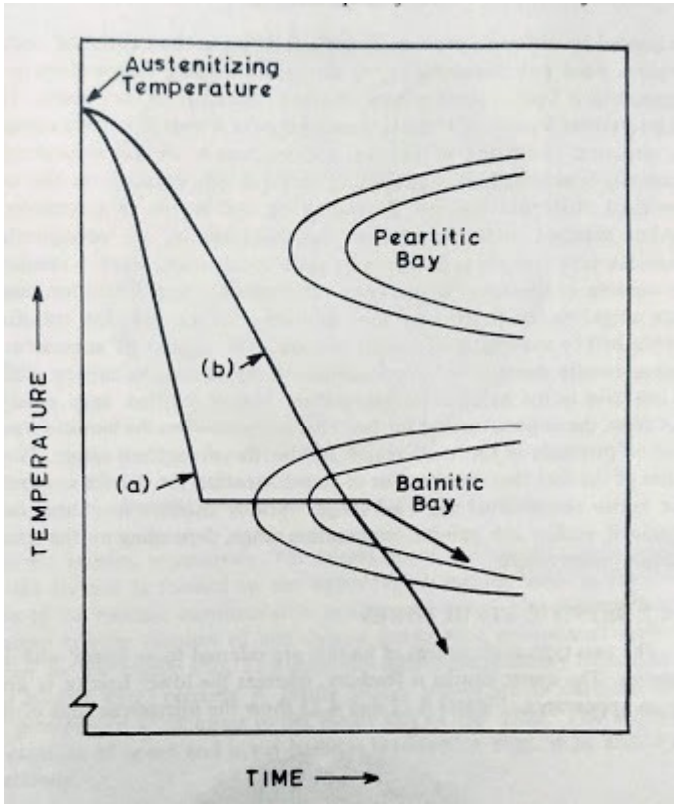
  All the alloying elements except Co lowers both nucleation and growth rate due to slow diffusion of alloying elements

  Carbide forming elements further reduces the diffusion of C by forming carbides. Ex. :Cr

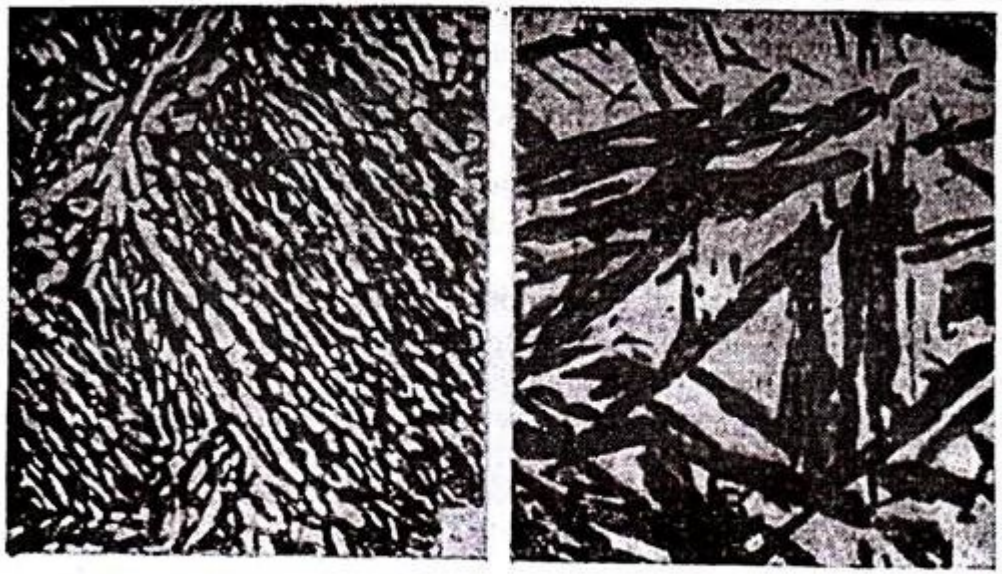

Pearlite
Bainite
10 µm
Bainite
Martensite

Bainitic Transformation

- Bainite –Mixture of ferrite and carbide.
- The nucleus of bainite is ferrite.
- It forms below pearlite transformation temp. and above M_s temp.
- For eutectoid steel, bainite forms between 200-500°C
- Mostly formed by isothermal transformations.
- In the presence of alloying element, it can form by CCT.



- The carbides distributed on the finer scale.
- There is variation in the morphology of bainite based on type of carbide, temp. of transformation and composition of steel
- Classified as
  - Upper bainite
  - Lower bainite



(*a*) (*b*)

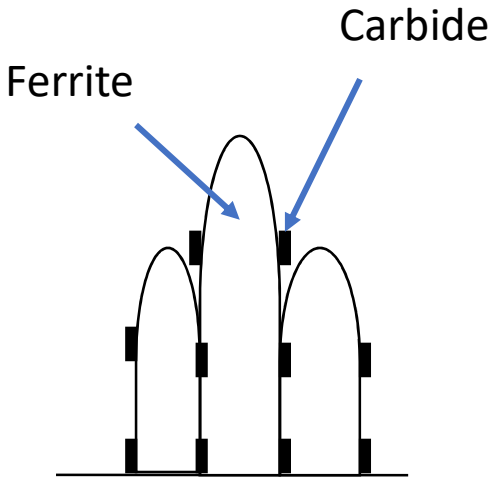
Fig. 3.37. (*a*) Upper bainite (feather-like) × 5000, (*b*) Lower bainite-acicular-darker black needles × 500

Mechanism

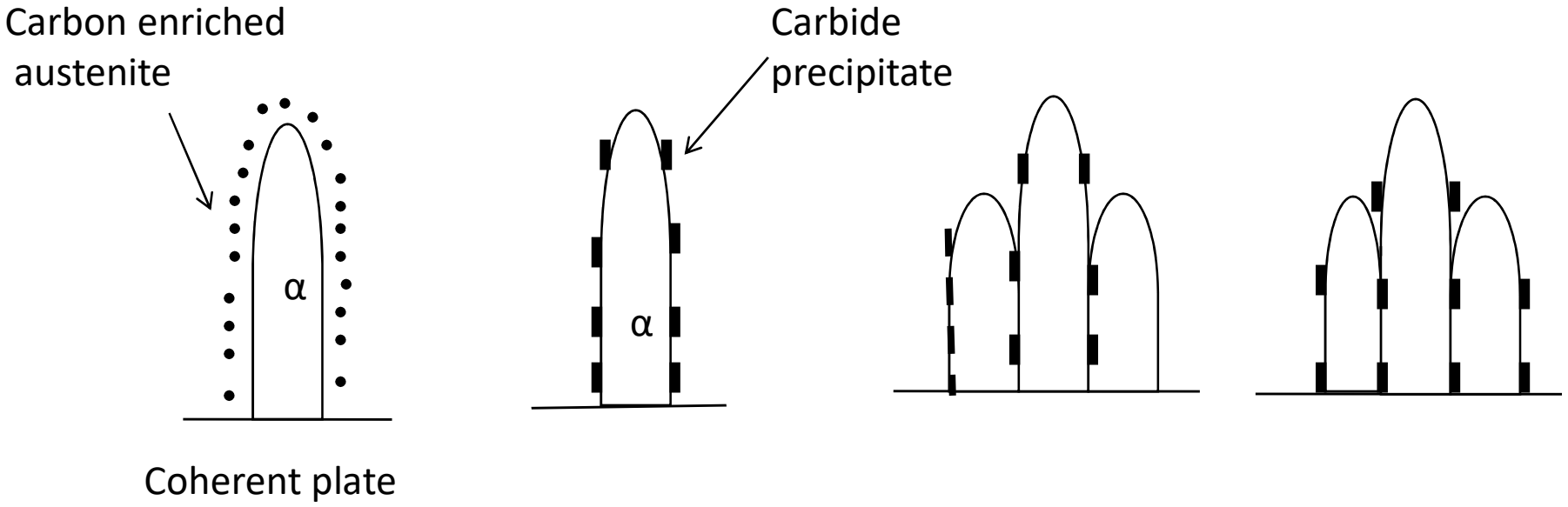
- Diffusion controlled transformation with diffusion less transformation
- At B_s, diffusion rate of Fe < Diffusion rate of C
- Half pearlite and half martensite characteristic
- Formation of bainite accompanied by surface distortion or shear process
- During undercooling below B_s temp., carbon atom redistribute in austenite by diffusion.
  - Some regions are enriched in C and some regions depleted in C.
  - Redistribution C lead to stress development
  - Low C region of austenite transforms to ferrite by shear process.
    - Portion of C enriched region transform to partially martensite.
    - Structure consists of bainite and martensite or bainite and retained austenite.
  - C enriched region transform to carbides.
- The solubility of C in Ferrite is low. The transformed ferrite in supersaturated with C. The degree of supersaturation increases with decreasing temperature. C may precipitate out from the supersaturated ferrite. It happens in lower bainite

Upper Bainite

- Also called as feathery bainite
- Forms at temp. range around 550 to 400^{o}C
- Low C austenitic region transform into ferrite which is coherent with the parent austenite
- Lath – shaped ferrite with precipitated carbides parallel to the needle axis.
- The diffusivity of the C is high enough to cause the partition of carbon between ferrite and austenite.
- Thus cementite does not precipitate within the laths, but in austenite at lath boundaries.



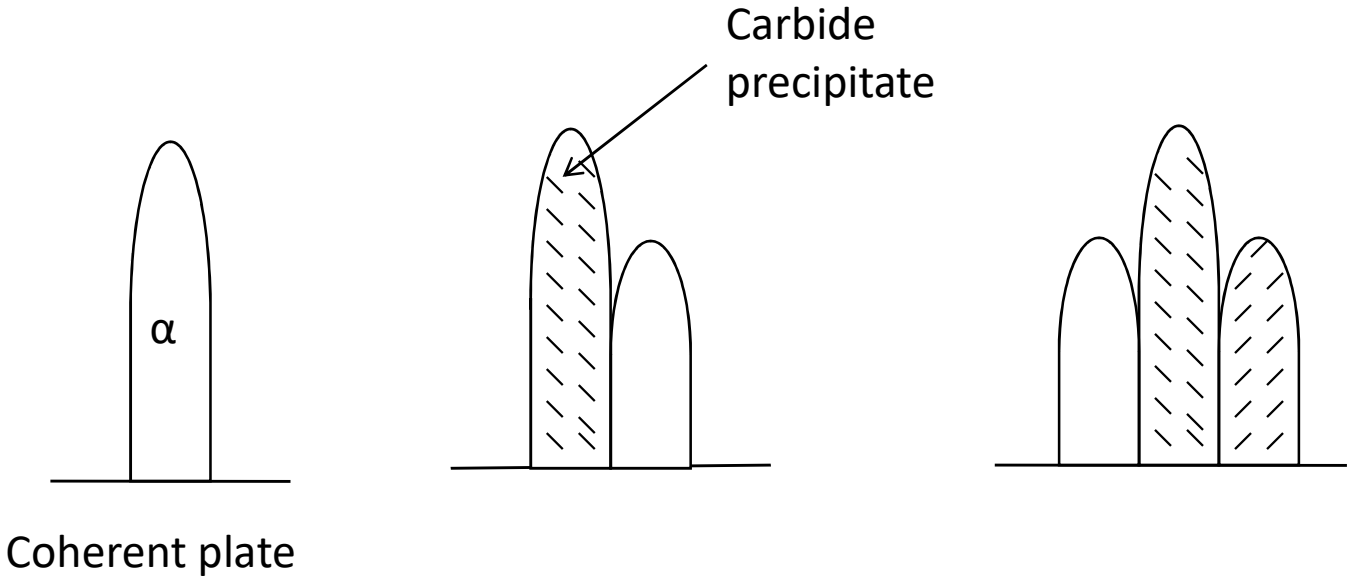
Stages of formation of upper bainite



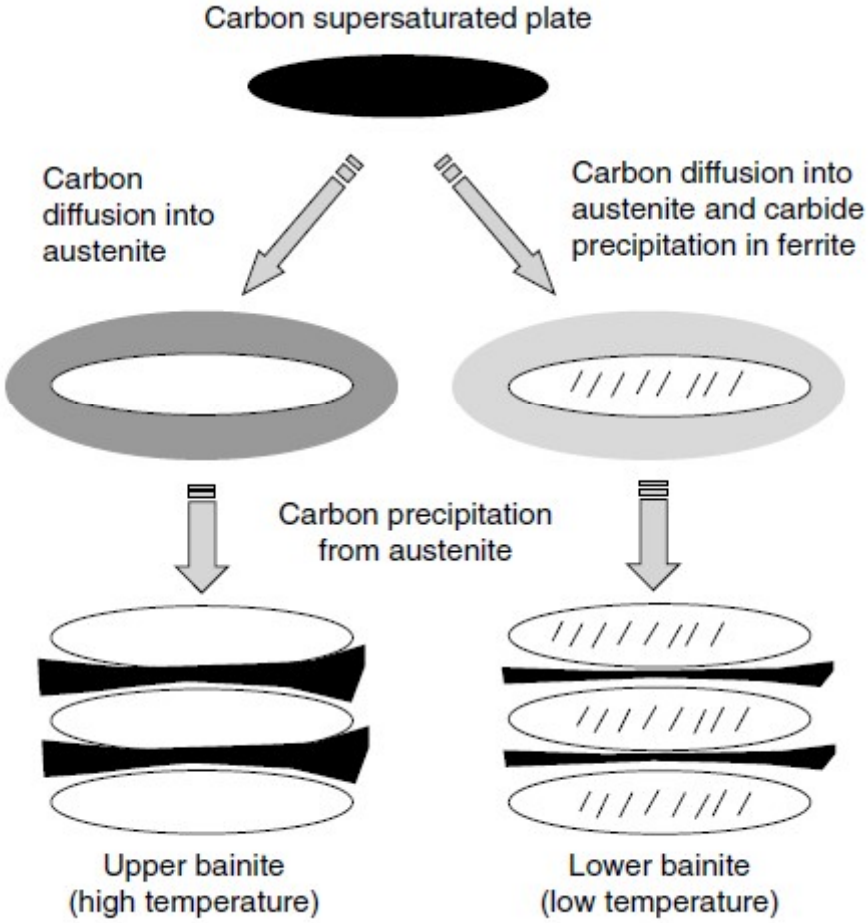
Lower Bainite

- Also called as plate bainite due to acicular appearance
- Forms in temp. range about 400 to 250^{o}C
- The finer plates of carbides are at an angle 55 to 60^{o} to the axis of bainite plate.
- The carbides in lower bainite precipitate within the ferrite plates.
- Carbides are either cementite or ε – carbide ($Fe_{2.4}C$) or a mixture of them depending on the temperature of transformation and the composition of the steel.

Stages of formation of lower bainite



Schematic illustration of upper and lower bainite transformation



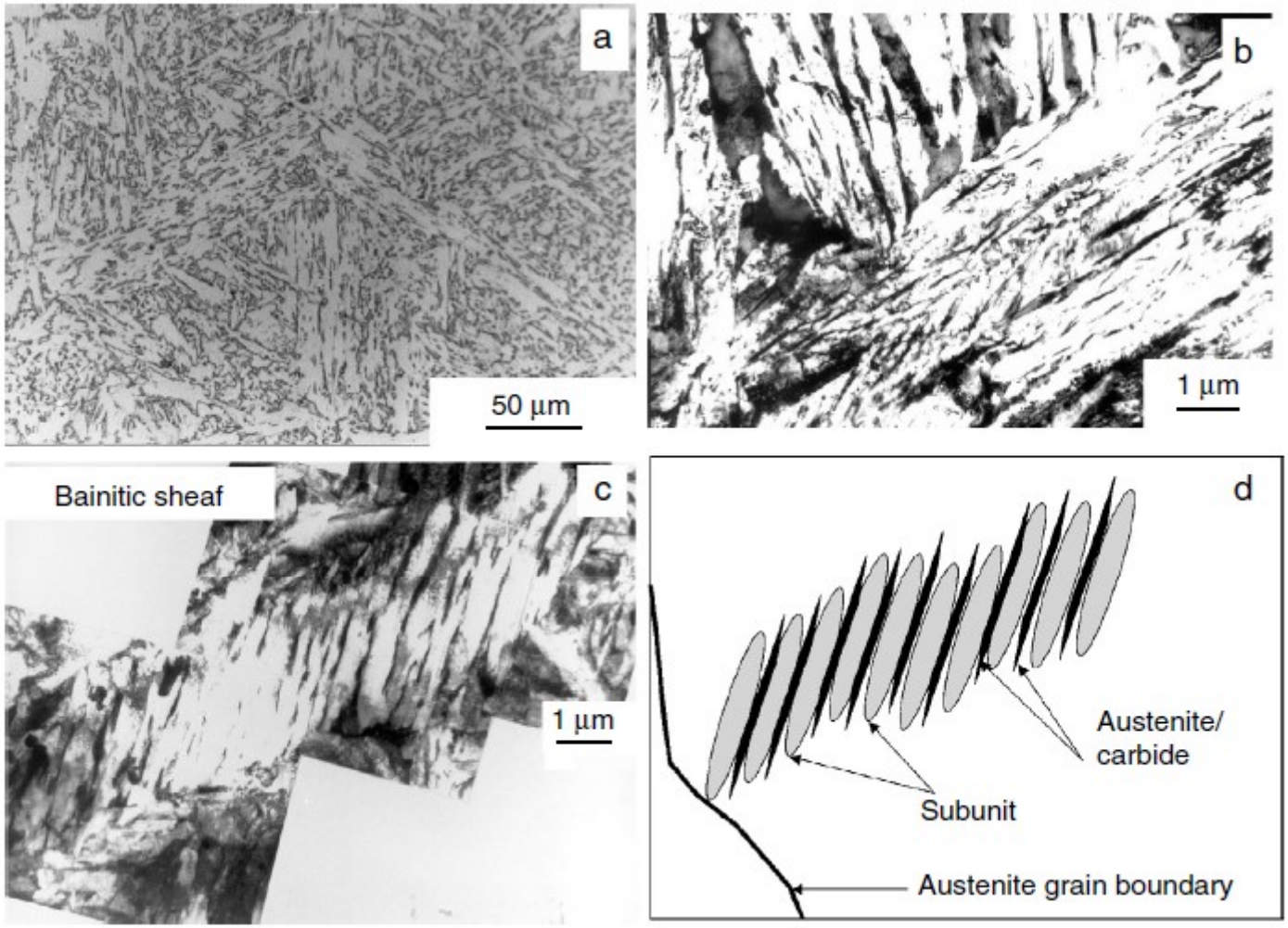


FIGURE 2.6 (a) Optical micrograph from an Fe–Cr–C steel showing a bainitic sheaf structure. (b) Transmission electron micrograph from an Fe–C–Si–Mn steel showing many sheaves of bainitic ferrite. (c) Another transmission electron micrograph of a bainitic sheaf structure from an Fe–Cr–C steel. (d) Schematic illustration of the growth mechanism by subunit nucleation and growth. (Adapted from H.K.D.H. Bhadeshia, *Bainite in Steels*, 2nd ed., The Institute of Materials, London, 2001.)

B_s-B_f Temperature

- Bainite transformation take place between the temperature range of B_s and B_f.
- In most of the low alloy steels and C steels, B_s temp. is not well defined. //ly, B_f temp. overlap with M_s temp.

Martensitic Transformation

- Diffusionless transformation
- Mechanism of transformation
- Kinetics of transformation
- M_s - M_f temperatures
- Athermal and isothermal martensites
- Effect of applied stress on transformation
- Habit planes, Bain distortion model / crystallographic theory of martensitic transformation,
- Tempered Martensite,
- Retained austenite
- Martensitic transformation in non-ferrous systems such as Fe-Ni and Cu-Al systems.

- Martensite: Supersaturated solid solution of C in alpha-Fe in BCT structure.
- When γ undercooled below ~ 200°C, it transforms into martensite
  - γ → α + Fe_3C diffusion transformation
  - γ → Martensite diffusion-less transformation

- Mechanism:
  - Diffusionless transofrmation.
  - Each atom moves less than one interatomic distance
  - Magnitude of driving force increases with decrease in temperature.

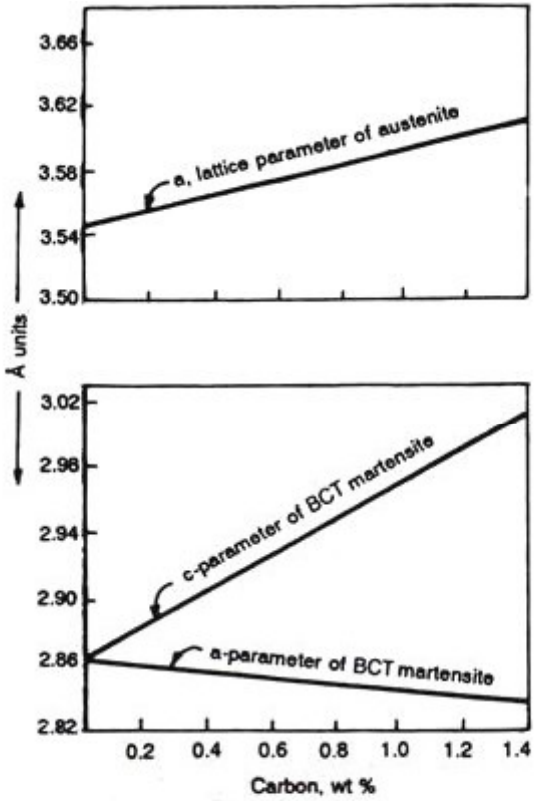
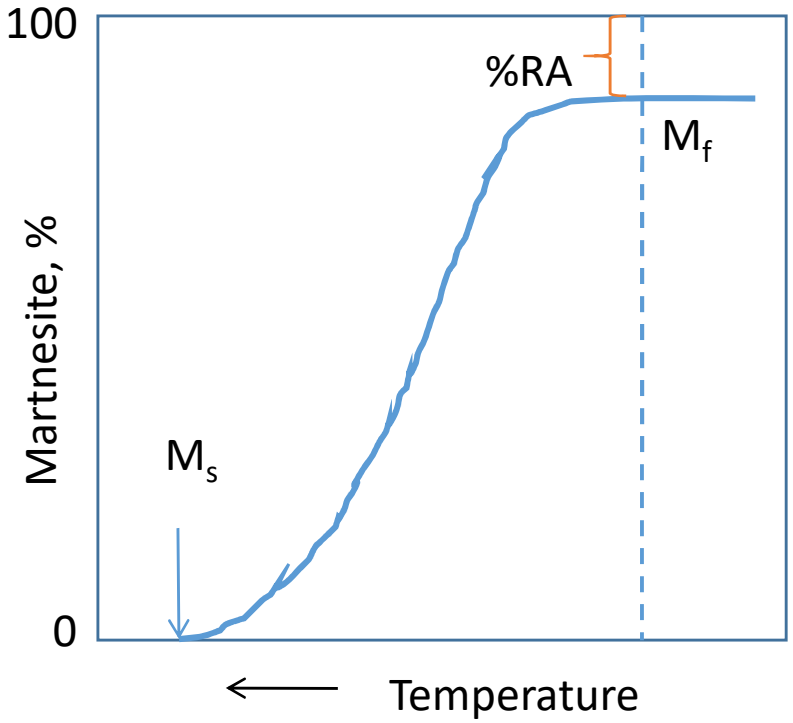


Fig. 3.51. Effect of carbon on lattice parameters of austenite and of martensite

Kinetics of Transformation

- Transformation of martensite take place in range of temp.
- % of martensite increases with decreasing temperature.
- Some amount of austenite always remains.
- Amount of martensite depends of transformation temperature and velocity of transformation.
- Each platelet of martensite formed in fraction of microsecond and transformation complete in fraction of millisecond.
- Martensite transformation is independent of holding time except few alloy steel.



M_s and M_f Temperature

The relationship between Ms temperature and chemical composition is given below.

$$M_s(°C) = 561 - 474(\%C) - 33(\%Mn) - 17(\%Ni) - 17(\%Cr) - 21(\%Mn)$$

- Except Al and Co all the alloying element lowers the M_s temp.
- M_s and M_f temperature decreases with increasing C content.

• M_s temp. is independent of cooling rate and M_f temp. is depend on the cooling rate

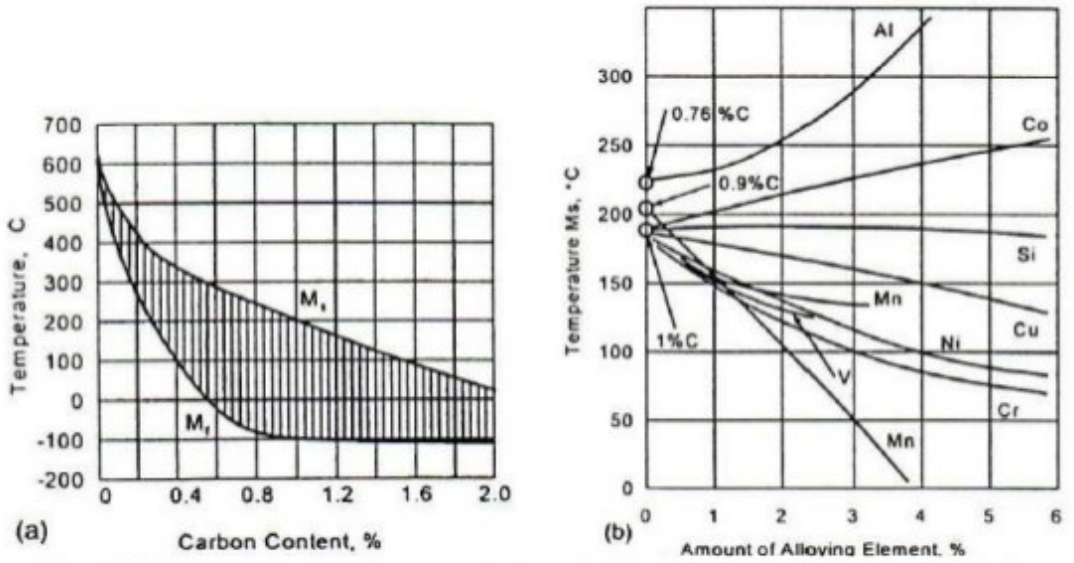
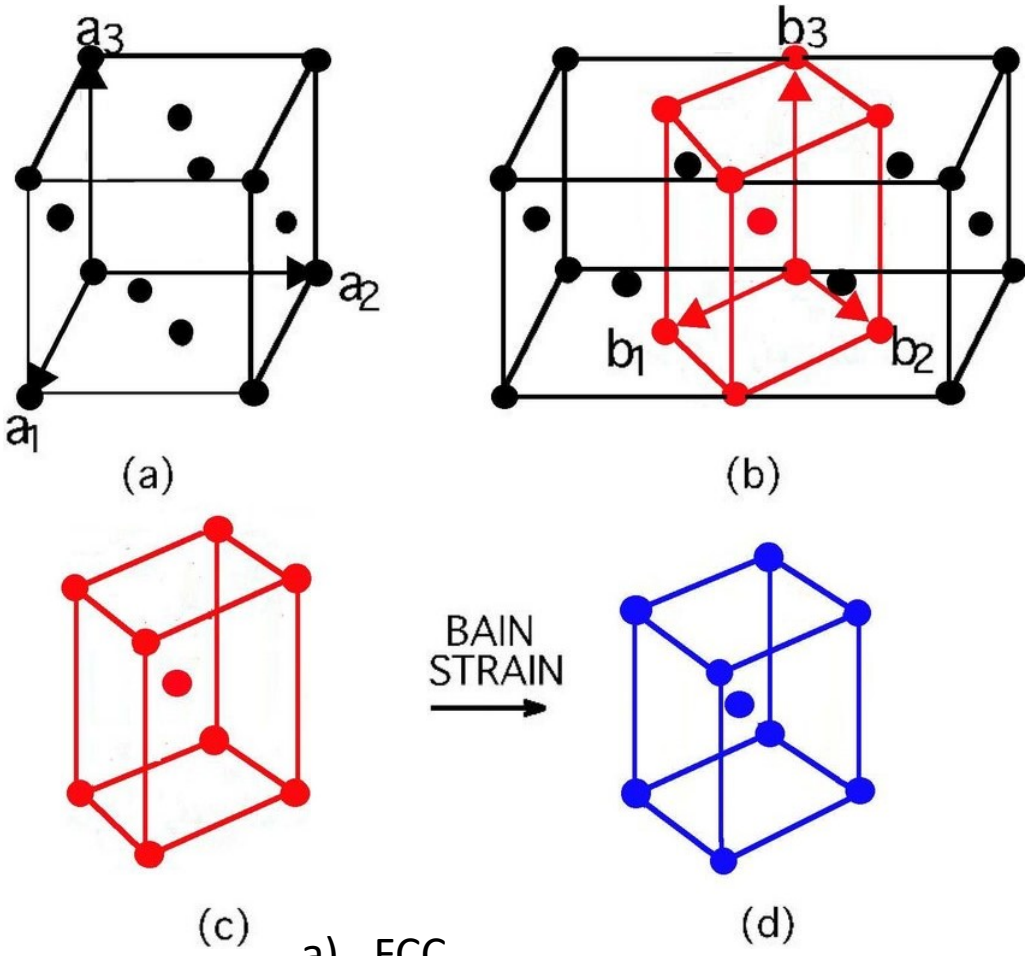


Fig. 10 Effect of (a) carbon content and (b) alloying elements at 1% C on the martensite transformation [5].

- Chemical composition of austenite and austenite grain size affect the Ms temp.
  - Temp. Increases the solubility of C increases in austenite which decreases Ms.
  - MS temperature increases with austenite grain size.
  - Predominance factor affect the Ms.
- Effect of applied stress:
  - Plastic deformation of austenite raises the M_s temperature.
  - The max. Temp. At which marteniste formed by plastic deformation is mentioned by M_d.
  - The % of martensite formed increases with decreasing temperature from M_d to M_s.
- Reversibility of transformation
  - It is irreversible.

Bain Distortion Model

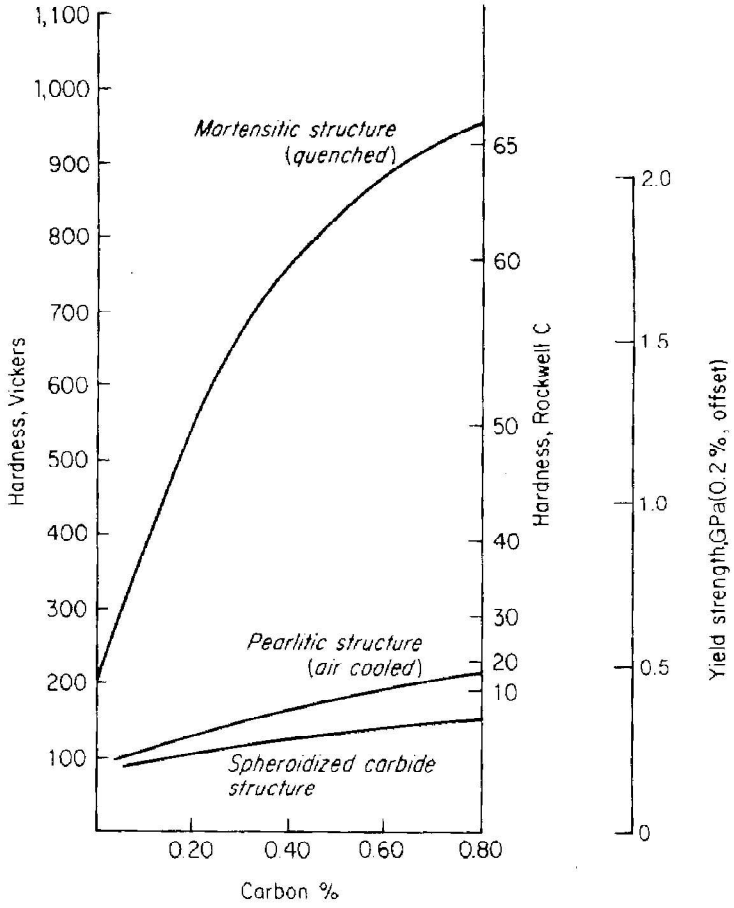
- Martensite → BCT (c/a ratio=1.08)
- In normal BCT c/a ratio =1.4
- During the transformation, [001] axis of the BCT cell compressed by about 20% and [110] axis expand by about 12 % each.
- The iron atoms move only a fraction of the interatomic distance.
- As the carbon atoms are all situated at the middle of the c axis which induces strain in the crystal.



a) FCC
b) formation of BCT from FCC
c) BCT structure
d) BCT of martensite

Hardness of Martensite

- C ↑ Hardness of Martensite ↑
  - High C steel has lower the M_s and M_f temperature. Hence have more amount of retained austenite which reduces the hardness.
  - The quantity of retained austenite is also depend on rate of cooling rate.
- Reason for hardness of martensite is
  - Internal strain within the alpha iron lattice due to excess C atoms
  - Plastic deformation of parent austenite surrounding the martensite plate.



Retained austenite

- Presence of austenite after completion of the heat treatment process is called as retained austenite (RA). Often observed in martensite transformation.
- If C↑, Ms and Mf ↓. The amount of RA also increases.
  - All alloying elements except Al and Co, decreases the Ms and Mf temp.
- RA have high dislocation density and other imperfections compared to original austenite. Hence surrounded by martensite.
- RA may change into bainite or martensite during service which introduces dimensional changes and even distortion.
- Presence of RA is undesirable.
- High carbon or high alloy steels are preferred for making tool or wear resistant components. But have more RA.
  - Alloying element decreases Ms and Mf temperature
  - Deformation process taking place in austenite phase which decreases the Ms temperature.

- Two heat treatment reduces RA content.
  - Subzero treatment
  - Tempering

Subzero Treatment:

- Subzero treatment consists in cooling the hardened steel to a temperature below 0°C.
- The temperature of the sub zero treatment depends on the position of Mf temperature of the steel. M_f temp. of steel lies between -30 to -70°C .
- Sub-zero treatment is more effective, if it is carried out immediately after quenching operation.
- Any lapse of time between hardening and the cold treatment causes the stabilization of austenite, makes the retained austenite resistant to further transformation.

Table : Subzero Coolants with Temperature of Application

Coolant	Minimum temperature °C
Dry ice (solid Co_2) + Acetone	-78
Ice + Salt (NaCl)	-23
Ice + Salt ($CaCl_2$)	-55
Liquid air	-183
Liquid Nitrogen	-196
Liquid Pentane	-129
Freon	-111

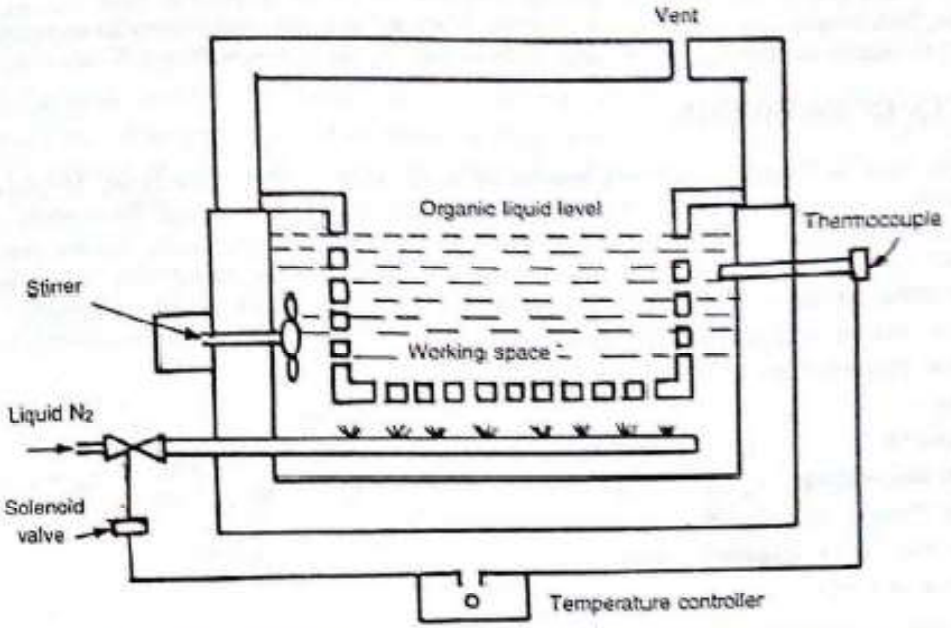


Figure : Liquid cooled (liquid N_2) system. Components are immersed in a bath of alcohol, or trichloro ethylene, which is cooled by a submerged liquid nitrogen spray (-150°C), cooling rates can be controlled.