

HEAT TREATMENT OF STEEL

Dr. RATNA PAL, Assistant Professor, RVCE

Heat Treatment

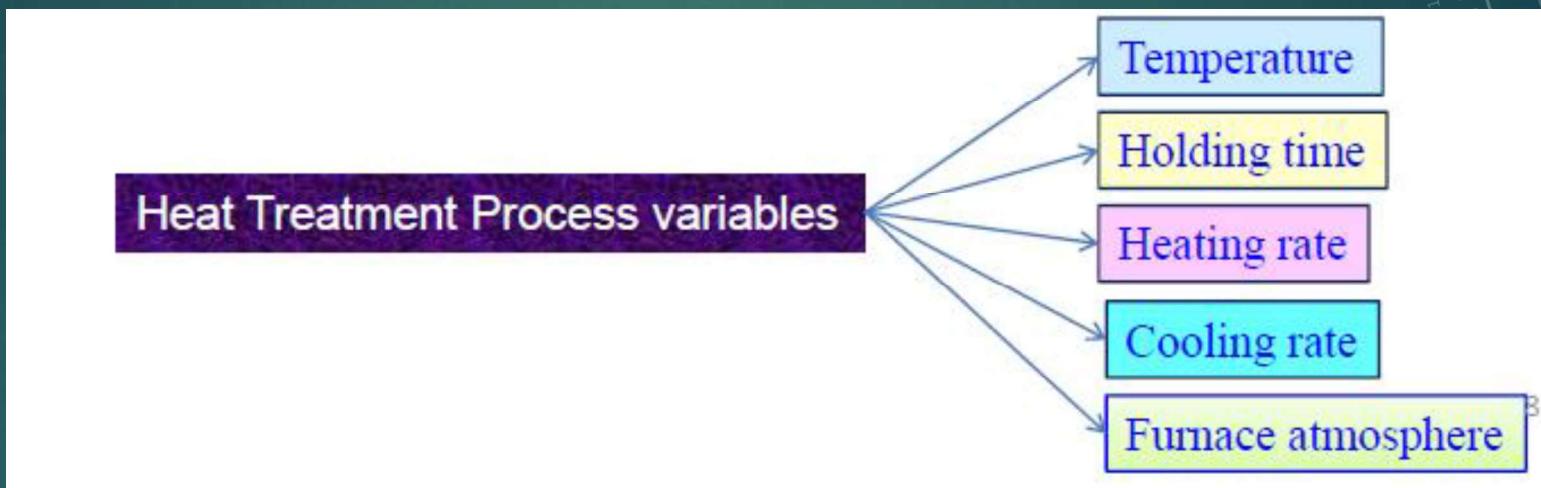
Heat Treatment – Controlled heating and cooling of metals or alloy for the primary purpose of altering their properties (strength, ductility, hardness, toughness, machinability, etc) used for

1. Strengthening Purposes (converting structure to martensite)
2. Softening and Conditioning Purposes (annealing, tempering, etc.)

Objectives of Heat Treatment

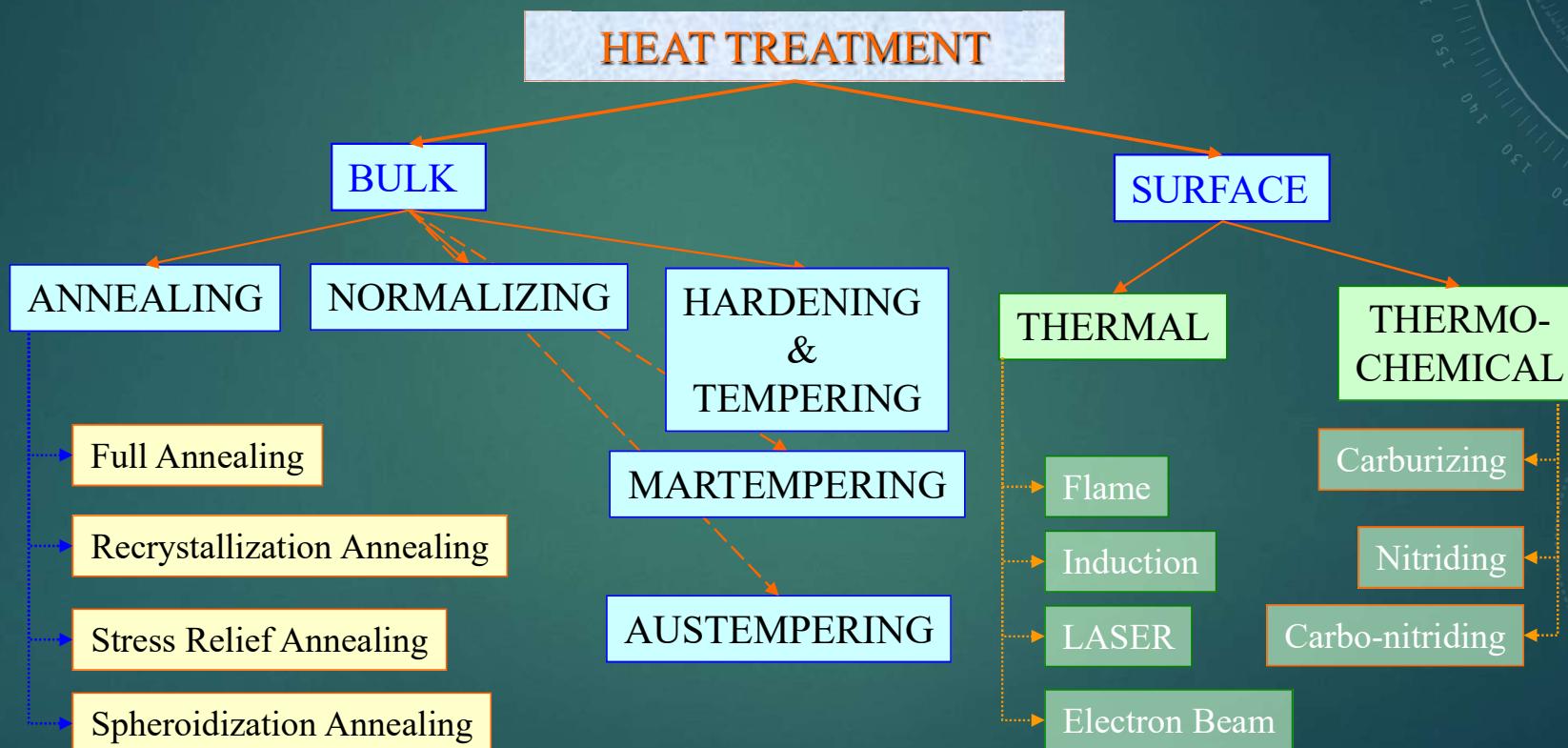
- To increase strength, hardness and wear resistance (*bulk hardening, surface hardening*)
- To increase ductility and softness (*Tempering, Recrystallization Annealing*)
- To increase toughness (*Tempering, Recrystallization annealing*)
- To obtain fine grain size (*Recrystallization annealing, Full annealing, Normalizing*)
- To remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (*Stress relief annealing*)
- To improve machinability (*Full annealing and Normalizing*)
- To improve cutting properties of tool steels (*Hardening and Tempering*)
- To improve surface properties (*surface hardening, high temperature resistance-resistance precipitation hardening, surface treatment*)
- To improve electrical properties (*Recrystallization, Tempering, Age hardening*)
- To improve magnetic properties (*Hardening, Phase transformation*)

Heat Treatment process variables



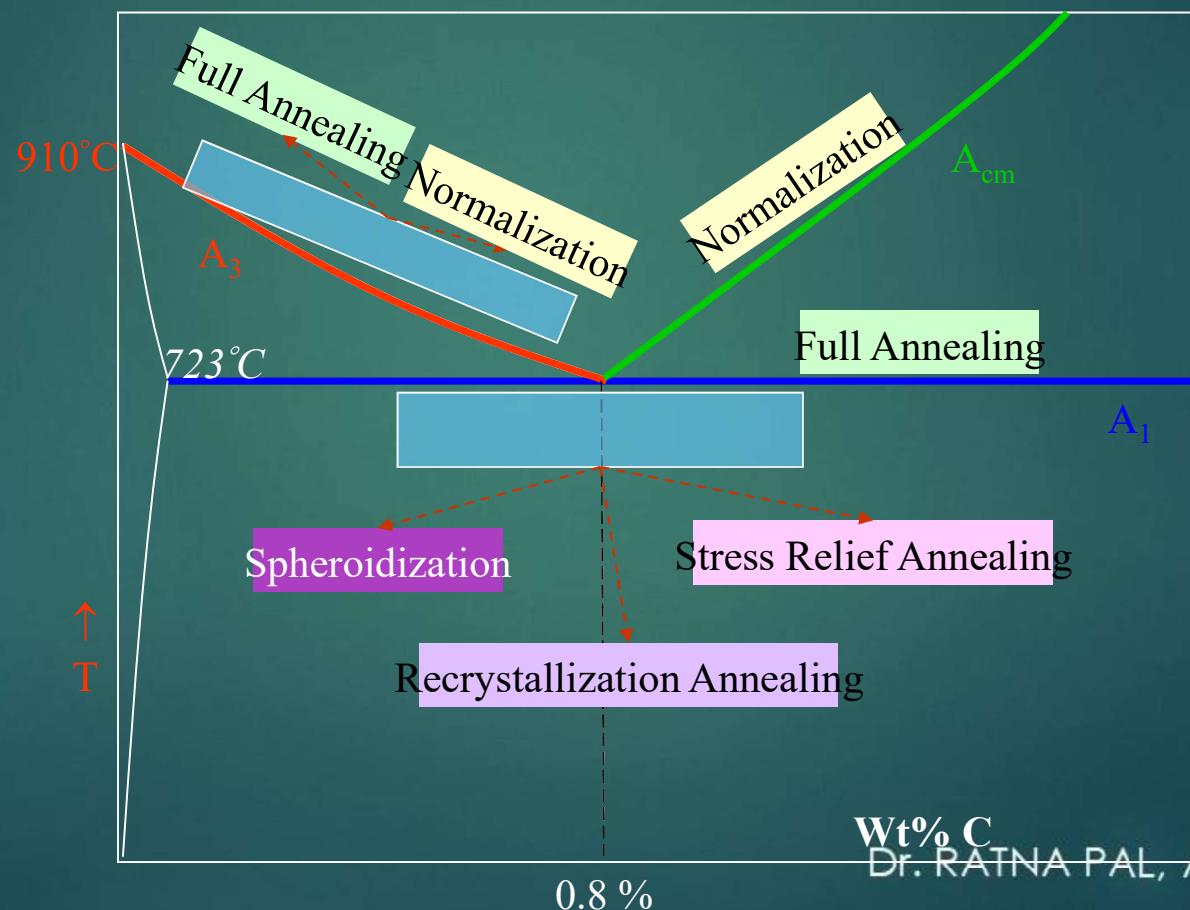
Classification of Heat Treatment

A broad classification of heat treatments possible are given below. Many more specialized treatments or combinations of these are possible.



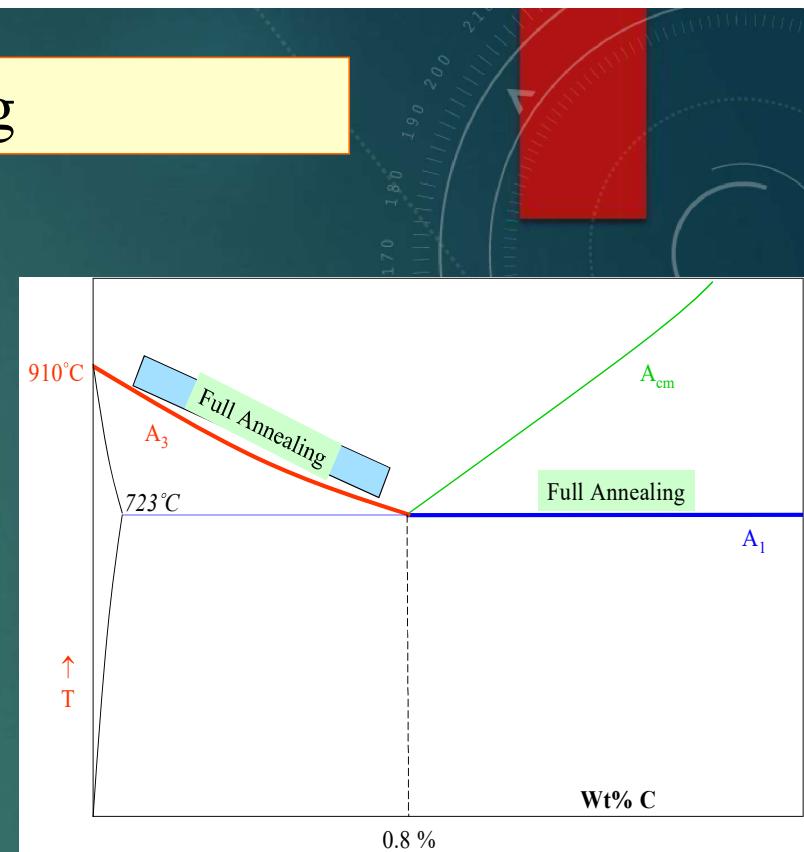
Temperature Range of Heat Treatment

Ranges of temperature where Annealing, Normalizing and Spheroidization treatment are carried out for hypo- and hyper-eutectoid steels.



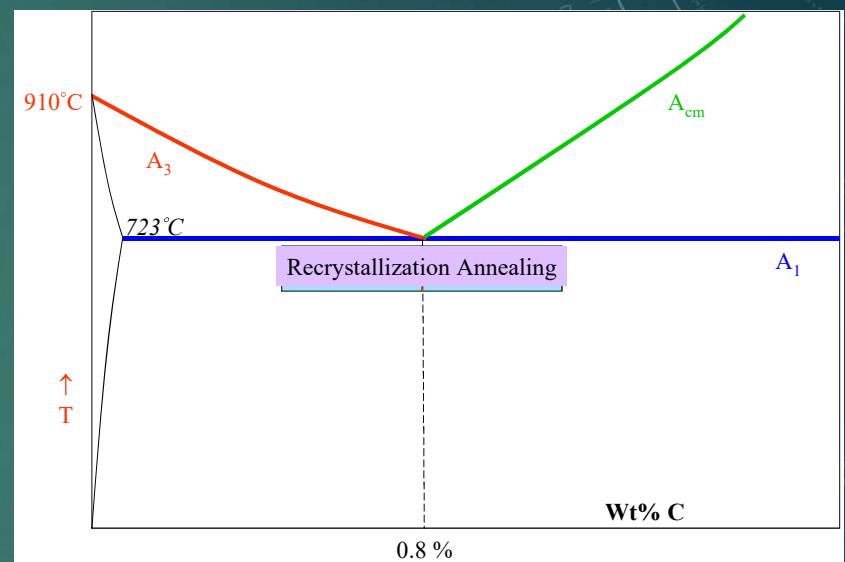
Full Annealing

- The purpose of Full Annealing is to obtain a material with high ductility. A microstructure with coarse pearlite (i.e. pearlite having high interlamellar spacing) is endowed with such properties.
- The range of temperatures used is given in the figure below.
- The steel is heated above A_3 (for hypo-eutectoid steels) & A_1 (for hyper-eutectoid steels) → (hold) → then the steel is furnace cooled to obtain Coarse Pearlite.
- Coarse Pearlite has low (\downarrow) Hardness but high (\uparrow) Ductility.
- For hyper-eutectoid steels the heating is not done above A_{cm} to avoid a continuous network of proeutectoid cementite along prior Austenite grain boundaries (presence of cementite along grain boundaries provides easy path for crack propagation).



Recrystallization Annealing

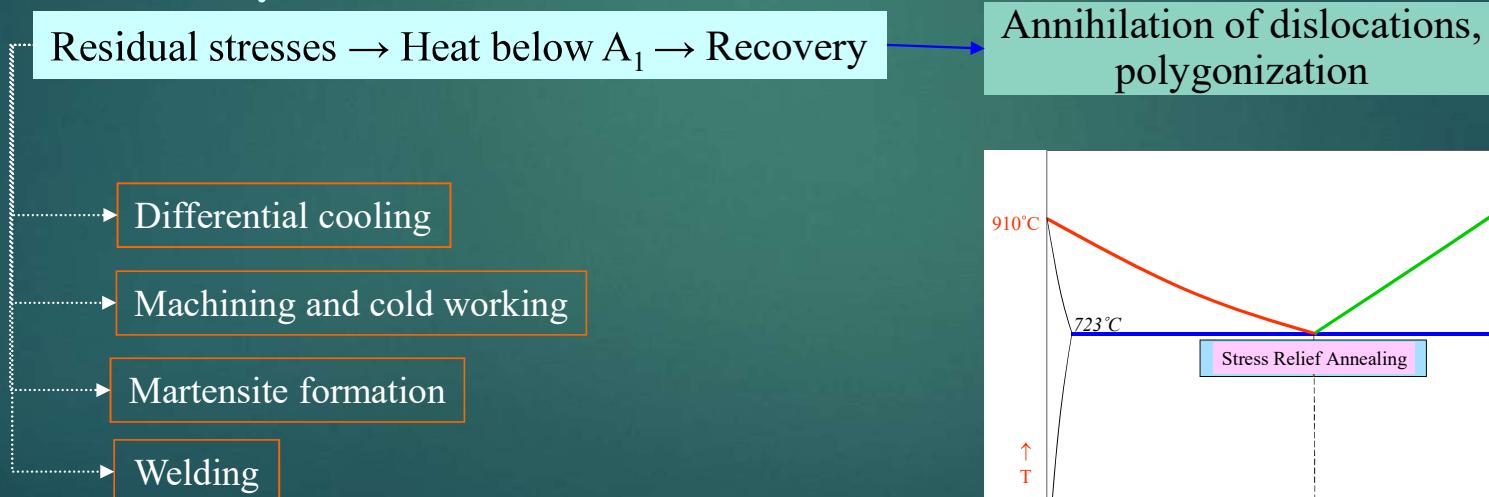
- During any cold working operation (say cold rolling), the material becomes harder (due to work hardening), but loses its ductility. This implies that to continue deformation the material needs to be recrystallized (wherein strain free grains replace the ‘cold worked grains’).
- Hence, recrystallization annealing is used as an intermediate step in (cold) deformation processing.
- To achieve this the sample is heated below A_1 and held there for sufficient time for recrystallization to be completed.



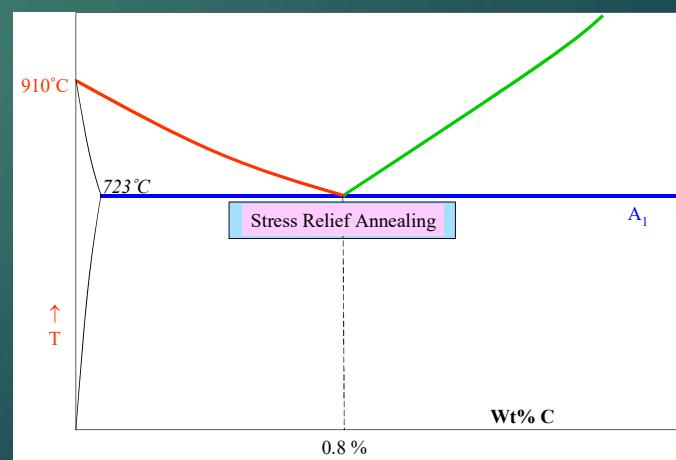
Heat below A_1 → Sufficient time → Recrystallization

Stress Relief Annealing

- Due to various processes like quenching (differential cooling of surface and interior), machining, phase transformations (like martensitic transformation), welding, etc. the residual stresses develop in the sample. Residual stress can lead to undesirable effects like warpage of the component.
- The annealing is carried out just below A_1 , wherein ‘recovery*’ processes are active (Annihilation of dislocations, polygonization).

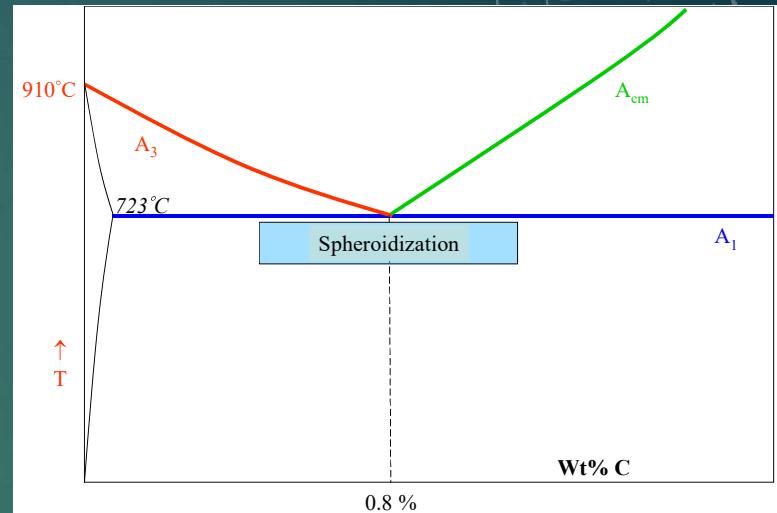


* It is to be noted that ‘recovery’ is a technical term.



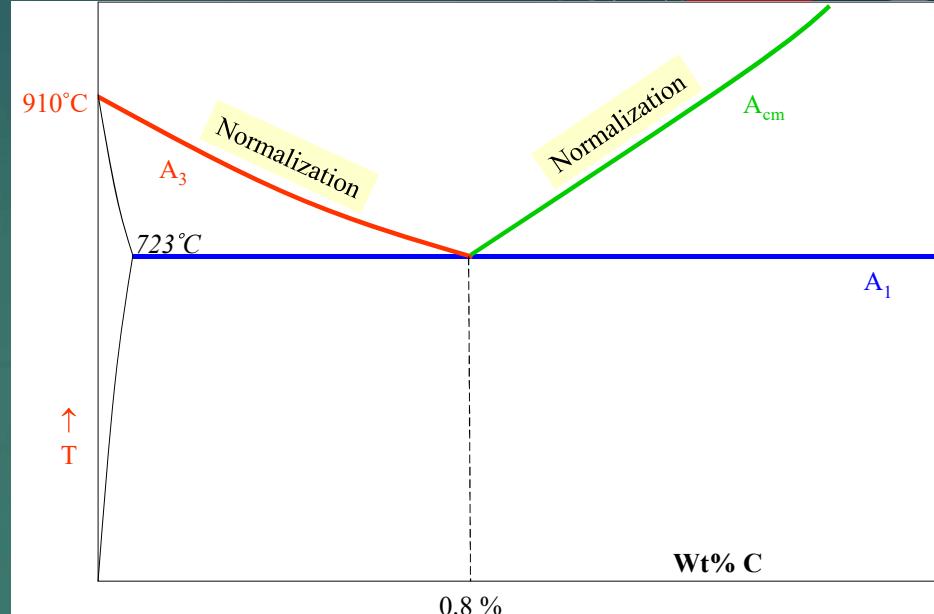
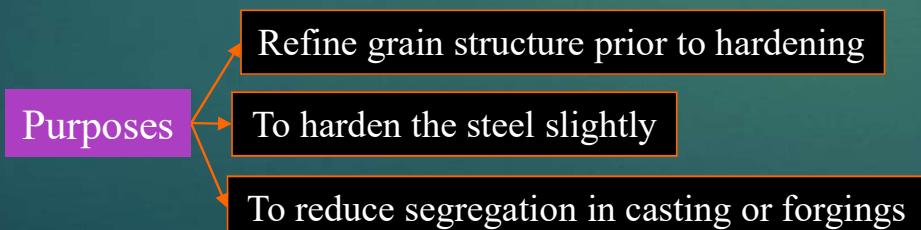
Spheroidization Annealing

- This is a very specific heat treatment given to high carbon steel requiring extensive machining prior to final hardening & tempering. The main purpose of the treatment is to increase the ductility of the sample.
- Like stress relief annealing the treatment is done just below A_1 .
- Long time heating leads cementite plates to form cementite spheroids. The driving force for this (microstructural) transformation is the reduction in interfacial energy.



NORMALIZING

- The sample is heat above A_3 / A_{cm} to complete Austenization. The sample is then air cooled to obtain Fine pearlite. Fine pearlite has a reasonably good hardness and ductility.
- In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature.
- In hyper-eutectoid steels normalizing done above $A_{cm} \rightarrow$ due to faster cooling cementite does not form a continuous film along GB.
- The list of uses of normalizing are listed below.



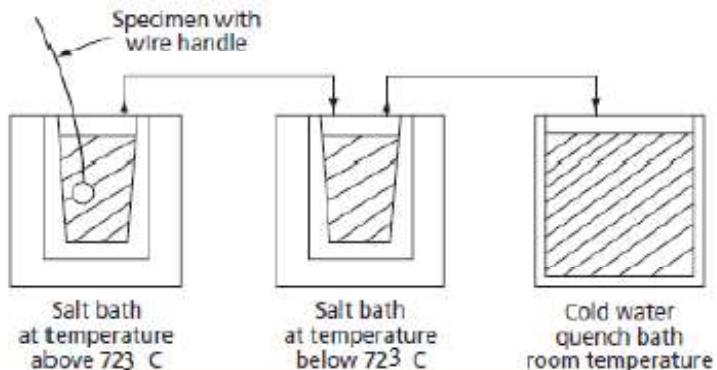
Time-Temperature-Transformation (TTT) Diagrams

- ❑ The temperature of transformation controls the nature of decomposed product (of austenite) which in turn decides the resultant properties of steel.
- ❑ The kinetics of austenitic transformation can be studied best at a constant temperature rather than by continuous cooling.
- ❑ The constant temperature transformation is also referred to as isothermal transformation which is studied by the following experiment.
- ❑ Davenport and Bain were the first to develop the TTT diagram of eutectoid steel. They determined pearlite and bainite portions whereas Cohen later modified and included M_s and M_f temperatures for martensite.
- ❑ There are number of methods used to determine TTT diagrams. The most popular method is salt bath techniques combined with metallography and hardness measurement with addition of this we have other techniques like dilatometry, electrical resistivity method, magnetic permeability, *in situ* diffraction techniques (X-ray, neutron), acoustic emission, thermal measurement techniques, density measurement techniques and thermodynamic predictions.
- ❑ TTT diagrams, also called as Isothermal (*temperature constant*) Transformation diagrams.
- ❑ For every composition of steel we should draw a different TTT diagram.

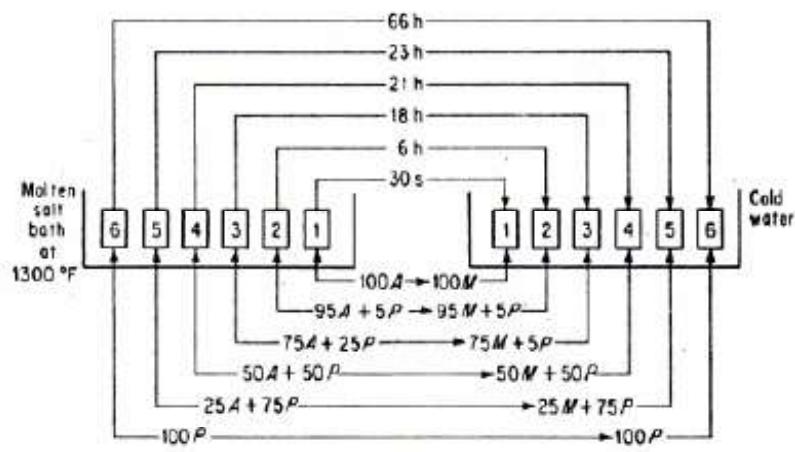
Determination of TTT diagram for eutectoid steel

- ❑ For the determination of isothermal transformation (or) TTT diagrams, we consider *molten salt bath technique* combined with metallography and hardness measurements.
- ❑ In *molten salt bath technique* two salt baths and one water bath are used.
- ❑ Salt bath I is maintained at austenising temperature (780°C for eutectoid steel).
- ❑ Salt bath II is maintained at specified temperature at which transformation is to be determined (below A_{e1}), typically $700-250^{\circ}\text{C}$ for eutectoid steel.
- ❑ Bath III which is a cold water bath is maintained at room temperature.
- ❑ In bath I number of samples are austenite at $A_1+20-40^{\circ}\text{C}$ for eutectoid, $A_3+20-40^{\circ}\text{C}$ for hypo-eutectoid steel and $A_{\text{Cm}}+20-40^{\circ}\text{C}$ for hyper-eutectoid steels for about an hour.
- ❑ Then samples are removed from bath I and put in bath II and each one is kept for different specified period of time say $t_1, t_2, t_3, t_4, \dots, t_n$ etc.
- ❑ After specified times, the samples are removed and quenched in cold water.
- ❑ The microstructure of each sample is studied using metallographic techniques. The type, as well as quantity of phases, is determined on each sample.
- ❑ Transformation of austenite to ferrite-cementite mixtures occurs after a definite time (say t_1). This time during which transformation does not proceed is known as incubation period.
- ❑ The magnitude of incubation period provides a qualitative idea about the relative stability of supercooled austenite. Smaller incubation period corresponds to lesser stability of austenite.

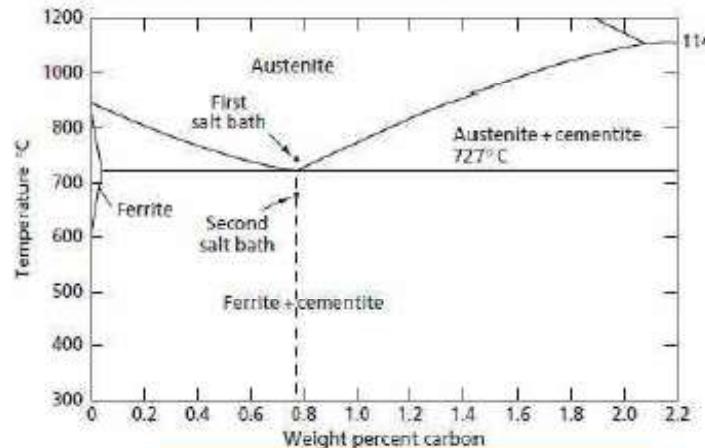
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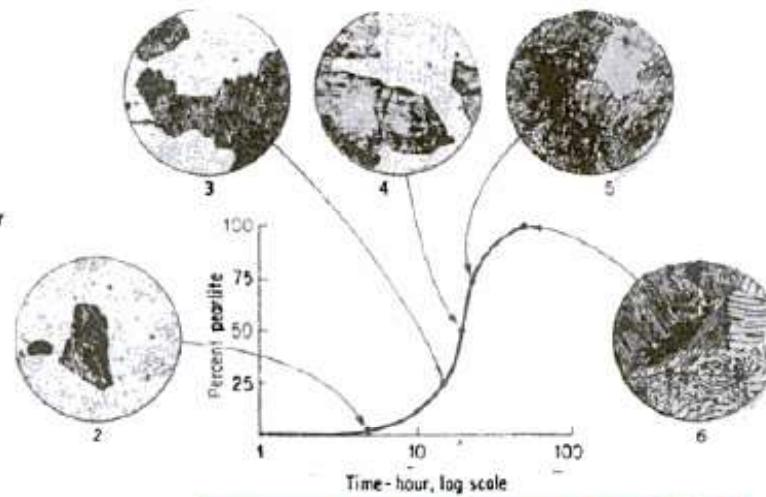
Simple experimental arrangement for determining
The kinetics of isothermal austenitic transformation



The progress of austenite transformation
A-austenite, P-pearlite, M-martensite

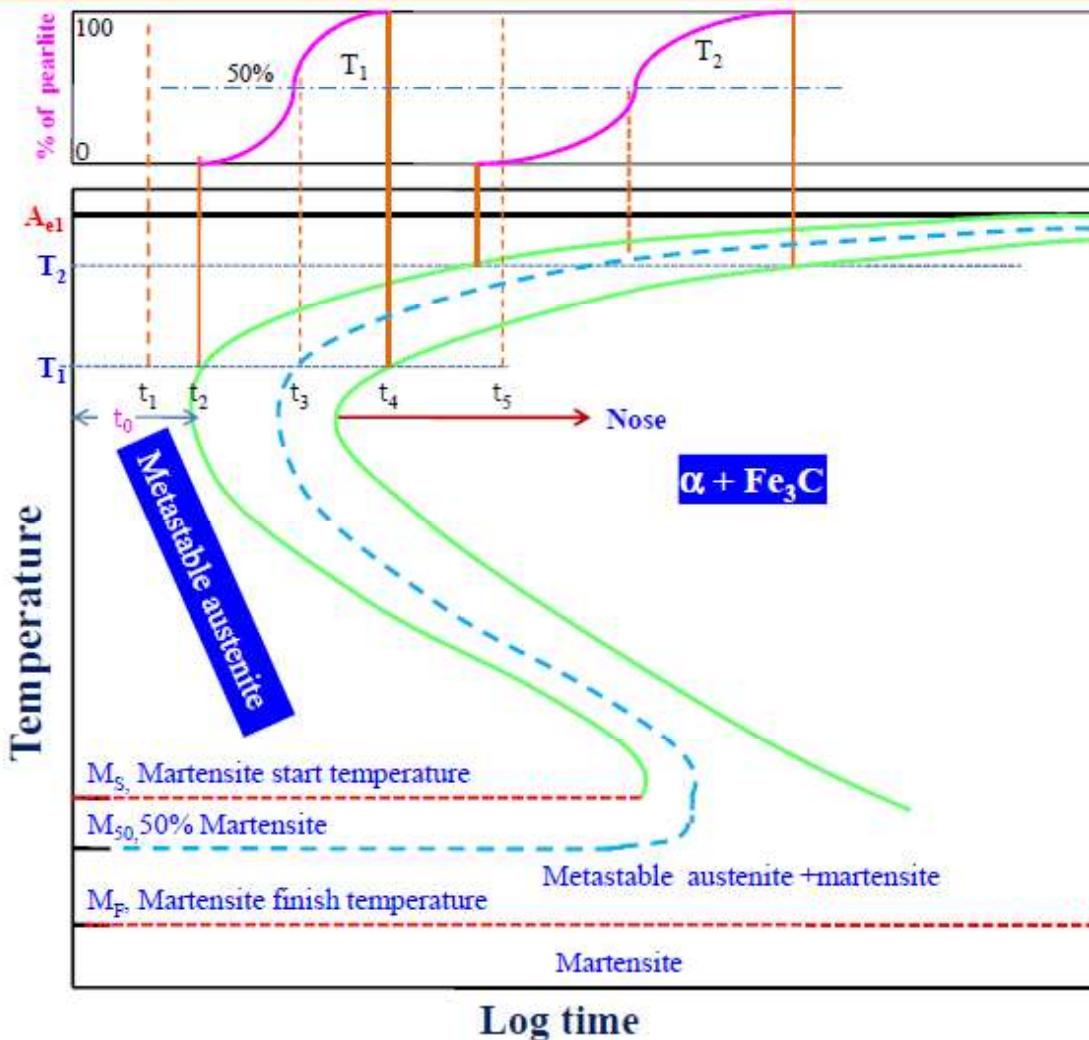


Eutectoid section of the iron - carbon diagram



TTT curve of austenite to pearlite for 1080 steel

Determination of TTT diagram for eutectoid steel



✓ At T_1 , incubation period for pearlite = t_2 , Pearlite finish time = t_4

✓ Minimum incubation period t_0 at the nose of the TTT diagram,

Important points to be noted:

✓ The x-axis is log scale. ‘Nose’ of the ‘C’ curve is in ~sec and just below T_E transformation times may be ~day.

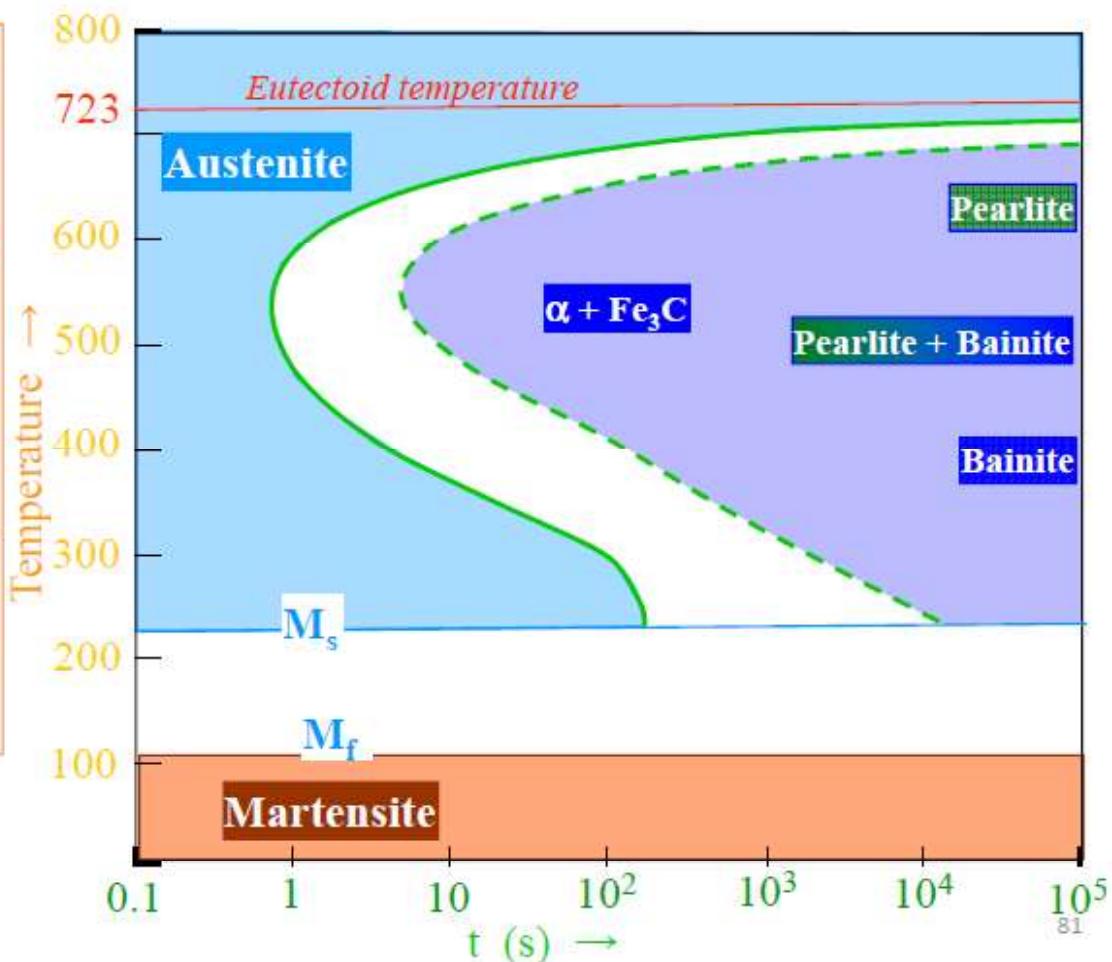
✓ The starting phase (left of the C curve) has to γ .

✓ To the right of finish C curve is ($\gamma + \text{Fe}_3\text{C}$) phase field. This phase field has more labels included.

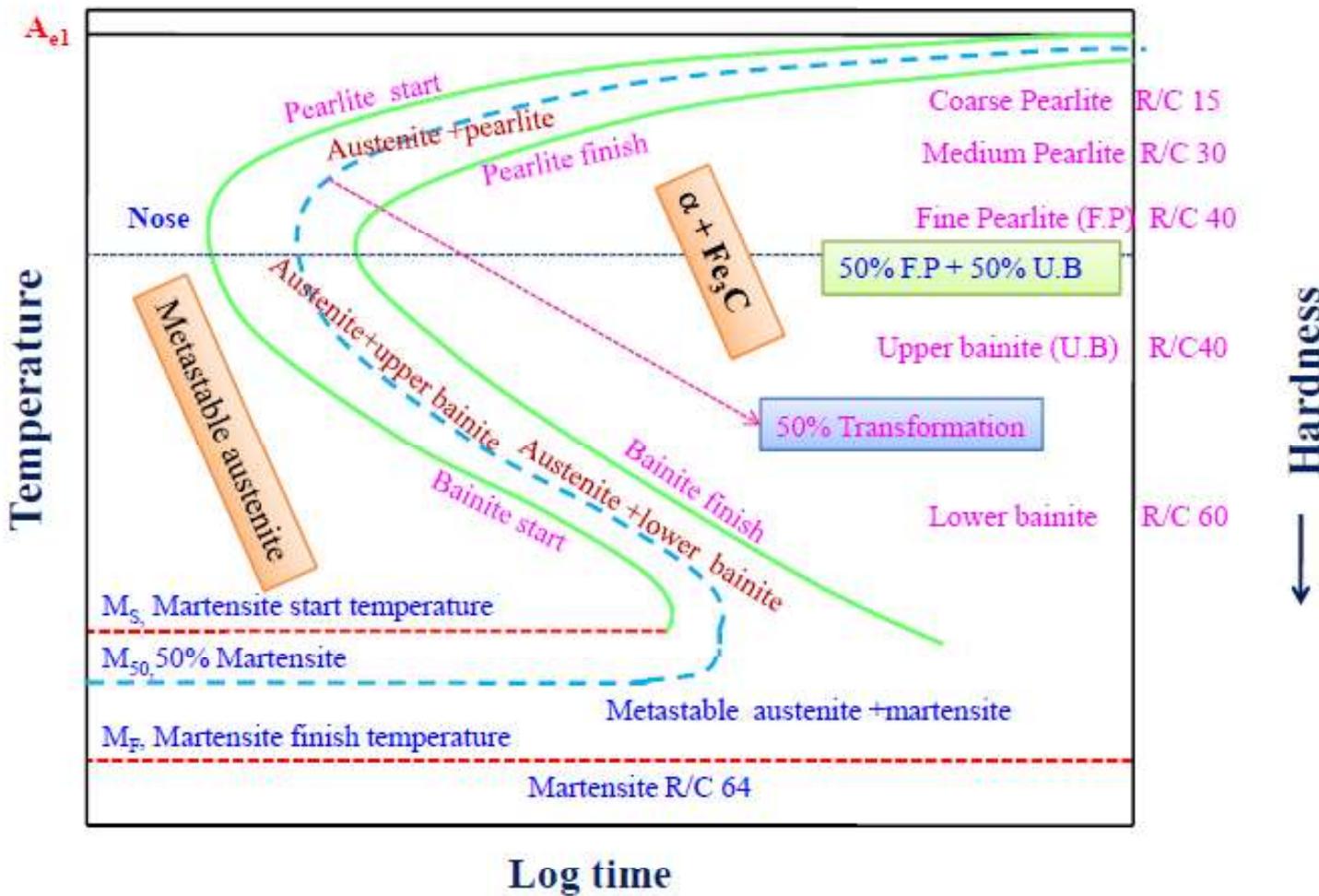
Determination of TTT diagram for eutectoid steel

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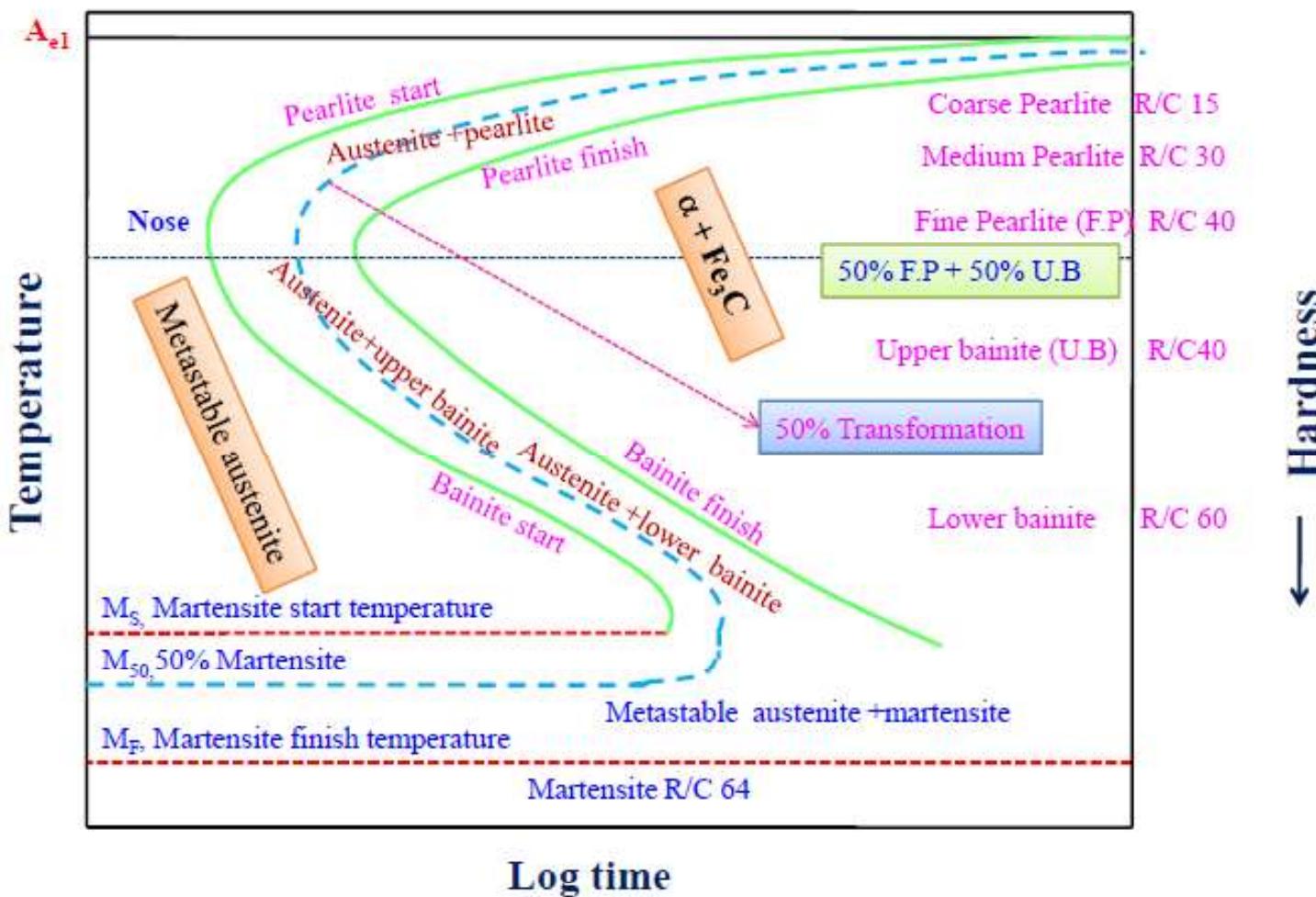
- ✓ The x-axis is log scale. 'Nose' of the 'C' curve is in ~sec and just below T_E transformation times may be ~day.
- ✓ The starting phase (left of the C curve) has to γ .
- ✓ To the right of finish C curve is ($\gamma + Fe_3C$) phase field. This phase field has more labels included.



Possible phases in TTT diagram for eutectoid steel



Possible phases in TTT diagram for eutectoid steel



Isothermal Transformation diagram for eutectoid steel

- ❑ As pointed out before one of the important utilities of the TTT diagrams comes from the overlay of micro-constituents (microstructures) on the diagram.
- ❑ Depending on the T , the $(\gamma + \text{Fe}_3\text{C})$ phase field is labeled with micro-constituents like Pearlite, Bainite.
- ❑ The time taken to 1% transformation to, say pearlite or bainite is considered as transformation start time and for 99% transformation represents transformation finish.
- ❑ We had seen that TTT diagrams are drawn by instantaneous quench to a temperature followed by isothermal hold.
- ❑ Suppose we quench below ($\sim 225^\circ\text{C}$, below the temperature marked M_s), then Austenite transforms via a diffusionless transformation (*involving shear*) to a (hard) phase known as Martensite. Below a temperature marked M_f this transformation to Martensite is complete. Once γ is exhausted it cannot transform to $(\gamma + \text{Fe}_3\text{C})$.
- ❑ Hence, we have a new phase field for Martensite. The fraction of Martensite formed is not a function of the time of hold, but the temperature to which we quench (between M_s and M_f).
- ❑ Strictly speaking cooling curves (including finite quenching rates) should not be overlaid on TTT diagrams (*remember that TTT diagrams are drawn for isothermal holds!*).

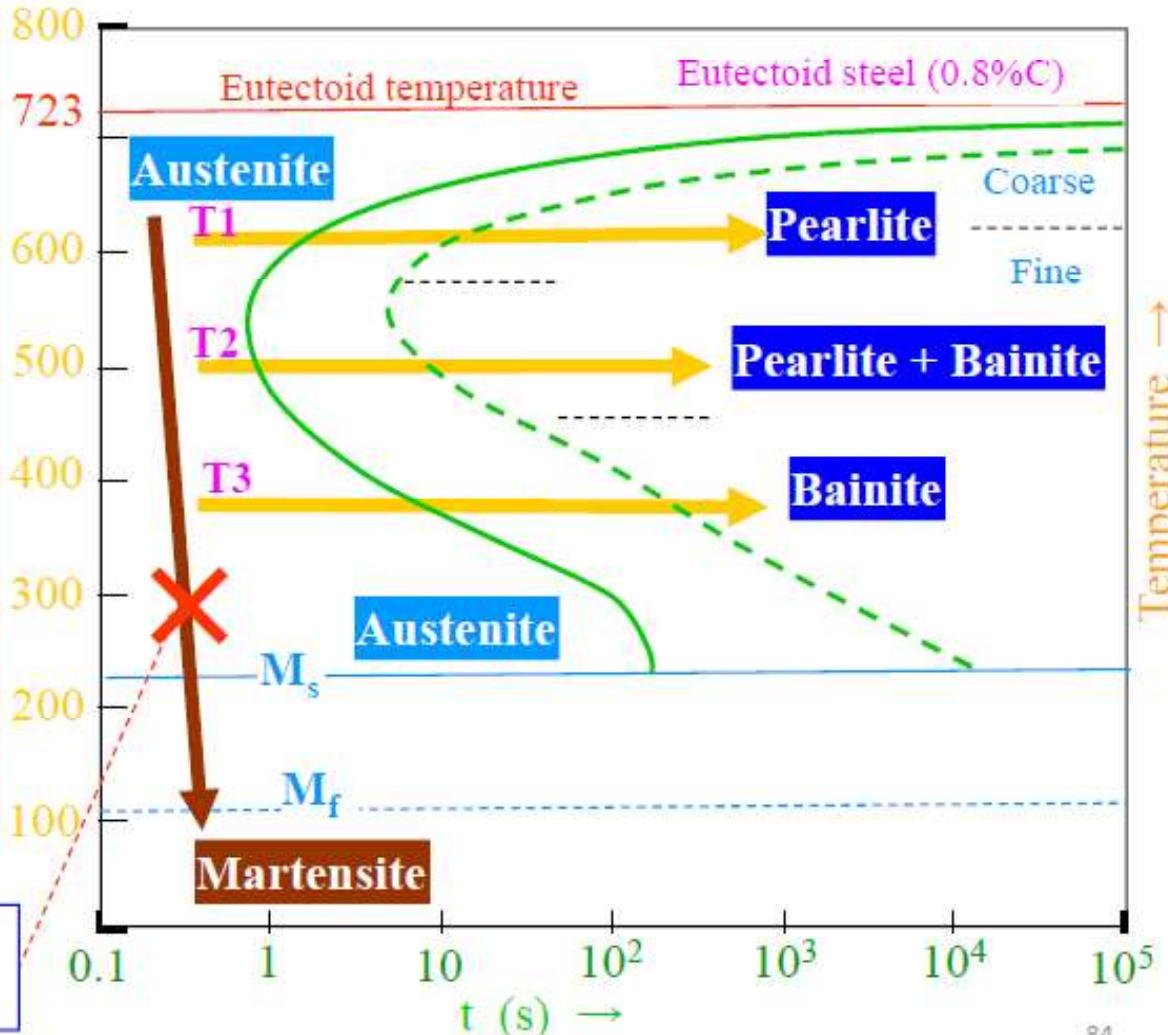
Isothermal Transformation diagram for eutectoid steel

✓ Isothermal hold at: (i) T₁ gives us Pearlite, (ii) T₂ gives Pearlite+Bainite, (iii) T₃ gives Bainite. Note that Pearlite and Bainite are both $\alpha+Fe_3C$ (but their morphologies are different).

✓ To produce Martensite we should quench at a rate such as to avoid the nose of the start 'C' curve. Called the critical cooling rate.

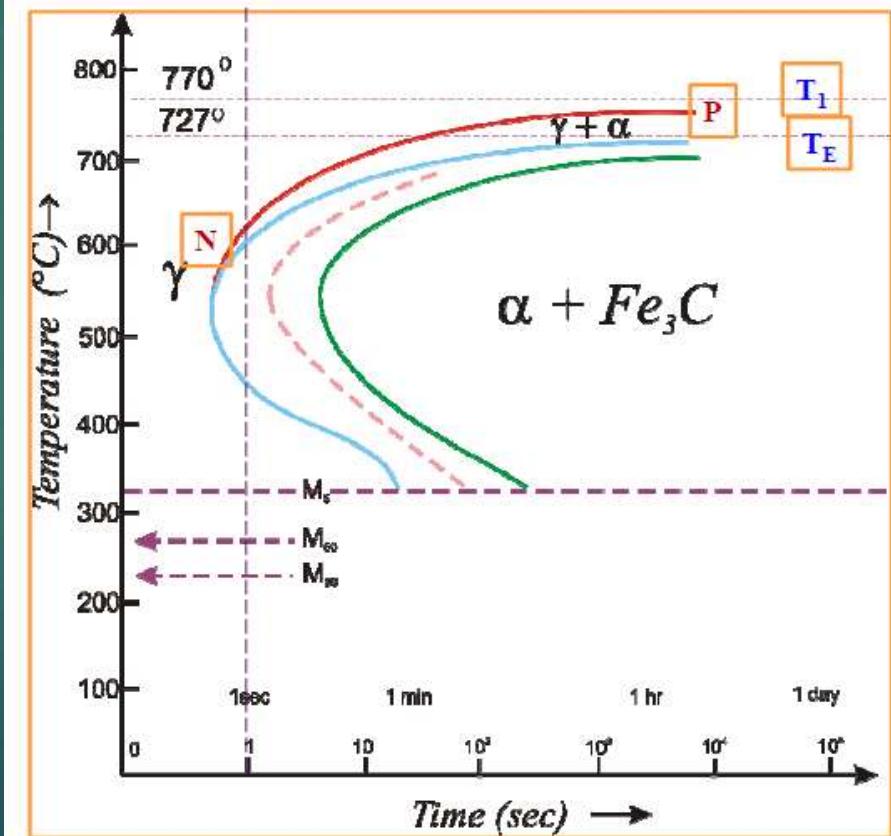
✓ If we quench between M_s and M_f we will get a mixture of Martensite and γ (called retained Austenite).

Not an isothermal transformation



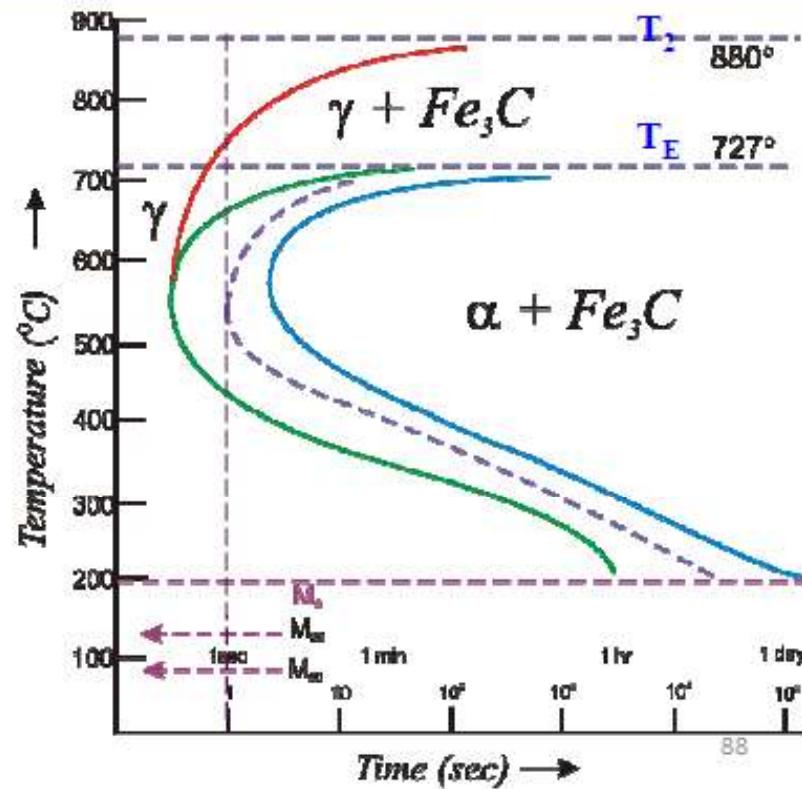
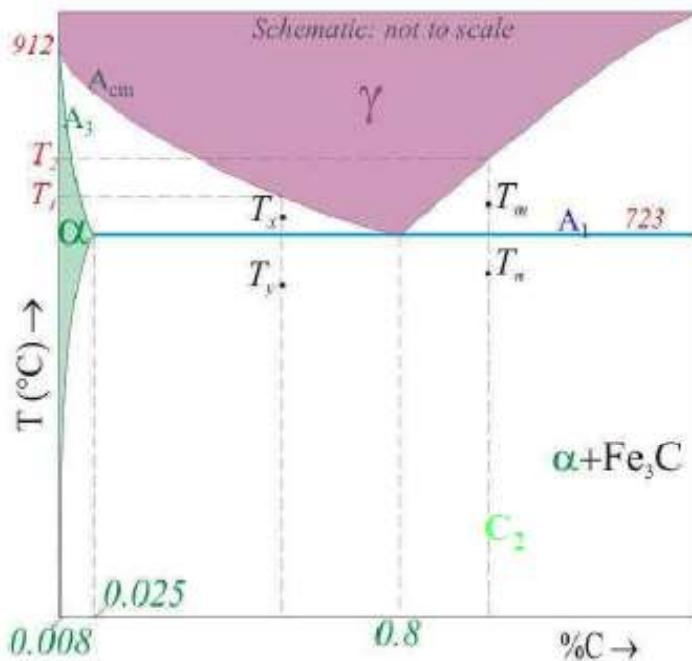
TTT diagram for Hypo-eutectoid steel

- ❑ In hypo- (and hyper-) eutectoid steels (say composition C_1) there is one more branch to the 'C' curve-NP (next slide: marked in red).
- ❑ The part of the curve lying between T_1 and T_E (marked in fig : next slide) is clear, because in this range of temperatures we expect only pro-eutectoid α to form and the final microstructure will consist of α and γ . (E.g. if we cool to T_x and hold).



TTT diagram for Hyper-eutectoid steel

- Similar to the hypo-eutectoid case, hyper-eutectoid compositions C_2 have a $\gamma + Fe_3C$ branch.
- For a temperature between T_2 and T_E (say T_m (not melting point- just a label)) we land up with $\gamma + Fe_3C$.
- For a temperature below T_E (but above the nose of the 'C' curve) (say T_n), first we have the formation of pro-eutectoid Fe_3C followed by the formation of eutectoid $\gamma + Fe_3C$.



Factors affecting on TTT Diagram

- Composition
- Grain size
- Heterogeneity of Austenite

Effect of alloying elements on TTT diagram

- ❑ Almost all alloying elements (except, Al, Co, Si) increases the stability of supercooled austenite and retard both proeutectoid and the pearlitic reaction and then shift TTT curves of start to finish to right or higher timing. This is due to
 - ✓ low rate of diffusion of alloying elements in austenite as they are substitutional elements.
 - ✓ reduced rate of diffusion of carbon as carbide forming elements strongly hold them.
 - ✓ Alloyed solute reduce the rate of allotropic change, i.e. $\gamma \rightarrow \alpha$, by solute drag effect on $\gamma \rightarrow \alpha$ interface boundary.
- ❑ Additionally those elements (Ni, Mn, Ru, Rh, Pd, Os, Ir, Pt, Cu, Zn, Au) that expand or stabilise austenite, depress the position of TTT curves to lower temperature. In contrast elements (Be, P, Ti, V, Mo, Cr, B, Ta, Nb, Zr) that favour the ferrite phase can raise the eutectoid temperature and TTT curves move upward to higher temperature.
- ❑ However Al, Co, and Si increase rate of nucleation and growth of both ferrite or pearlite and therefore shift TTT diagram to left. In addition under the complex diffusional effect of

Factors affecting on TTT diagram

Composition of steel

- ❑ Carbon and alloying elements affect the transformation of austenite in many ways. As the amount of carbon and most alloying elements increase in steel, the lower part of the curves is progressively lowered because except for aluminium, all the elements lower the M_s temperature.
- ❑ The austenite stabilizers lower the Ac_3 as well as Ac_1 temperatures, i.e., these elements (Ni, Mn, C etc) lower the upper part of the TTT curve. This probably is the reason of having overlapping 'C' curves for pearlitic and bainitic transformations in plain carbon steel as well as in steels having Ni, etc.
- ❑ Ferrite stabilizers raise Ac_3 as well as Ac_1 temperatures. As the TTT curve for such steels get raised upward as well as gets lowered down ward, there are invariably two 'C' curves-one for pearlitic and the other for bainitic transformations. For example, presence of 0.8% Cr and 0.33% Mo in steel yield two 'C' curves.
- ❑ Andrew suggests the effect of the elements on Ac_3 and Ac_1 by equations :

$$Ac_3 = 910 - 203\sqrt{\%C} - 15.2(\%Ni) + 44.7(\%Si) + 104(\%V) + 31.5(\%Mo) + 13.1(\%W)$$

$$Ac_1 = 727 - 10.7(\%Mn) - 16.9(\%Ni) + 29.1(\%Si) + 290(\%As) + 16.9(\%Cr) + 6.38(\%W)$$

Effect of grain size

- All the composition products of austenite nucleate heterogeneously preferentially at the grain boundaries.
- A fine grained steel has larger grain boundary area than a coarse grained steel, and consequently favors nucleation of pearlite, bainite, ferrite, cementite and thus, reduces the incubation period, that means the TTT curve of the fine grained steel is more towards left, significantly in the pearlitic range, than a coarse grained steel of same composition.

Effect of Heterogeneity of Austenite

- Heterogeneous austenite increases transformation time range, start to finish of ferritic, pearlitic and bainitic range as well as increases the transformation temperature range in case of Martensitic transformation and bainitic transformation. Undissolved cementite, carbides act as powerful inoculants for pearlite transformation. Therefore heterogeneity in austenite increases the transformation time range in Diffusional transformation and temperature range of shear transformation products in TTT diagram.
- This heterogeneity of austenite, when the steel is heated to temperatures not higher than 50°C above A_1 is put to advantage to obtain spheroidized pearlite by letting it decompose within 50°C below A_1 to improve the ductility and the machinability (high carbon steels).

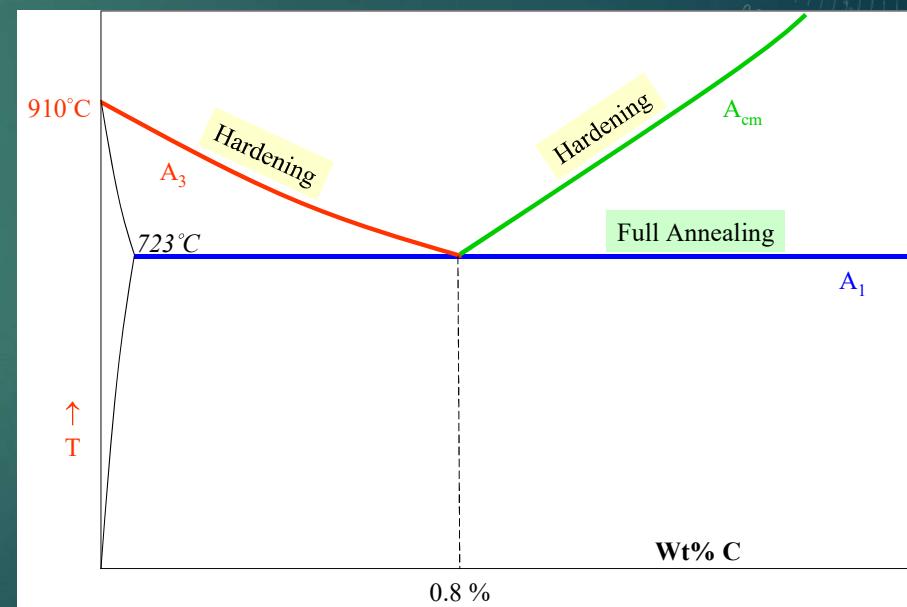
Hardening

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HARDENING

Heat above A_3 | A_{cm} → Austenization → Quench (higher than critical cooling rate)

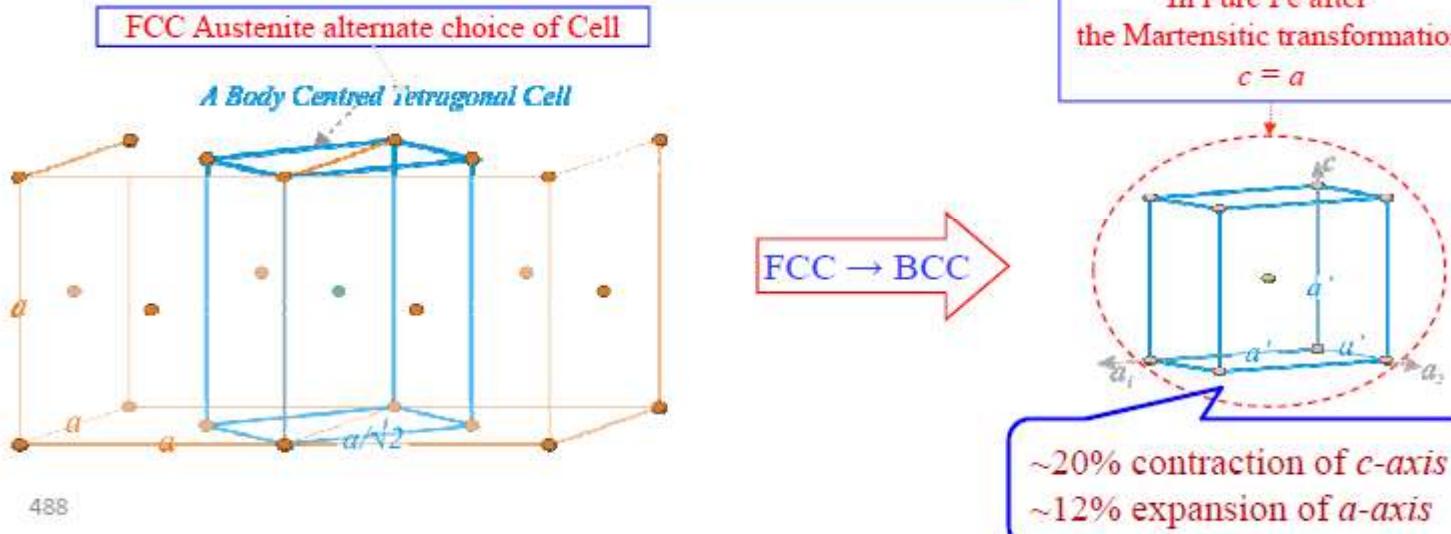
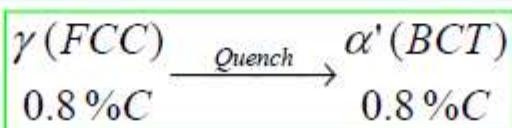
- The sample is heated above A_3 | A_{cm} to cause Austenization. The sample is then quenched at a cooling rate higher than the critical cooling rate (i.e. to avoid the nose of the CCT diagram).
- The quenching process produces residual strains (thermal, phase transformation).
- The transformation to Martensite is usually not complete and the sample will have some retained Austenite.
- The Martensite produced is hard and brittle and tempering operation usually follows hardening. This gives a good combination of strength and toughness.



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Characteristics of Martensitic transformations

- ❑ Martensitic transformation can be understood by first considering an alternate unit cell for the Austenite phase as shown in the figure below.
- ❑ If there is no carbon in the Austenite (as in the schematic below), then the Martensitic transformation can be understood as a ~20% contraction along the c-axis and a ~12% expansion of the a-axis → accompanied by no volume change and the resultant structure has a BCC lattice (the usual BCC-Fe) → c/a ratio of 1.0.

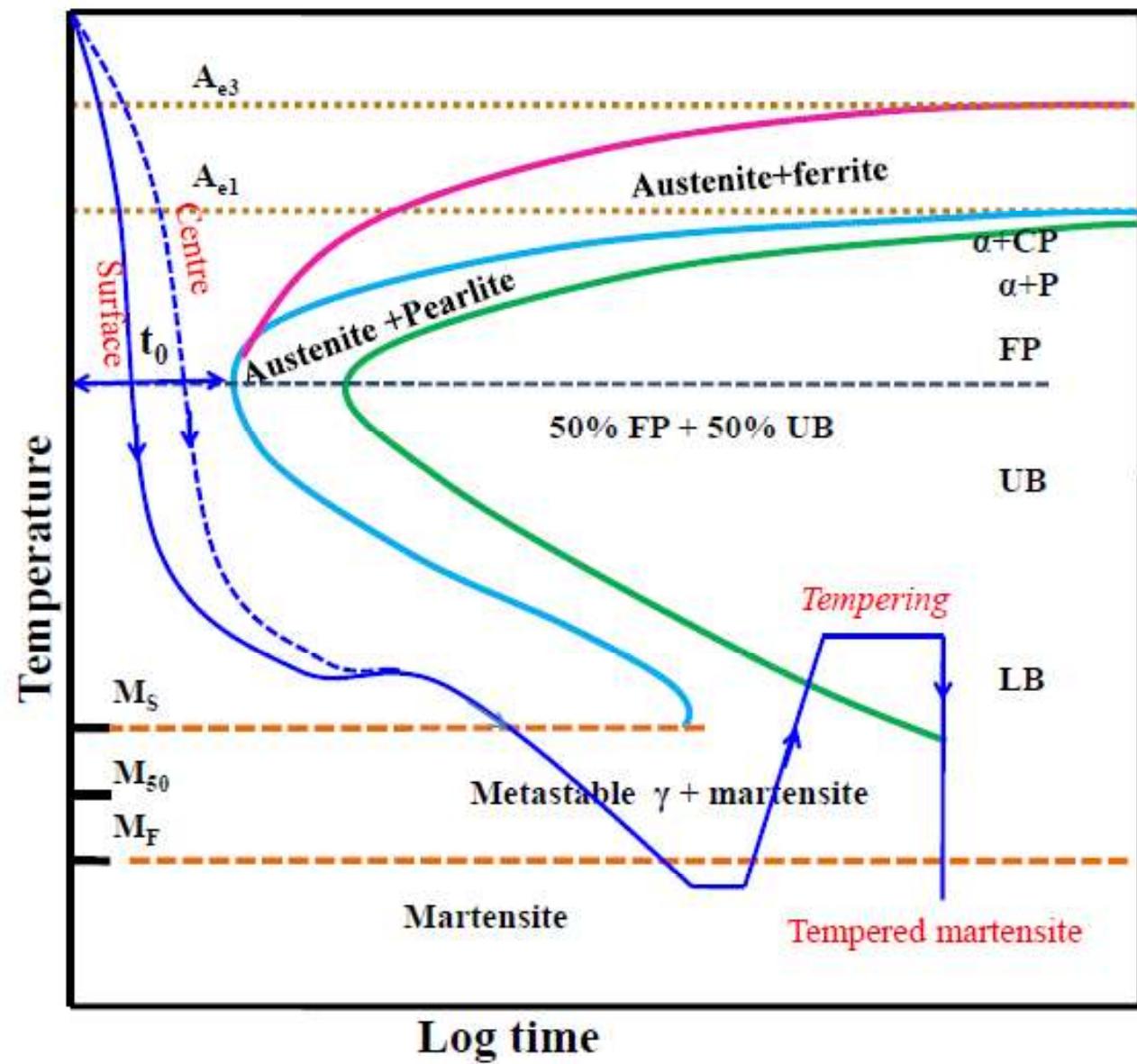


Application of TTT Diagram

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MARTEMPERING

- ❑ This heat treatment is given to oil hardenable and air hardenable steels and thin section of water hardenable steel sample to produce martensite with minimal differential thermal and transformation stress to avoid distortion and cracking.
- ❑ The steel should have reasonable incubation period at the nose of its TTT diagram and long bainitic bay.
- ❑ The sample is quenched above M_S temperature in a salt bath to reduce thermal stress (instead of cooling below M_F directly) Surface cooling rate is greater than at the centre.
- ❑ The cooling schedule is such that the cooling curves pass behind without touching the nose of the TTT diagram. The sample is isothermally hold at bainitic bay such that differential cooling rate at centre and surface become equalize after some time.
- ❑ The sample is allowed to cool by air through M_S - M_F such that martensite forms both at the surface and centre at the same time due to not much temperature difference and thereby avoid transformation stress because of volume expansion. The sample is given tempering treatment at suitable temperature.
- ❑ The rate of cooling from austenising temperature should avoid formation of pearlitic and bainite. Thus the success of Martempering depends on the incubation period at the pearlitic nose, and also at the bainitic bay, and thus the steel suitable for Martempering should have sufficient hardenability. *Plain carbon steels with dia. > 10mm are difficult to mar-temper and thus, this process is restricted to alloy steels.*

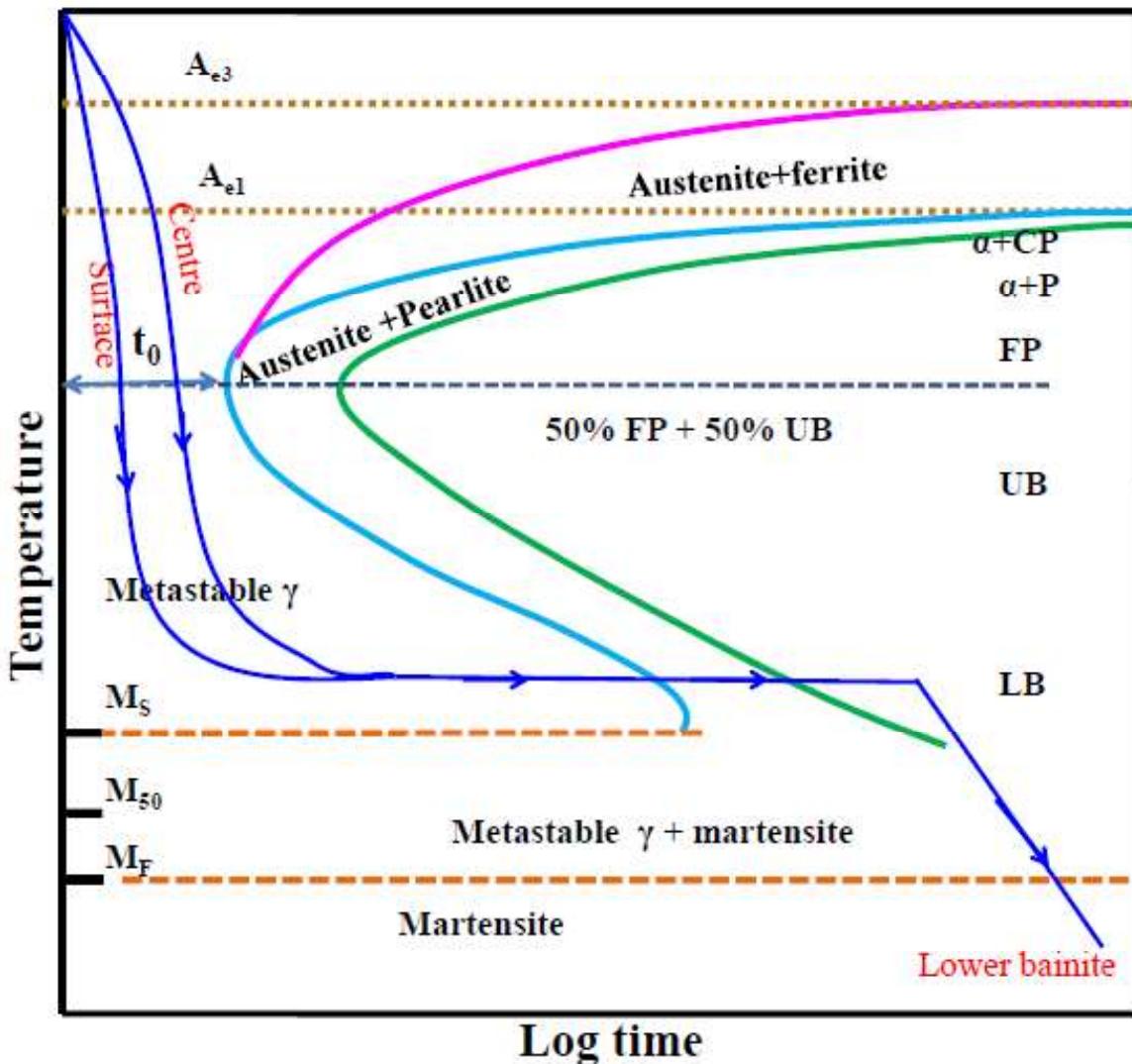


γ =austenite
 α =ferrite
 CP=coarse pearlite
 P=pearlite
 FP=fine pearlite
 t_0 =minimum incubation period
 UB=upper bainite
 LB=lower bainite
 M=martensite
 M_S =Martensite start temperature
 M_{50} =temperature at which 50% martensite is obtained
 M_F =martensite finish temperature

AUSTEMPERING

- Austempering heat treatment is given to steel to produce lower bainite in high carbon steel without any distortion or cracking to the sample.
- The heat treatment is cooling of austenite rapidly in a bath maintained at lower bainitic temperature (above M_s) temperature (avoiding the nose of the TTT diagram) and holding it here to equalize surface and centre temperature and till bainitic finish time.
- At the end of bainitic reaction sample is air cooled. The microstructure contains fully lower bainite. This heat treatment is given to 0.5-1.2 wt% C steel and low alloy steel.
- The product hardness and strength are comparable to hardened and tempered martensite with improved ductility and toughness and uniform mechanical properties. Products do not require to be tempered.
- TTT diagram is great help in scheduling Austempering as it fixes
 - ✓ Temperature of holding of the bath
 - ✓ Duration of holding time
 - ✓ Section which can be quenched to avoid pearlite formation
 - ✓ Whether Austempering is worth while , or not, as the time at the bay may be too long.

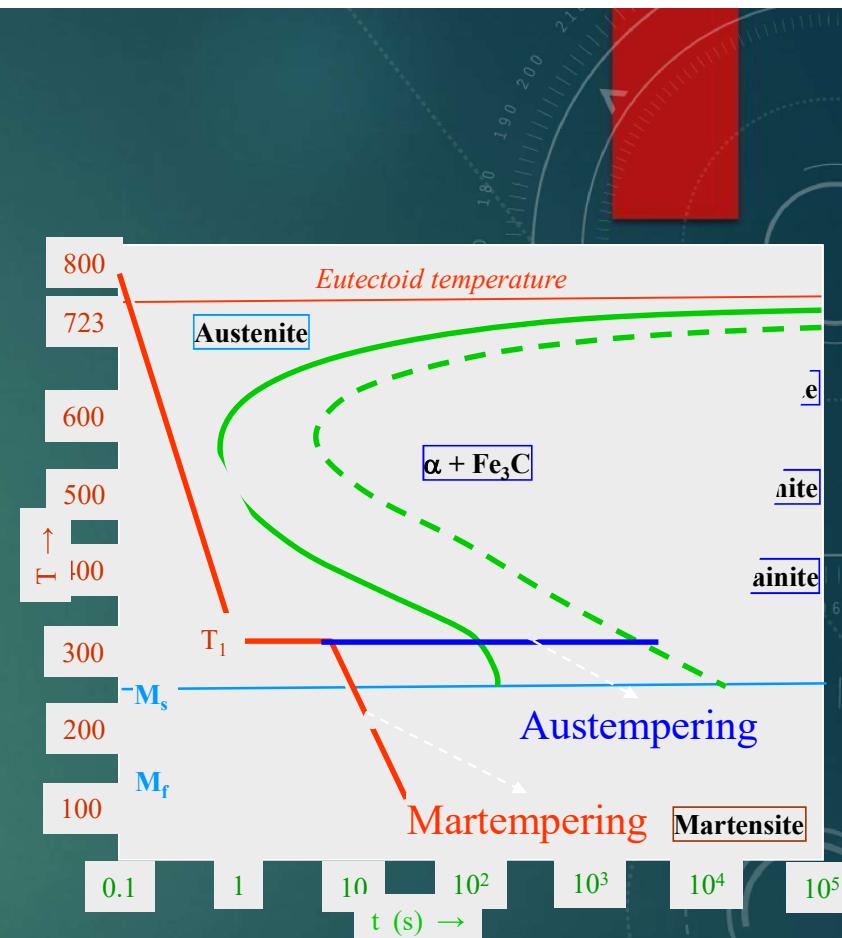
Austempering



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MARTEMPERING & AUSTEMPERING

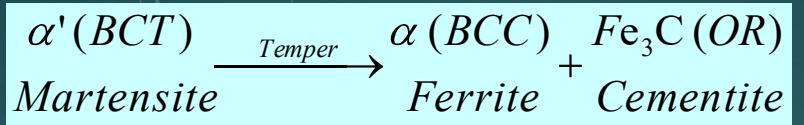
- These processes have been developed to avoid residual stresses generated during quenching.
- In both these processes Austenized steel is quenched above M_s (say to a temperature T_1) for homogenization of temperature across the sample.
- In **Martempering** the steel is then quenched and the entire sample transforms simultaneously to martensite. This is followed by tempering.
- In **Austempering** instead of quenching the sample, it is held at T_1 for it to transform to bainite.



Tempering

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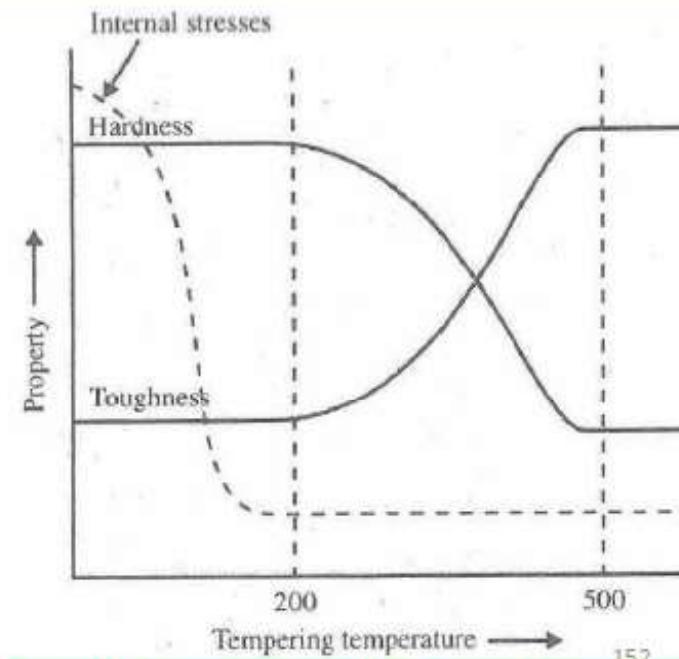
Tempering



- A sample with martensitic microstructure is hard but brittle. Hence after quenching the sample (or component) is tempered. Martensite being a metastable phase decomposes to ferrite and cementite on heating (providing thermal activation).
 - Tempering is carried out just below the eutectoid temperature (heat → wait → slow cool).
 - In reality the microstructural changes which take place during tempering are very complex.
 - The time temperature cycle for tempering is chosen so as to optimize strength and toughness. E.g. tool steel has a quenched hardness of R_c 65, which is tempered to get a hardness of R_c 45-55.

Tempering

- ❑ The hardened steel is not readily suitable for engineering applications. It possesses following three drawbacks.
 - ✓ Martensite obtained after hardening is extremely brittle and will result in failure of engineering components by cracking.
 - ✓ Formation of martensite from austenite by quenching produces high internal stresses in the hardened steel.
 - ✓ Structures obtained after hardening consists of martensite and retained austenite. Both these phases are metastable and will change to stable phases with time which subsequently results in change in dimensions and properties of the steel in service.
- ❑ Tempering helps in reduce these problems. Tempering is the process of heating the hardened steel to a temperature maximum up to lower critical temperature (A_1), soaking at this temperature, and then cooling, normally very slowly.



Variation in properties with tempering temperature

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Tempering

Objective

Relieve Internal stresses

Restore ductility and toughness

To improve dimensional stability

To improve magnetic properties

Structure in as Quenched state

Highly supersaturated martensite

Retained austenite

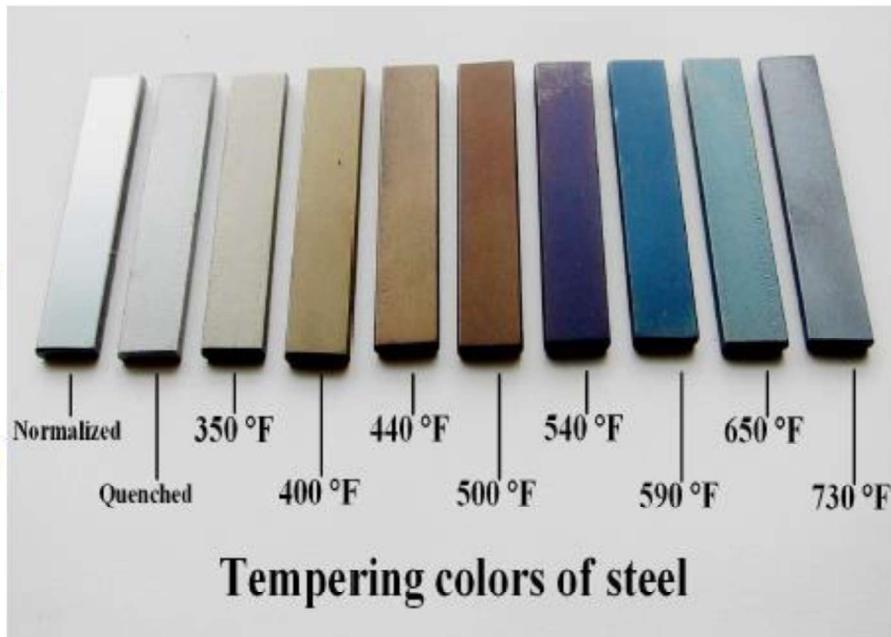
Undissolved carbides

Rods, or plates of carbide particles produced during 'auto-tempering'

Segregation of carbon

➤ Depending on temperatures, tempering processes can be classified as:

- 1) Low- temperature tempering (150 – 250 °C),
- 2) Medium – temperature tempering (350 – 450 °C),
- 3) High – temperature tempering (500 – 650 °C).



Tempering of plain carbon steels

First stage of Tempering

- ❑ First Stage of tempering temperature extends from room temperature to 200°C. The tempering reactions in steels, containing carbon less than 0.2%, differ somewhat from the steels containing more than 0.2% carbon.
- ❑ In the former, if carbon atoms have not yet segregated (during quenching) to dislocations, these diffuse and segregate around the dislocations and lath boundaries in the first stage of tempering. No ϵ -carbide forms as all the carbon gets locked up to the dislocations (defects).
- ❑ Martensite in steels with more than 0.2% carbon is highly unstable because of super saturation, and interstitial diffusion of carbon in BCT martensite can occur. Thus in the first stage of tempering, the decomposition of martensite into low-tetragonality martensite (containing ~0.2%C, c/a ~ 1.014) and ϵ -carbide, $\text{Fe}_{2.4}\text{C}$ occurs. (*There are reports of precipitation of eta-carbide, Fe_2C and Haggs carbide, $\text{Fe}_{2.2}\text{C}$.*)
- ❑ ϵ -carbide is a separate phase and is not a preliminary step in the formation of cementite, but it nucleates and grows more rapidly than cementite. It has HCP structure with $c = 4.33\text{\AA}^\circ$, $a = 2.73\text{\AA}^\circ$, $c/a = 1.58\text{\AA}^\circ$ and forms as small (0.015-0.02 μm) platelets, or needles observed under electron microscope.
- ❑ The structure at this stage referred to as tempered martensite, which is double phase mixture of low tetragonal martensite and ϵ -carbide.
- ❑ In this stage volume \downarrow because specific volume of martensite \downarrow due to rejecting of C atoms.

Tempering of plain carbon steels

Second stage of Tempering

- ❑ Second Stage of tempering temperature lies between 200-300°C. The amount of retained austenite in the as-quenched steel depends mainly on the composition of the steel, and the temperature to which steel is quenched.
- ❑ In the second stage of tempering retained austenite transforms to lower bainite (the carbide in bainite is ϵ -carbide). The matrix in lower bainite is cubic ferrite ($c/a = 1$), whereas in tempered martensite, the low tetragonal martensite has $c/a \sim 1.014$
- ❑ When retained austenite changes to lower bainite, there takes place increase in volume.

Third stage of Tempering

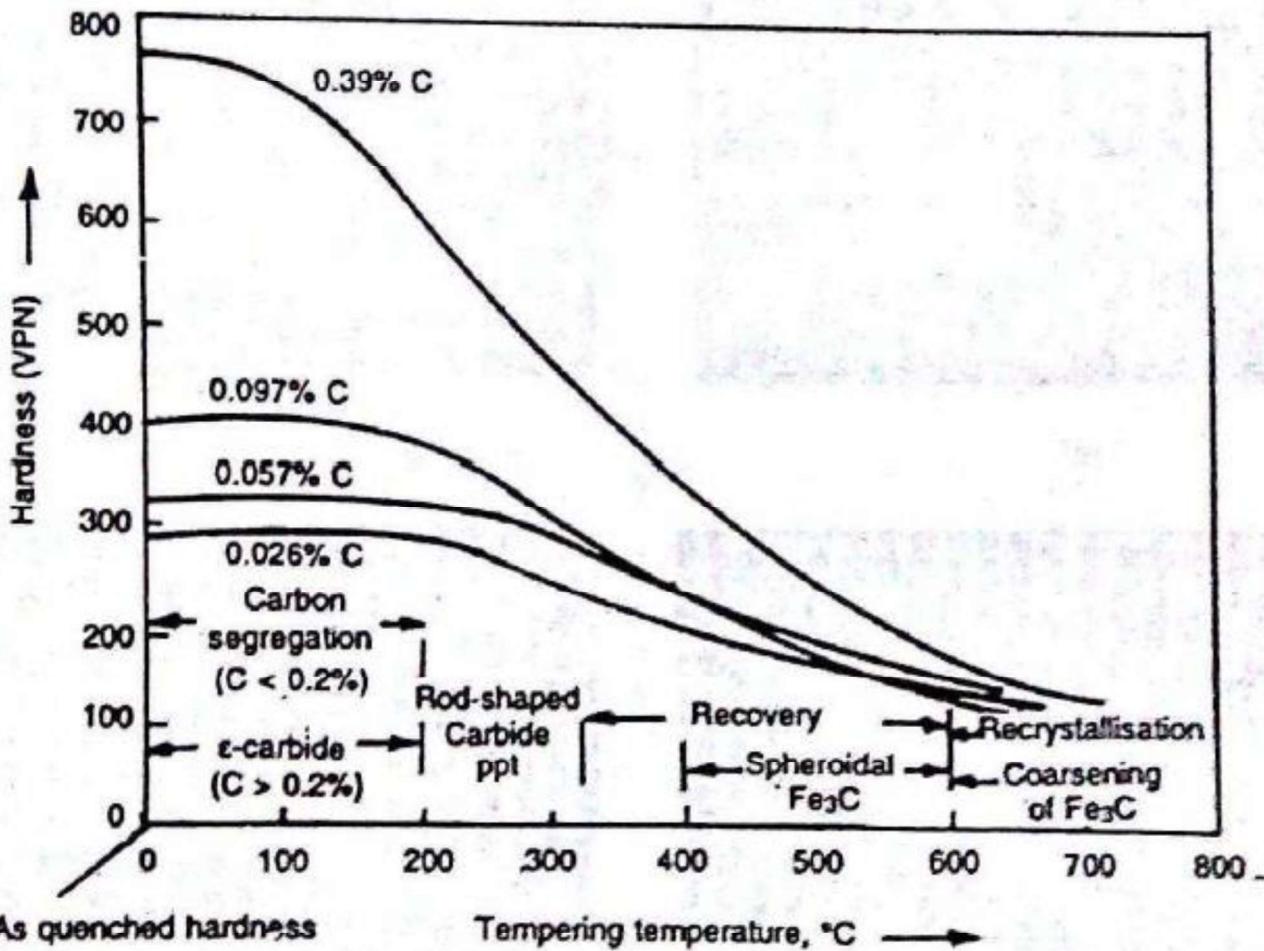
- ❑ Third Stage of tempering temperature lies between 200-350°C. In this stage of tempering, ϵ -carbide dissolves in matrix, and low tetragonal martensite loses its completely its carbon and thus, the tetragonality to become ferrite .
- ❑ Cementite forms as rods at interfaces of ϵ -carbide and matrix, twin boundaries, interlath boundaries, or original austenite grain boundaries.
- ❑ During this stage, volume decreases just as in stage one, due to complete loss of tetragonality. In a 1% carbon steel , the total decrease in length in the first and third stages is around 0.25%

Tempering of plain carbon steels

Fourth stage of Tempering

- ❑ Fourth Stage of tempering temperature lies between 350-700°C.
- ❑ Growth and spheroidisation of cementite, as well as recovery and Recrystallization of ferrite occur. Though the growth of cementite starts above 300°C, its spheroidisation starts above 400°C to 700°C.
- ❑ Spheroidisation takes place due to reduction in interfacial energy of ferrite-cementite interfaces. As quenched martensite has high concentration of lattice defects. Though their annealing out starts in the third stage of tempering, but the cementite precipitates retard the recovery processes.
- ❑ Substantial recovery processes starts occurring only above 400°C. original lathe boundaries are stable up to 600°C, but above this, these are replaced by equiaxed-ferrite grain boundaries – the process, which is best described as ‘Recrystallization’.
- ❑ In the end, the optical microstructure consists of equiaxed ferrite grains with coarse Spheroidal particles of cementite, and then the structure is called globular pearlite, or spheroidized cementite.
- ❑ The structure perhaps is the most stable of all ferrite- cementite aggregates, and is the softest with highest ductility with best machinability.

Effect of carbon on Tempering



Effect of tempering temperature(1 hour at each temperature) on hardness and reactions

essor, RVCE

Heat Treatment Defects

- ❑ Heat treatment of steels or aluminum can lead to several defects. The principal types of defects found in quenching of steels are internal and external cracks in the work, distortion and warping.
- ❑ **CRACK** : When the internal tensile stresses exceed the resistance of the steel to separation the crack occurs. The insertion of the tools in the furnace without preheating for tempering is one of the main causes of crack propagation. The crack formation is reduced by preheating the tool between 200°C to 300°C .
- ❑ **DISTORTION** : Distortion occurs due to uneven heating, too fast cooling, part incorrectly supported in furnace, incorrect dipping in quenching and stresses present before preheating. Distortion can be prevented by preheating the tool or check furnace capacity, reduce the hardening temperature, and by reviewing the method of dipping.
- ❑ **WARPING** : Asymmetrical distortion of the work is often called warping in heat-treating practice. Warping is usually observed upon non-uniform heating or over heating for hardening. It also occurs when the work is quenched in the wrong position and when the cooling rate is too high in the temperature range of the martensite transformation. An elimination of these causes should subsequently reduce warping.
- ❑ The properties required in the heat treated part are obtained without the parts being distorted beyond the acceptable limits.
- ❑ The ideal design for a heat treatable part is the shape that when heated (or cooled) would have the same temperature at every point with in the part.

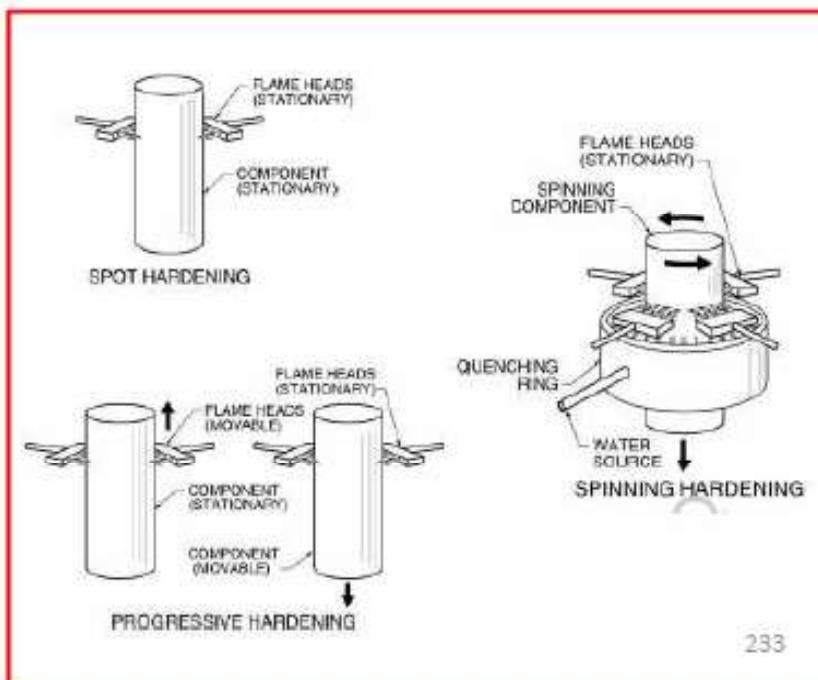
Surface Hardening treatment of steels

Dr. RATNA PAL, Assistant Professor, RVCE

Flame Hardening

- ❑ Flame hardening is the simplest form of surface hardening heat treatment.
- ❑ This process consists of heating the large work-piece, such as crank shaft, axle, large gear, cam, bending roller, or any other complicated cross-section, by an oxy-acetylene, or oxy-fuel blow pipe, followed by spraying of jet of water as coolant.
- ❑ After hardening, reheating of the parts is carried out in furnace or oil bath at about 180-200 °C for stress relieving.
- ❑ Normally, case depth up to 3mm can be achieved.

- ❑ Four methods are generally used for Flame Hardening
 - ✓ Stationary (Spot): Torch and work is stationary
 - ✓ Progressive: Torch moves over a work piece
 - ✓ Spinning: Torch is stationary while work piece rotates
 - ✓ Progressive-spinning: Torch moves over a rotating work piece.



Surface Hardening: Flame Hardening

- The flame hardening involves heating the surface of a steel to a temperature above upper critical point ($850\text{ }^{\circ}\text{C}$) with a oxyacetylene flame and then immediately quenched the surface with cold water.
- Heating transforms the structure of surface layers to austenite, and the quenching changes it to martensite.

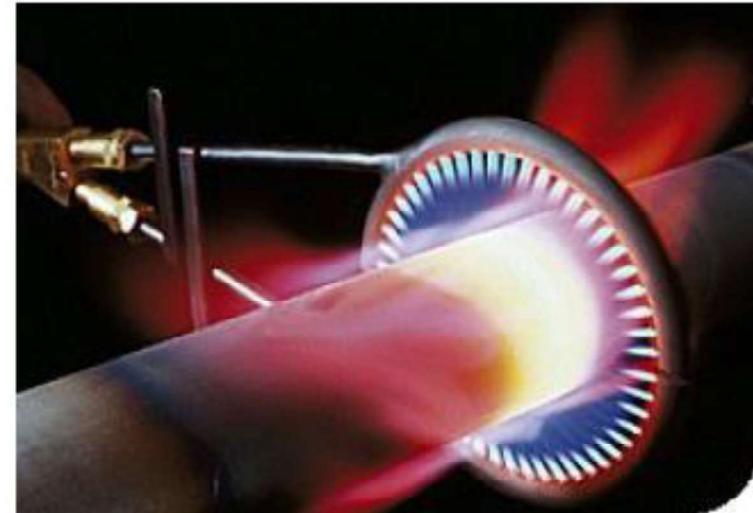


Gear Flame Hardening



Surface Hardening: Flame Hardening

- The surface layers are hardened to about 50 – 60 HRC. It is less expensive and can be easily adopted for large and complex shapes.
- Flame hardened parts must be tempered after hardening. The tempering temperature depends on the alloy composition and desired hardness.

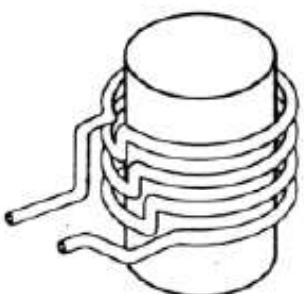


- The flame hardening methods are suitable for the steels with carbon contents ranging from 0.40 to 0.95% and low alloy steels.

Induction Hardening

- ❑ Induction hardening may be used for local surface heat treatment. Generally, it is used to surface harden crank shafts, cam shafts, gears, crank pins and axles. In this process, heating of the component is achieved by electromagnetic induction.
- ❑ Here, an alternating current of high frequency passes through an induction coil enclosing the steel part to be heat treated. The induced emf heats the steel. the depth up to which the heat penetrates and rises the temperature above Ac_3 is inversely proportional to the square root of the AC frequency.
- ❑ Correspondingly, the hardened depth decreases with increasing frequency in induction hardening, the heating time is usually a few seconds. Immediately after heating water jets are activated to quench the surface . Martensite is produced at the surface, making it hard and wear resistant. The microstructure of the core remains unaltered. Induction hardening is suitable for mass production of articles of uniform cross section

Five basic designs of work coils with the heat patterns developed by each are shown below

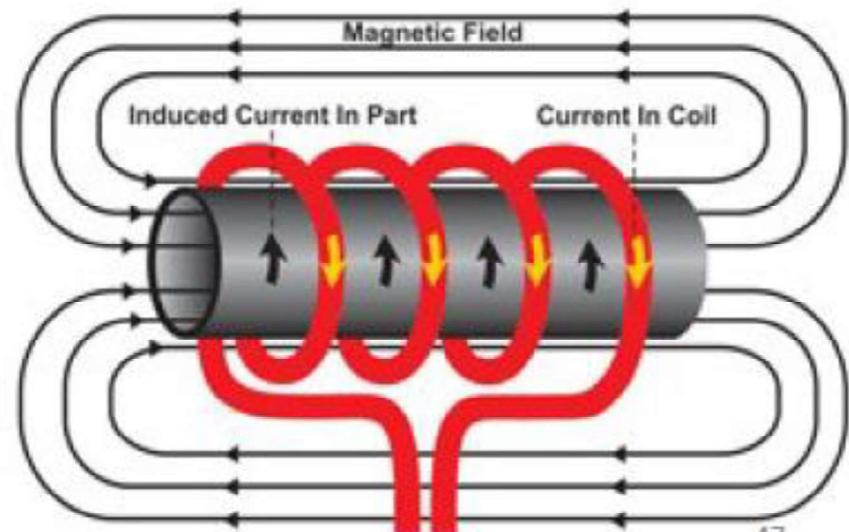
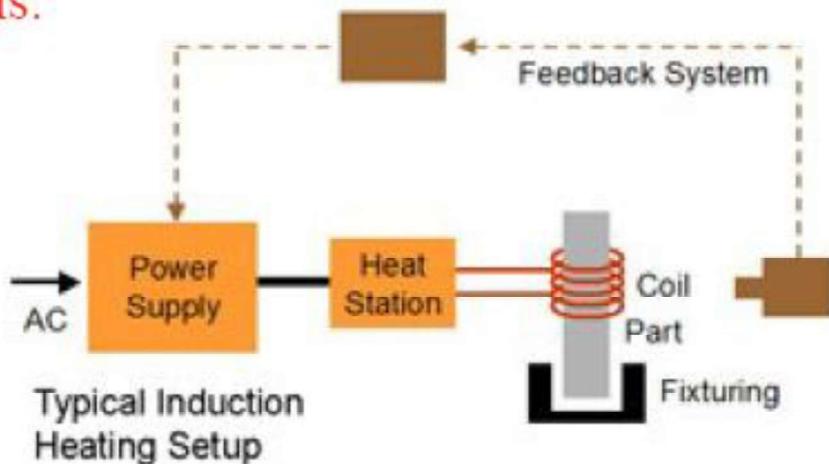


Heating pattern

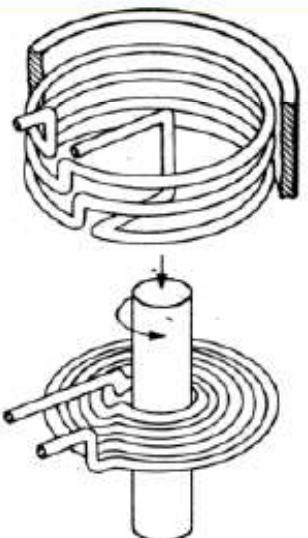
A Simple Solenoid for
external heating

Surface Hardening: Induction Hardening

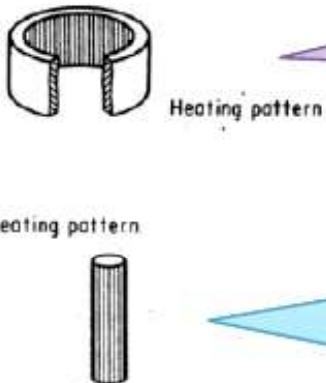
- Induction hardening involves placing the steel components within a coil through which high frequency current is passed. The current in the coil induces eddy current in the surface layers, and heat the surface layers up to austenite state.
- Then the surface is immediately quenched with the cold water to transfer the austenite to martensite. The principle of induction hardening is:



Induction Hardening



A Single turn coil for scanning a rotating surface, provided with a contoured half turn that will aid in heating the fillet

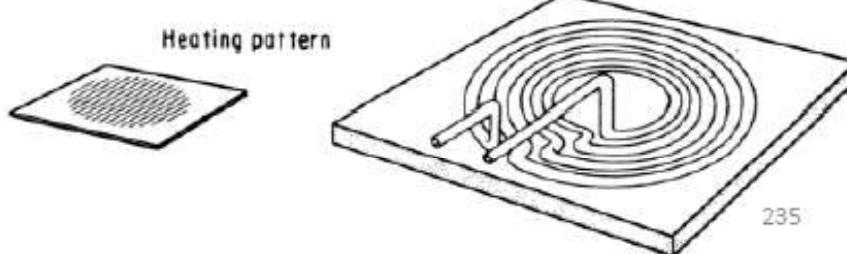
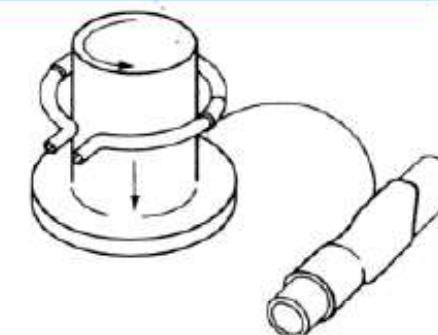


A coil to be used internally for heating bores

A “pie-plate” type of coil designed to provide high current densities in a narrow band for scanning applications.



A ‘Pancake’ coil for spot heating.

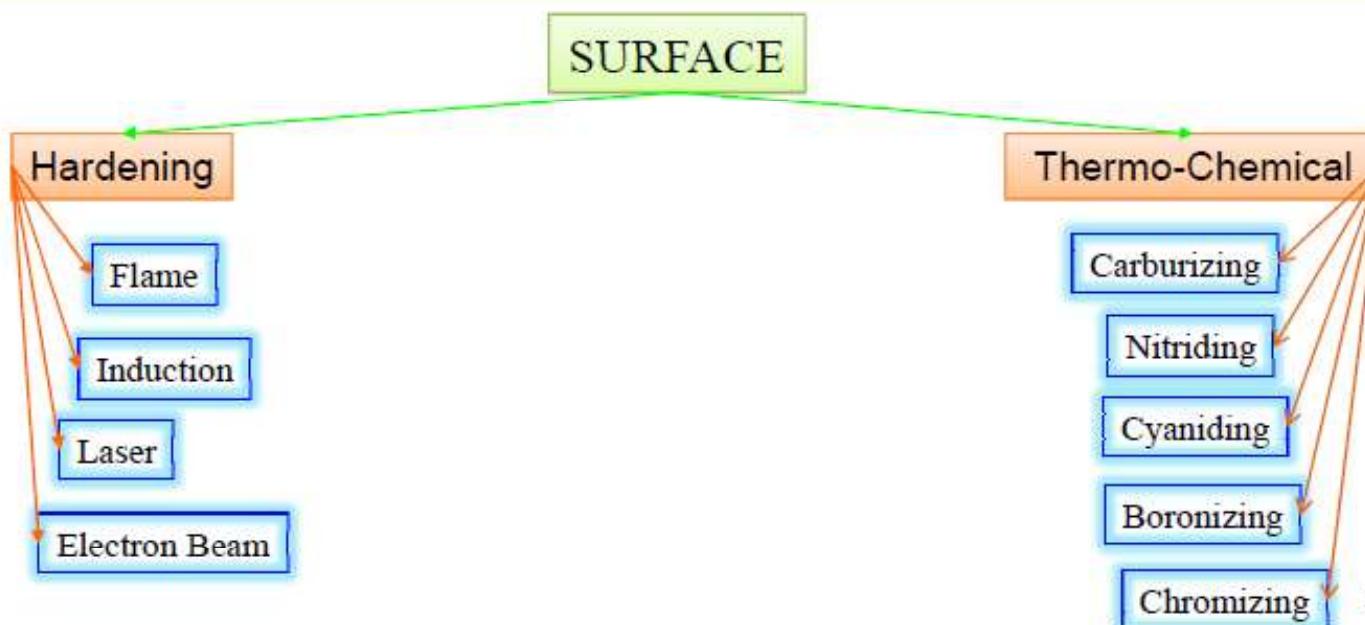


Thermo chemical treatment of steels

Dr. RATNA PAL, Assistant Professor, RVCE

Introduction

- ❑ Chemical heat treatment is the process used to achieve different properties in core and steel components. Numerous industrial applications require a hard wear resistant surface called the *case*, and a relatively soft, tough inside called the *core*. Example: Gears
- ❑ There are two different methods. The first method is known as thermochemical treatment because the surface composition of steel changes by diffusion of carbon and/or nitrogen and sometimes other elements.
- ❑ The second method is known has surface hardening, it involves phase transformation by rapid heating and cooling of the outer surface . The aim of both methods are same



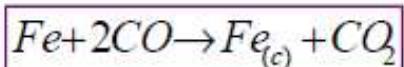
Surface Hardening: Carburising

- Carburising is carried out on steels containing carbon less than 0.2%. It involves increasing the carbon contents on the surface layers upto 0.7 to 0.8%.
- In this process, the steel is heated in contact with carbonaceous material from which it absorbs carbon. This method is mostly used for securing hard and wear resistance surface with tough core carburising is used for gears, cams, bearings and clutch plates.



Carburizing

- ❑ Carburizing is the most widely used method of surface hardening. Here, the surface layers of a low carbon steel (<0.25) is enriched with carbon up to 0.8-1.0%. The source of carbon may be a solid medium, a liquid or a gas.
- ❑ In all cases, the carbon enters the steel at the surface and diffuses into the steel as a function of time at an elevated temperature. Carburizing is done at 920-950°C. at this temperature the following reaction takes place



- ❑ Where $Fe_{(c)}$ represents carbon dissolved in austenite. the rate of diffusion of carbon in austenite, at a given temperature is dependent upon the diffusion coefficient and the carbon concentration gradient.
- ❑ The carburizing equation given previously, $Fe + 2CO \rightarrow Fe_{(c)} + CO_2$ is reversible and may proceed to the left, removing carbon from the surface layer if the steel is heated in an atmosphere containing carbon dioxide (CO_2). This is called decarburization.
- ❑ Decarburization may be prevented by using an endothermic gas atmosphere in the furnace to protect the surface of the steel from oxygen, carbon dioxide and water vapor. An endothermic gas atmosphere is prepared by reacting relatively rich mixtures of air and hydrocarbon gas (usually natural gas) in an externally heated generator in the presence of a nickel catalyst.
- ❑ Carburizing can be done by Pack carburizing, Liquid carburizing, Gas carburizing and vacuum carburizing.

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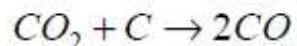
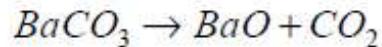
Assistant Professor, RVCE



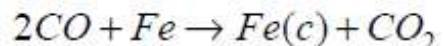
Pack Carburizing

- ❑ This method of carburizing is also known as solid carburizing.
- ❑ In this process, steel components to be heat treated are packed with 80% granular coal and 20% BaCO₃ as energizer in heat resistant boxes and heated at 930°C in furnace for a specific time which depends on the case depth required.
- ❑ Such a high temperature in furnace helps in absorption of carbon at the outer layer. The following reactions takes place:

- i. Energizer decomposes to give CO gas to the steel surface

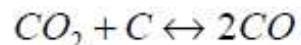


- ii. Carbon monoxide reacts with the surface of steel :



- iii. Diffusion of carbon into steel

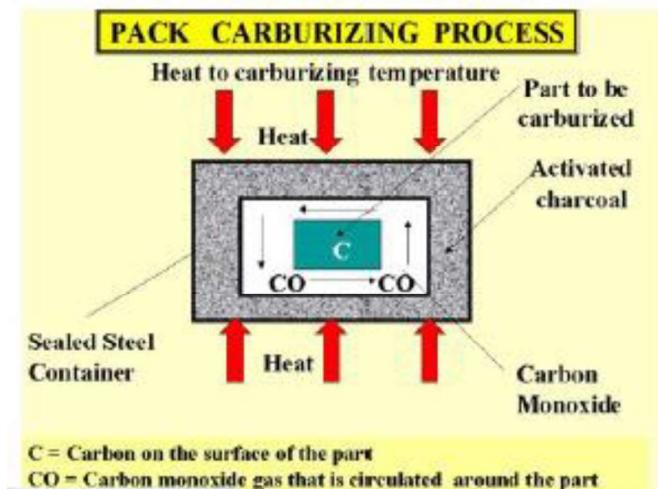
- iv. CO₂ formed in step (ii) reacts with "C" in the coal



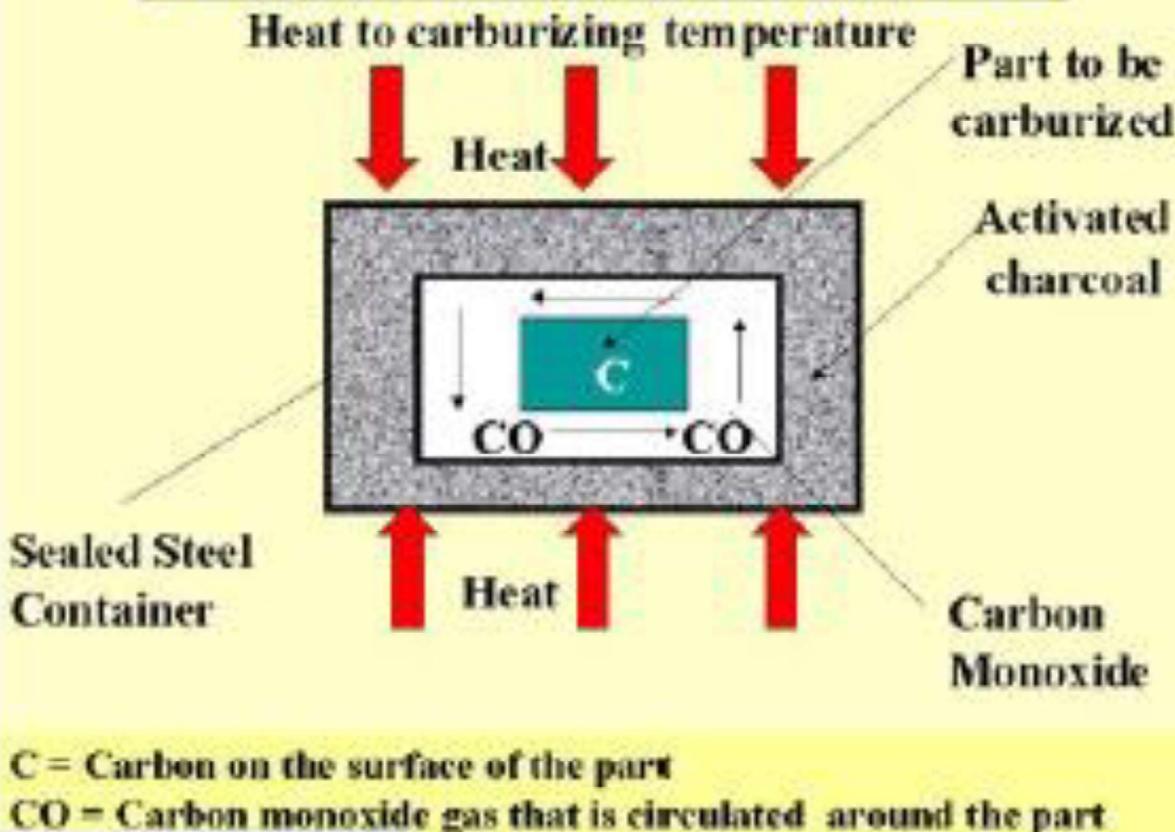
- ❑ For a given steel at a given temperature, the depth of penetration is dependent on diffusion and can be related to the time t by the equation

$$\text{casedepth} = k\sqrt{t} \quad \text{Where } k \text{ is constant}$$

- ❑ Generally, carburizing time varies from 6 hours to 8 hours, and case depth obtained varies from 1 mm to 2 mm.

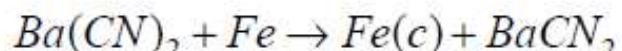
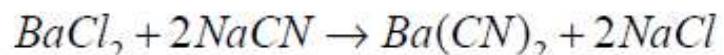


PACK CARBURIZING PROCESS



Liquid Carburizing

- ❑ It is also popularly known as salt bath carburizing. In this process, carburizing occurs through molten cyanide (CN) in low carbon steel cast pot type furnace heated by oil or gas. Bath temperature is maintained between $815^{\circ}C$ and $900^{\circ}C$.
- ❑ The life of pot depends on quality of material, operating temperature and mode of operation, viz. whether it is continuous or intermittent. Continuous and automatic processes give good end results.
- ❑ The bath surface is covered with graphite or coal to reduce radiation losses and excessive decomposition of cyanide.
- ❑ Different salt mixtures used in this processes are named according to their carbon potential activity. Besides sodium or potassium cyanide, the bath contains (i) Sodium and potassium chloride (ii) Barium chloride which acts as an activator



- ❑ Some beneficial nitrogen diffusion may also take place through oxidation of CN to CNO . In liquid carburizing, heating time is short and heat transfer is rapid. There is complete uniformity of the carburized layer in the component.
- ❑ This process gives a thin and clean hardened layer of $\sim 0.08mm$ thick.

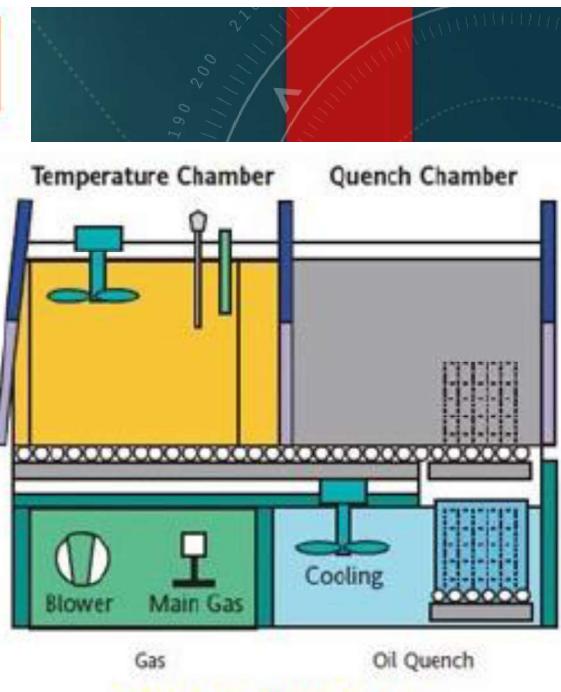


Gas Carburizing

- ❑ This is the most widely used method of carburizing. It is carried out in retort type, sealed quench type, or continuous pusher type furnaces. These furnaces are either gas fired or are heated electrically. Gas carburizing temperature varies from 870°C to 950°C.
- ❑ Gas atmosphere for carburizing is produced from liquid (methanol, isopropanol) or gaseous hydrocarbons (propane and methane). An endothermic gas generator is used to supply endothermic gas.
- ❑ A mixture of propane or methane with air is cracked in hot retort of an endogas generator to form carrier gas, whose dew point is adjusted at about +4°C by proper gas/air ratio. The approximate composition of this gas is as follows.

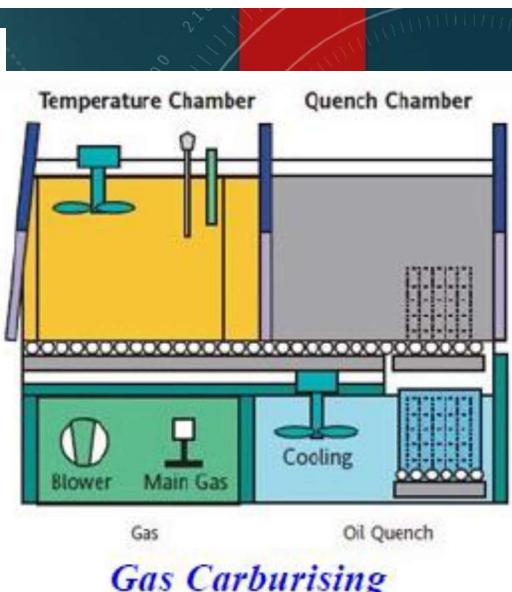
- ❑ Such a gas acts as a 'carrier gas' for the process. Furnace chamber is purged with this gas to maintain a slightly positive pressure. This in turn prevents infiltration of air from atmosphere.
- ❑ This gas also prevents oxidation of the steel during heating. When the material reaches carburizing temperatures, propane or methane is introduced to maintain a specific carbon potential

Nitrogen	40%
Hydrogen	40%
Carbon monoxide	20%
Carbon dioxide	0.3%
Methane	0.5%
Water vapour	0.8%
Oxygen	In traces



Gas Carburizing

- ❑ During gas carburizing, the following reactions take place:
 - i. $C_3H_8 \rightarrow 2CH_4 + C$ (cracking of hydrocarbon)
 - ii. $CH_4 + Fe \rightarrow Fe(C) + 2H_2$
 - iii. $CH_4 + CO_2 \rightarrow 2CO + 2H_2$
 - iv. $2CO + Fe \rightarrow Fe(C) + CO_2$
- ❑ Carburizing occurs mainly due to conversion of CO to CO_2 through reaction (iv). Hydrogen reacts with CO_2 and increases CO concentration by the reaction
$$H_2 + CO_2 \rightarrow CO + H_2O$$
- ❑ Traces of O_2 are also present due to the following reactions:
$$2CO_2 \rightarrow 2CO + O_2$$
$$CO_2 + Fe \rightarrow Fe(c) + O_2$$
- ❑ Average concentrations of CO_2 , H_2O , and O_2 are 0.2%, 0.5% and 10^{-14} ppm respectively.
- ❑ One of the recent developments in the gas carburizing technique is the use of nitrogen as a carrier gas. Normally, nitrogen gas is used with some minor additives. Carbon potential is controlled by adjusting the level of oxidizing constituents.
- ❑ Currently the cost of equipment for this modified process is high. Also, skilled and well trained operators are required for successful operation of this process.



Gas Carburising

Surface Hardening: Nitriding

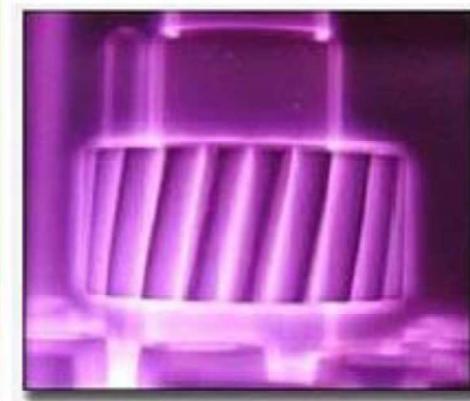
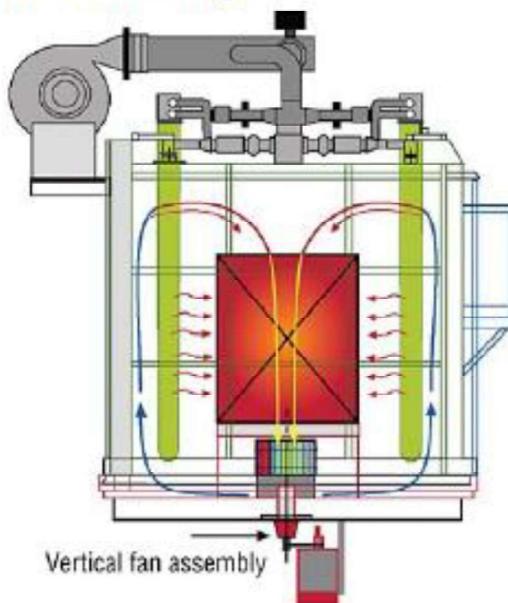
- Nitriding involves diffusion of nitrogen into the product to form nitrides. The resulting nitride case can be harder than the carburized steel. This process is used for alloy steels containing alloying elements (Aluminum, Chromium and Molybdenum) which form stable nitrides.
- Nitriding consists if heating a component in a retort to a temperature of about 500 to 600 °C. Through the retort the ammonia gas is allowed to circulate. At this temperature the ammonia dissociates by the following reaction.



- The atomic nitrogen diffuses into steel surface, and combines with the alloying elements (Cr, Mo, W, V etc) to form hard nitrides. The depth to which nitrides are formed in the steel depends on the temperature and the time allowed for the reaction. After the nitriding the job is allowed to cool slowly. Since there is no quenching involved, chances of cracking and distortion of the component are less.

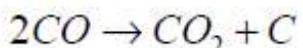
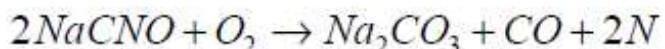
Surface Hardening: Nitriding

- The depth of nitrided case ranges from 0.2 to 0.4 mm and no machining is done after nitriding.
- Nitriding increase wear and corrosion resistance and fatigue strength of the steel. Since nitriding is done at low temperature, it requires more time than carburising, and also the capital cost if the plant is higher than carburising.



Cyaniding and Carbonitriding

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



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

Cyaniding and Carbonitriding

- ❑ Cyaniding is a case-hardening process in which a steel is heated in a gaseous atmosphere of such composition that carbon and nitrogen are absorbed simultaneously.
- ❑ This process is also known as dry cyaniding or gas cyaniding. It is the gas carburizing process modified by the addition of anhydrous ammonia.
- ❑ The decomposition of ammonia provides the nitrogen, which enters the steel along with carbon.
- ❑ A typical gas mixture consists of 15% NH_3 , CH_4 , and 80% of neutral carrier gas. The temperature used is 750-900°C. With increasing temperature, a greater proportion of carbon enters the steel.
- ❑ The presence of nitrogen in the austenite accounts for the major differences between carbonitriding and carburizing.
- ❑ Carbon-nitrogen austenite is stable at lower temperatures than plain-carbon austenite and transforms more slowly on cooling. Carbonitriding therefore can be carried out at lower temperatures and permits slower cooling rates than carburizing in the hardening operation.
- ❑ In this process, surface hardenability, wear resistance and corrosion resistance are better than in the carburizing process. But the time required for heat treatment is longer than that for carburizing.