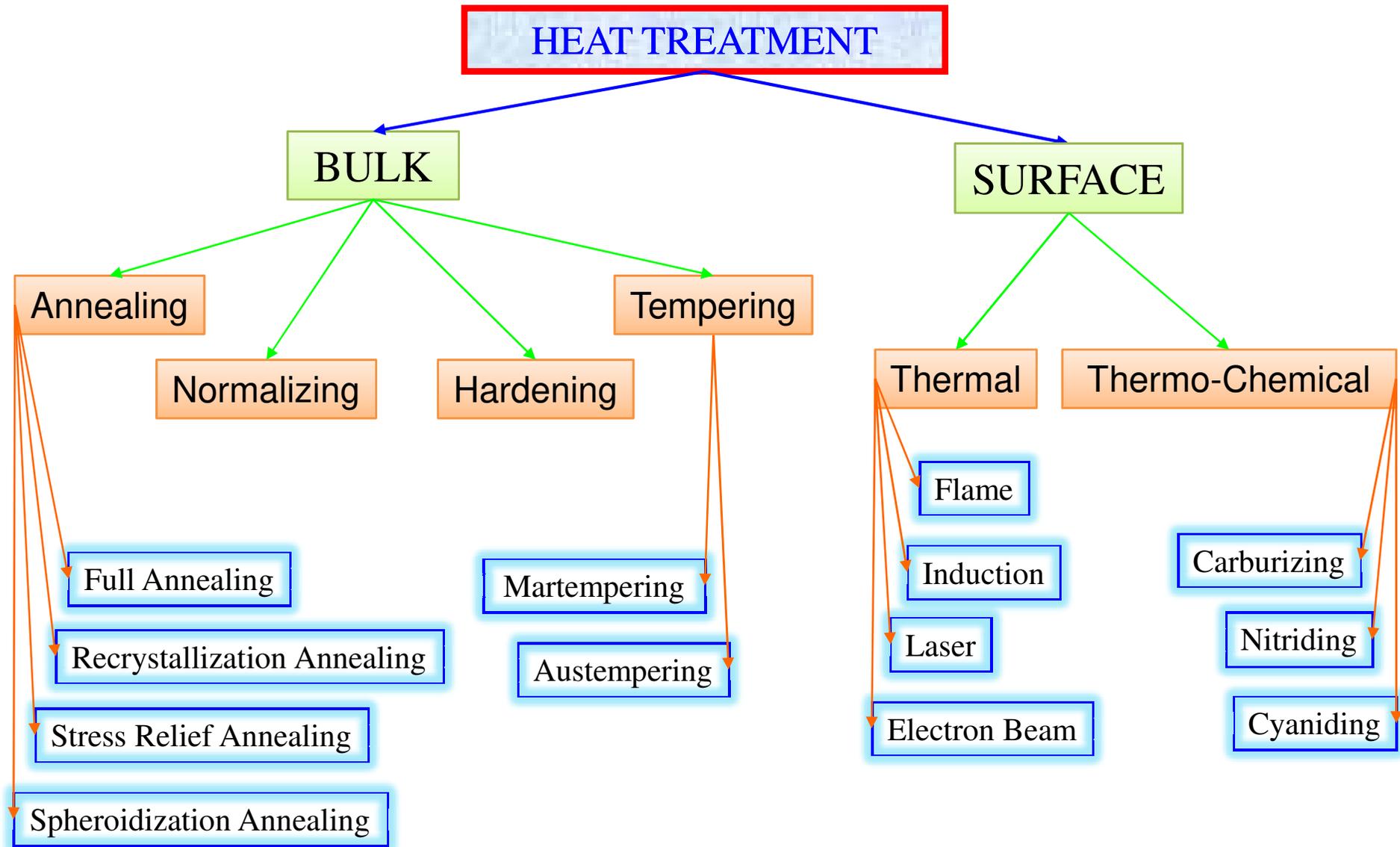


Objectives of Heat Treatment Processes

- ❑ 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-precipitation hardening, surface treatment*)
- ❑ To improve electrical properties (*Recrystallization, Tempering, Age hardening*)
- ❑ To improve magnetic properties (*Hardening, Phase transformation*)

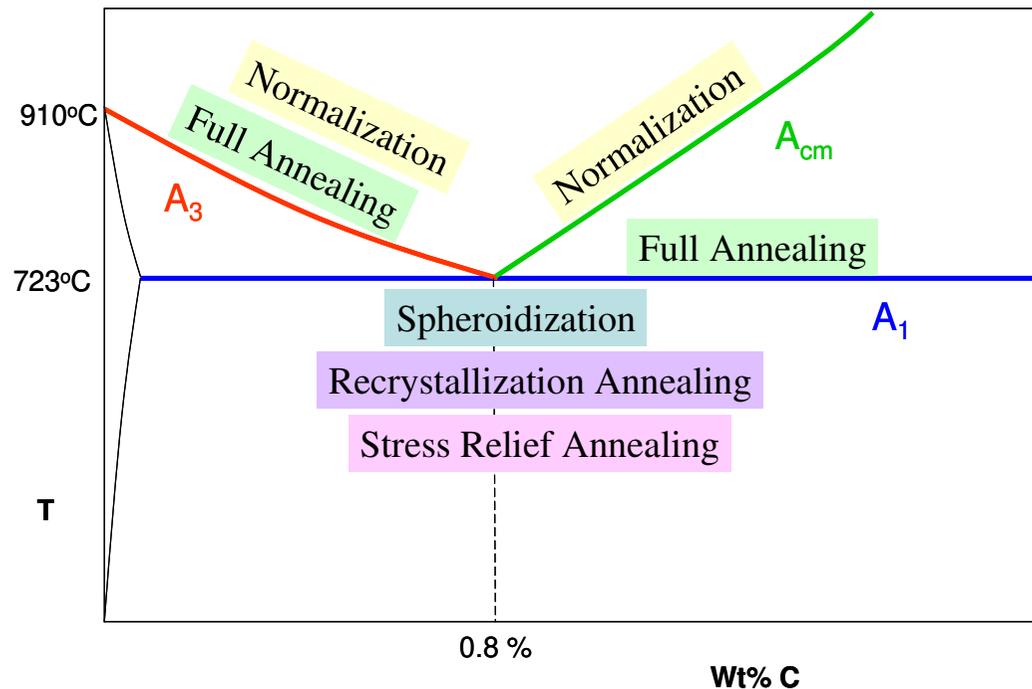
Classification



Annealing

Full Annealing

- ❑ 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 ↓ Hardness, ↑ Ductility
- ❑ Not above A_{cm} →to avoid a continuous network of proeutectoid cementite along grain boundaries (→path for crack propagation)



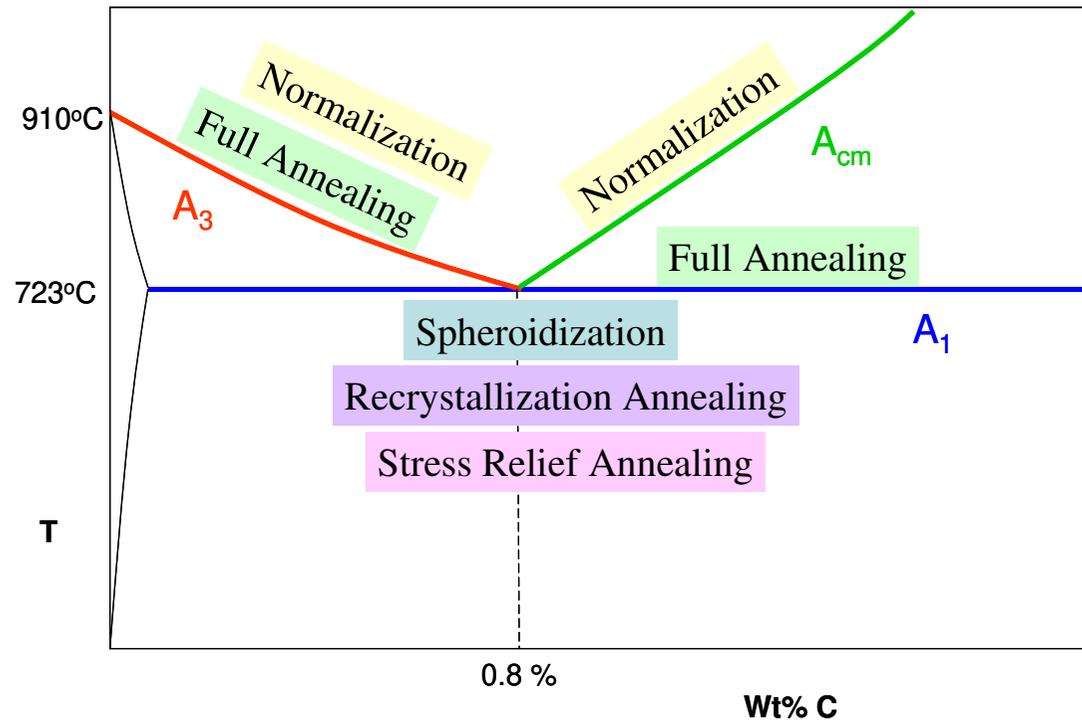
Annealing

Recrystallization Annealing

❑ The Heat below A_1 → Sufficient time → Recrystallization

Cold worked grains → New stress free grains

❑ Used in between processing steps (e.g. Sheet Rolling)



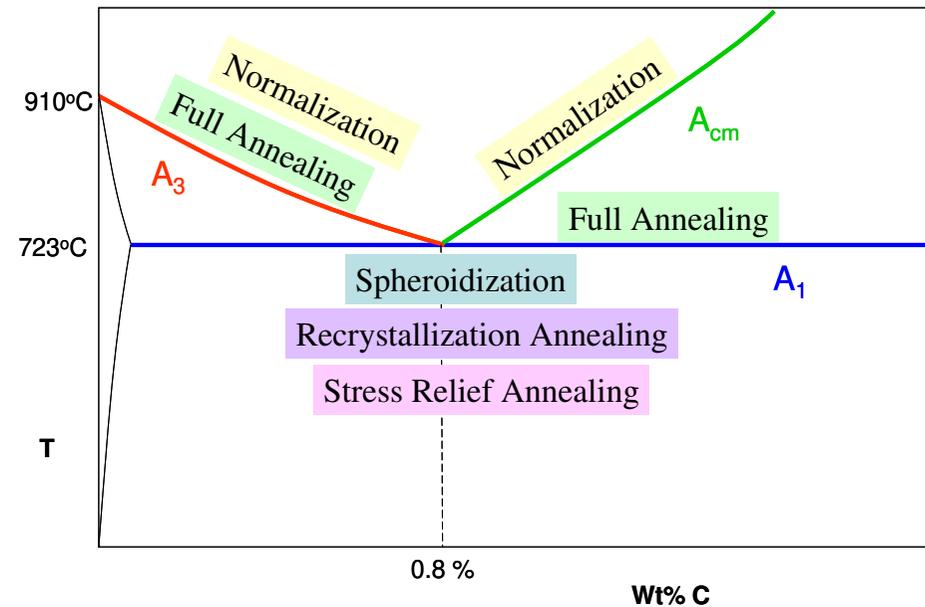
Annealing

Stress Relief Annealing

Residual stresses → Heat below A_1 → **Recovery**

- Differential cooling
- Martensite formation
- Machining and cold working
- Welding

Annihilation of dislocations,
polygonization



Annealing

Spheroidization Annealing

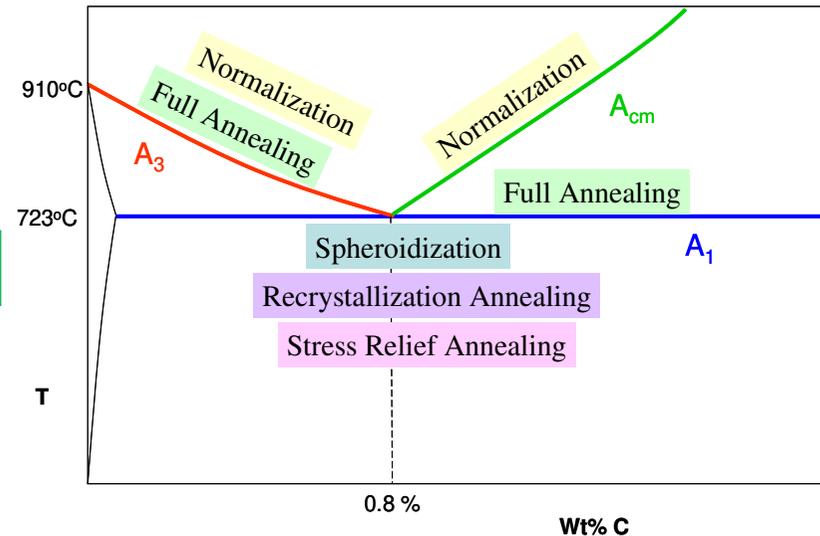
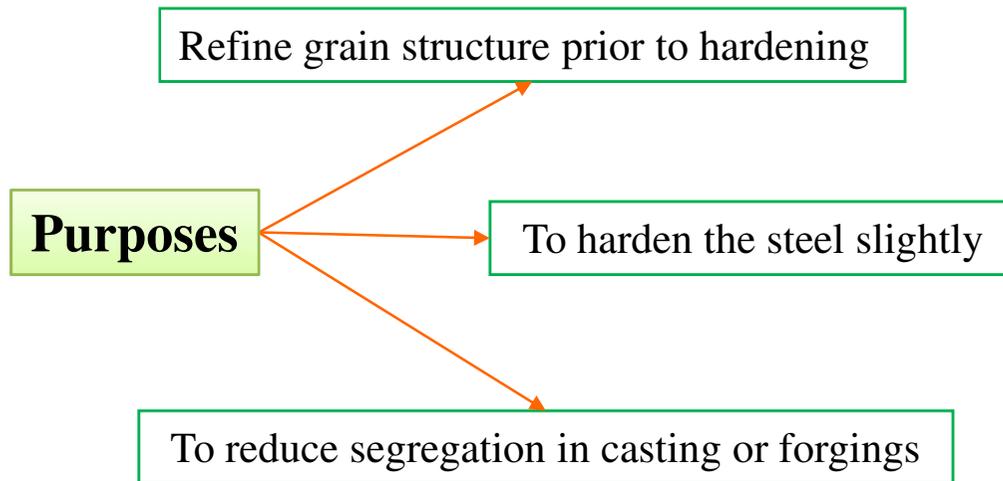
Heat below/above A_1 (Prolonged holding*)
Cementite plates \rightarrow Cementite spheroids \rightarrow \uparrow Ductility

- Used in high carbon steel requiring extensive machining prior to final hardening and tempering*
- Driving force is the reduction in interfacial energy*
- The spheroidized structure is desirable when minimum hardness, maximum ductility, or (in high-carbon steels) maximum machinability is important.
- Low-carbon steels are seldom spheroidized for machining, because in the spheroidized condition they are excessively soft and “gummy”.
- Medium-carbon steels are sometimes spheroidization annealed to obtain maximum ductility.

**If the steel is kept too long at the spheroidized-annealing temperature, the cementite particles will coalesce and become elongated thus reducing machinability*

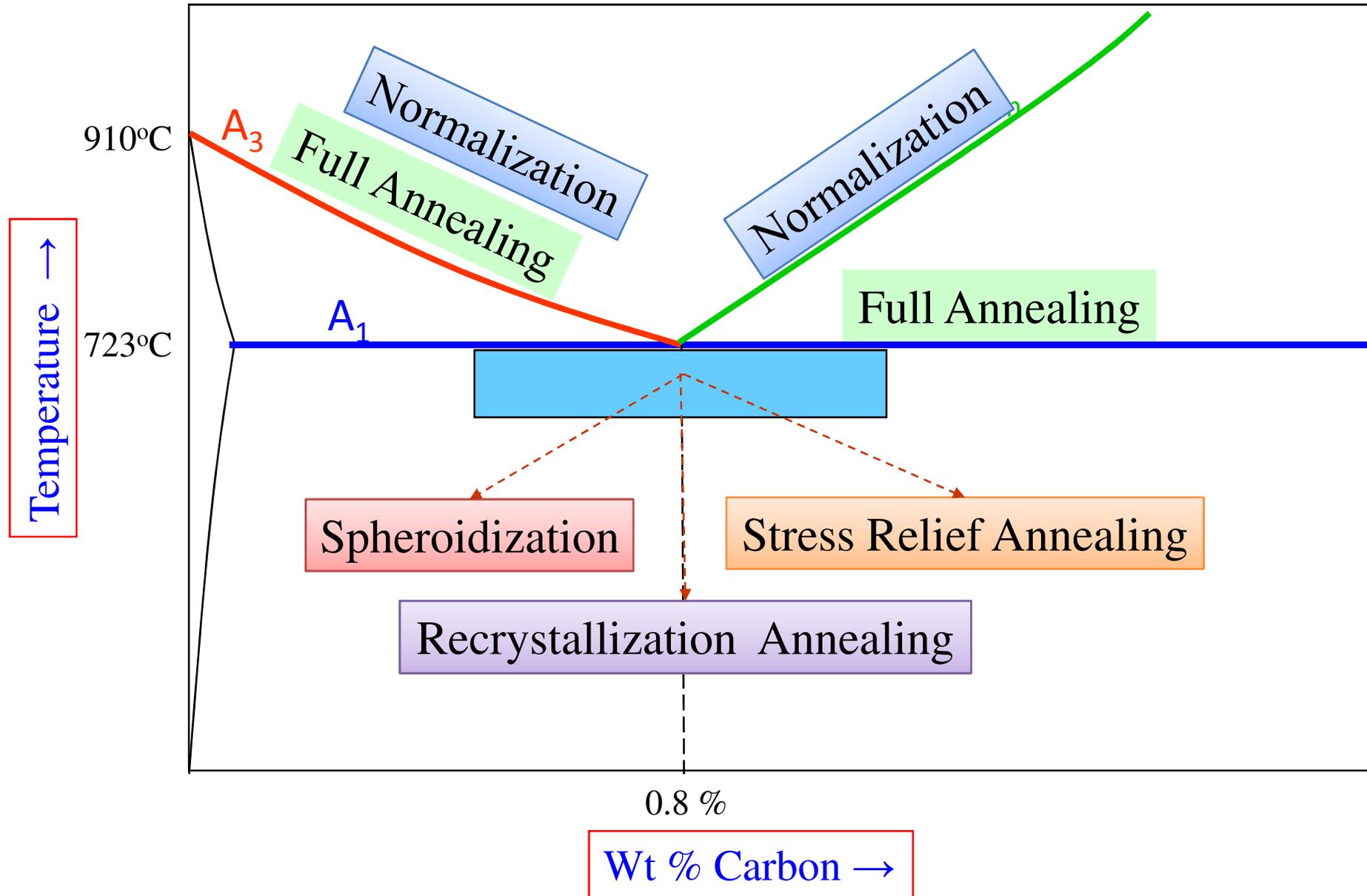
Normalizing

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



- ❑ In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature
- ❑ In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB

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



Time-Temperature-Transformation (TTT) Diagrams

- ❑ 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.
- ❑ TTT diagrams give the kinetics of isothermal transformations.
- ❑ For every composition of steel we should draw a different TTT diagram.

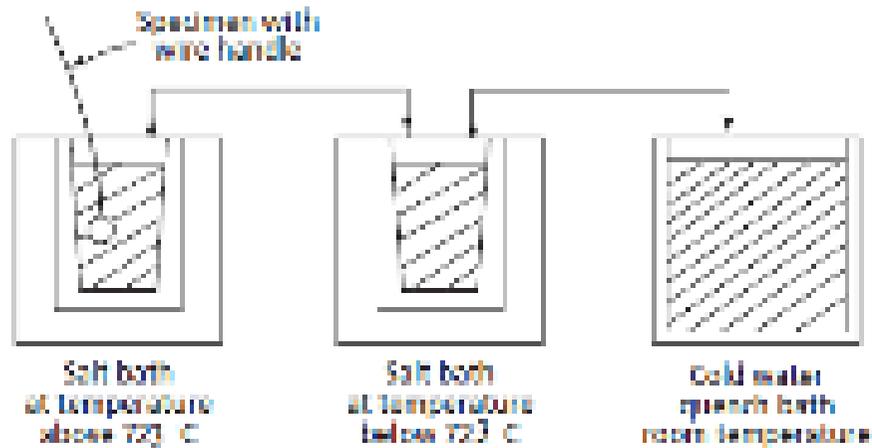
Equipments for determination of TTT Diagrams



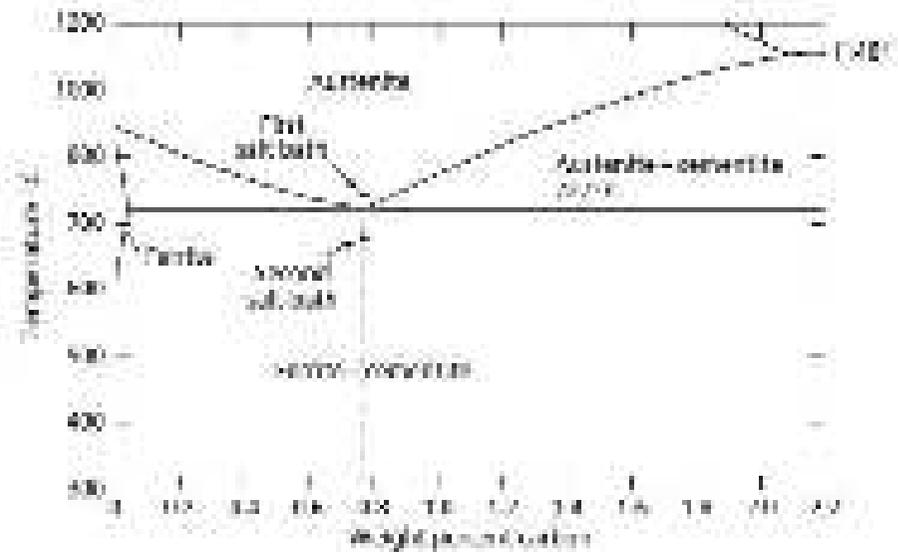
Determination of TTT diagram for eutectoid steel

- ❑ 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 $700\text{-}250^{\circ}\text{C}$ 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 $A_1+20\text{-}40^{\circ}\text{C}$ for eutectoid, $A_3+20\text{-}40^{\circ}\text{C}$ for hypo-eutectoid steel and $A_{Cm}+20\text{-}40^{\circ}\text{C}$ 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.

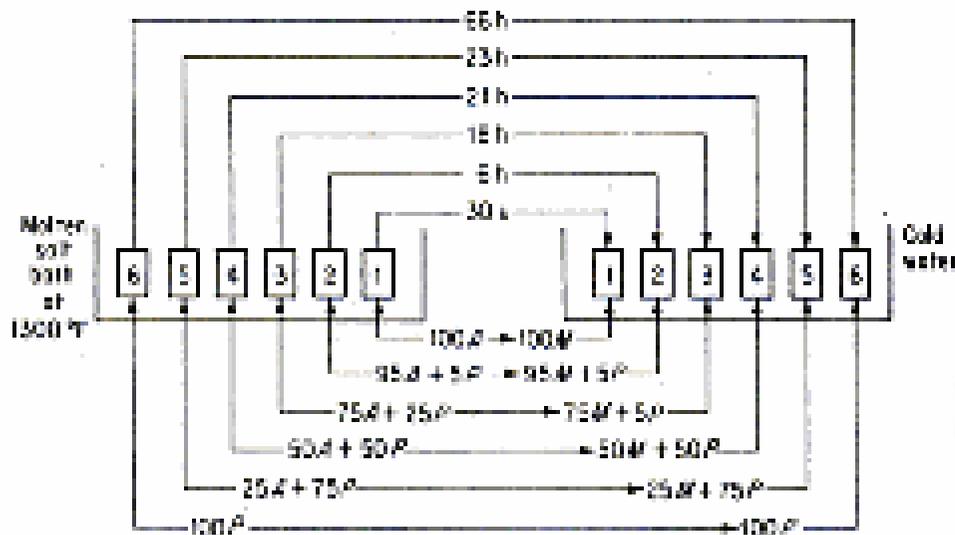
Determination of TTT diagram for eutectoid steel



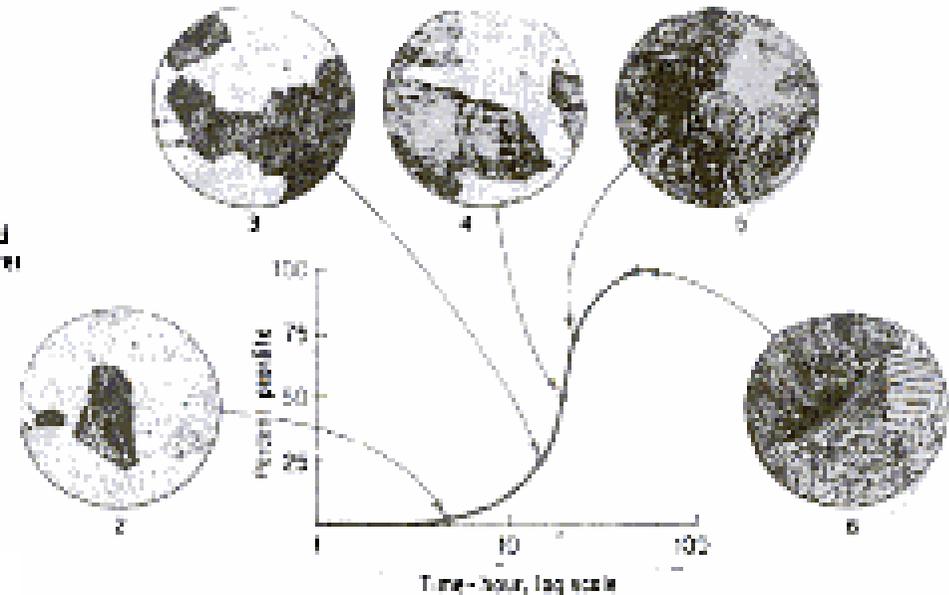
Simple experimental arrangement for determining The kinetics of isothermal austenitic transformation



Eutectoid section of the iron - carbon diagram

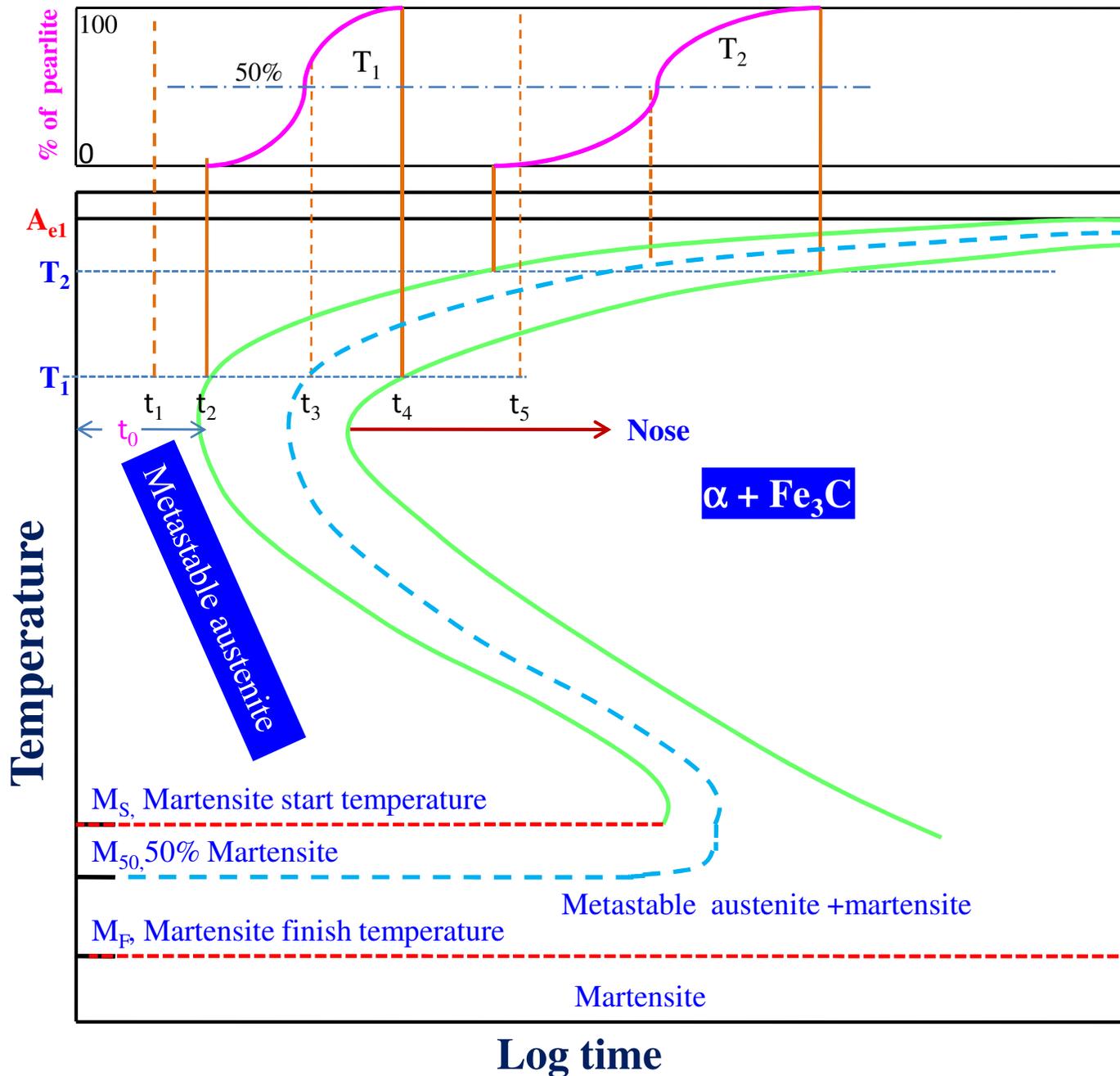


The progress of austenite transformation
A-austenite, P-pearlite, M-martensite



TTT curve of austenite to pearlite for 1080 steel

Determination of TTT diagram for eutectoid steel



✓ At T₁, incubation period for pearlite = t₂, Pearlite finish time = t₄

✓ Minimum incubation period t₀ 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 (γ + Fe₃C) phase field. This phase field has more labels included.

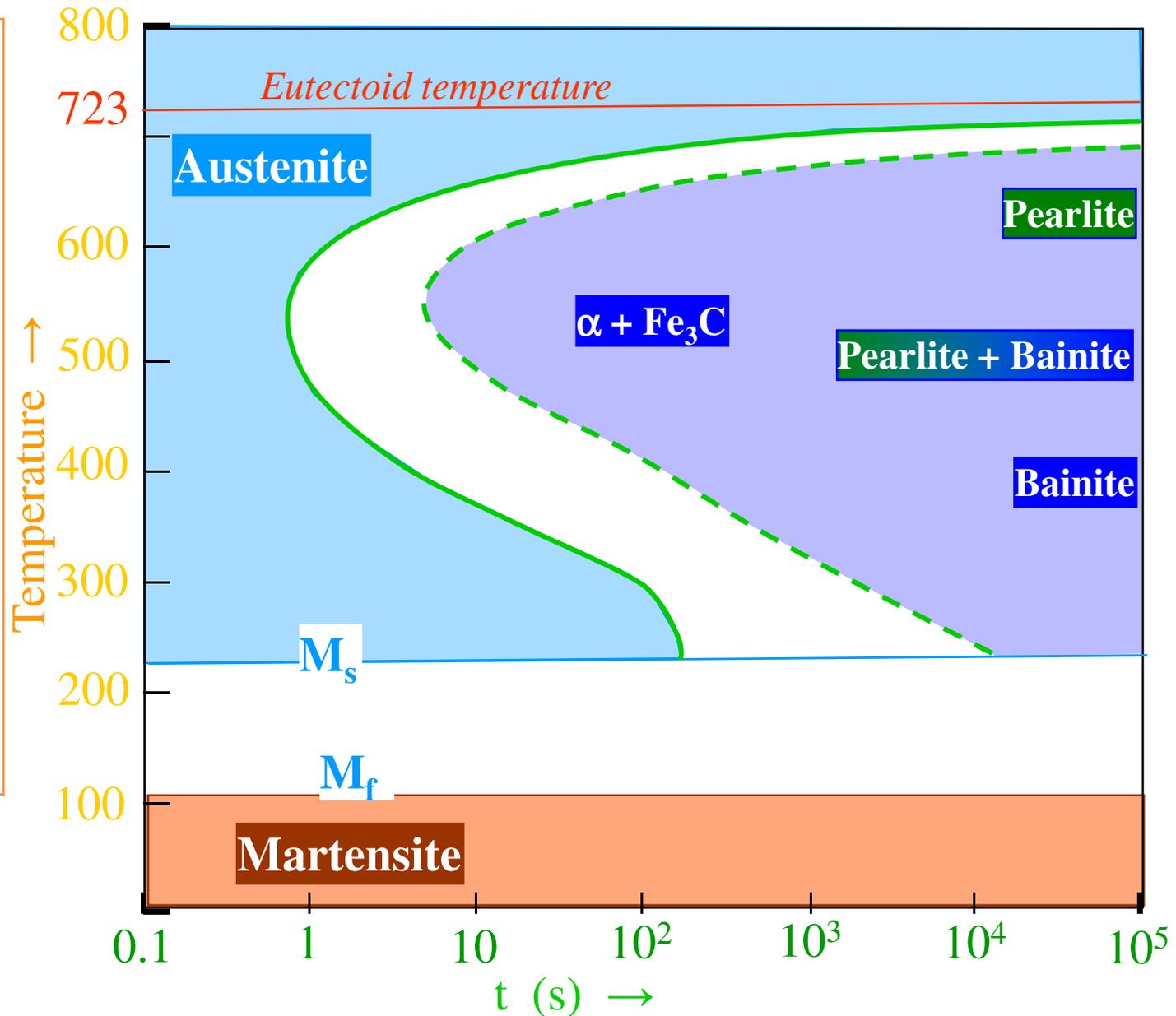
Isothermal Transformation diagram for eutectoid steel

Important points to be noted:

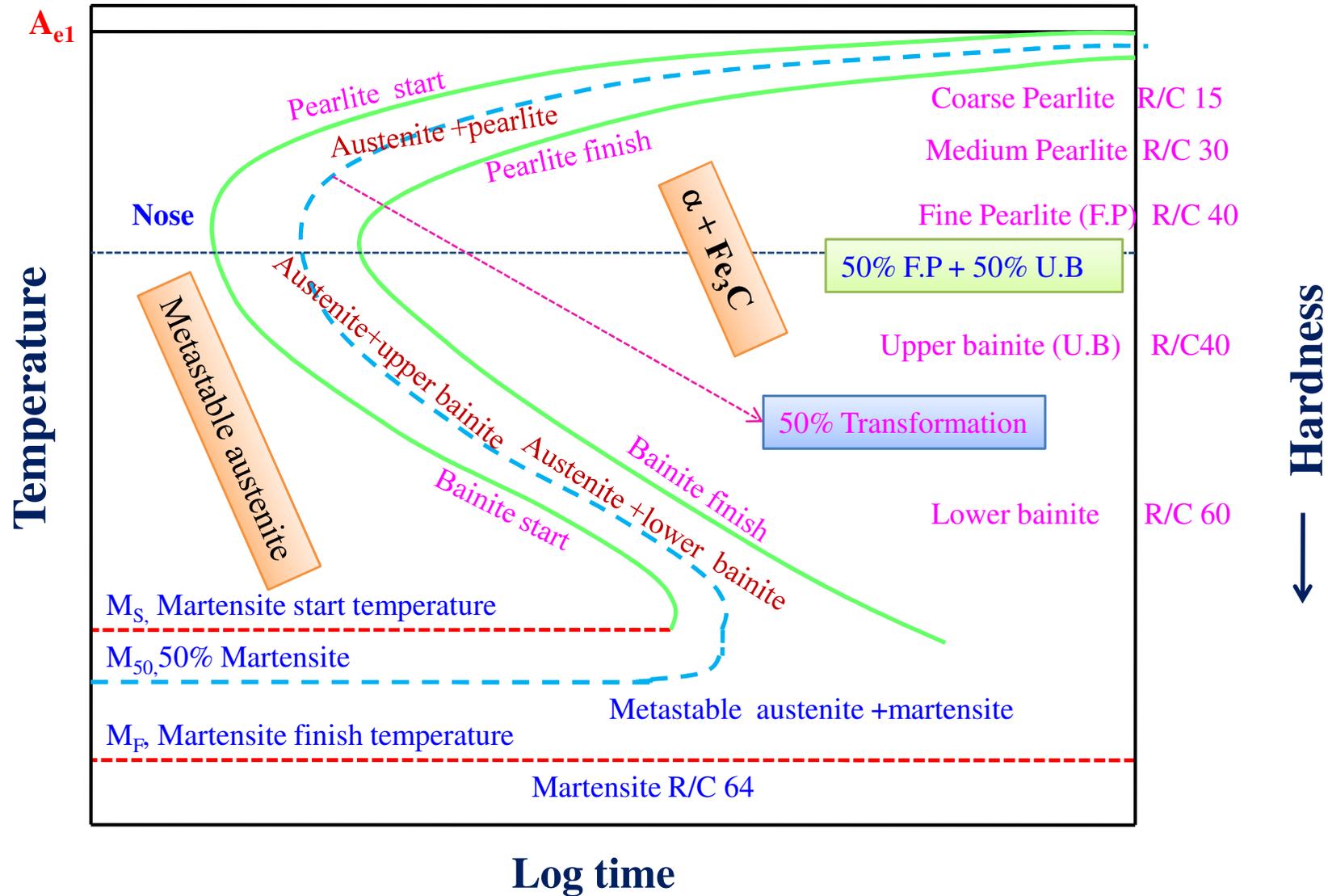
✓ The x-axis is log scale. 'Nose' of the 'C' curve is in ~sec and just below T_E transformation times may be ~day.

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

✓ To the right of finish C curve is ($\gamma + Fe_3C$) phase field. This phase field has more labels included.



Possible phases in TTT diagram for eutectoid steel



Isothermal Transformation diagram for eutectoid steel

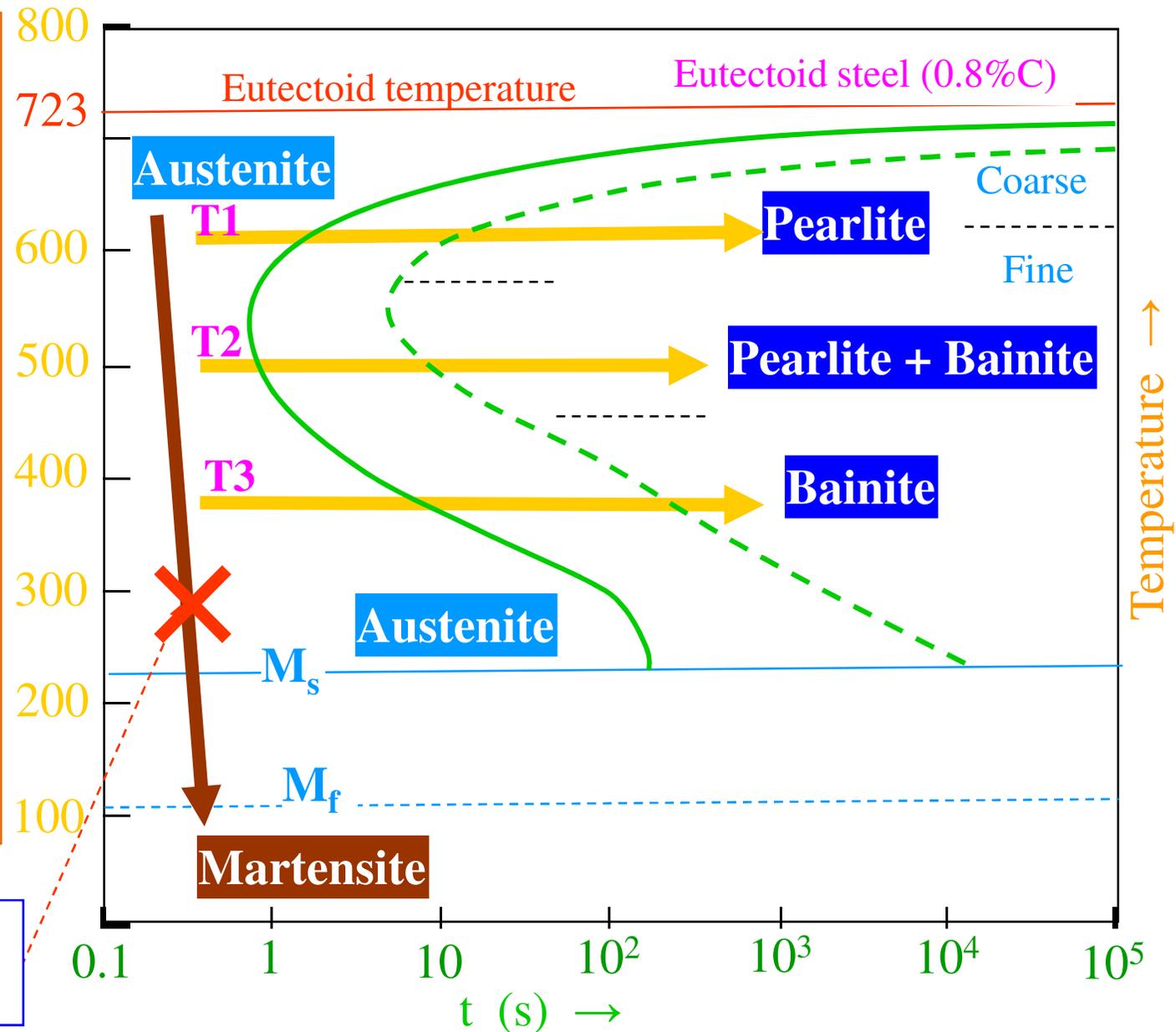
- ❑ As pointed out before one of the important utilities of the TTT diagrams comes from the overlay of micro-constituents (microstructures) on the diagram.
- ❑ Depending on the T, the ($\gamma + \text{Fe}_3\text{C}$) phase field is labeled with micro-constituents like Pearlite, Bainite.
- ❑ The time 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).*

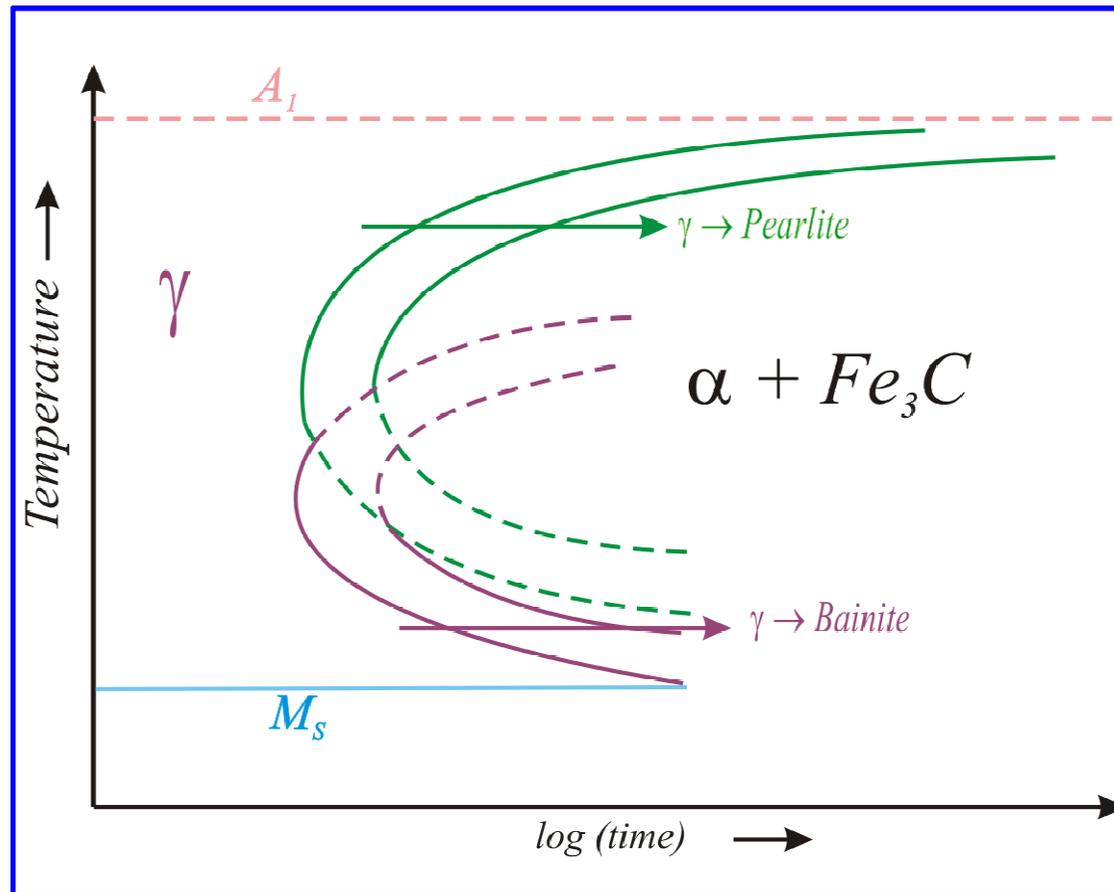
✓ To produce Martensite we should quench at a rate such as to avoid the nose of the start 'C' curve. Called the critical cooling rate.

✓ 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

Isothermal Transformation diagram for eutectoid steel



In principle two curves exist for Pearlitic and Bainitic transformations
→ they are usually not resolved in plain C steel
(In alloy steels they can be distinct)

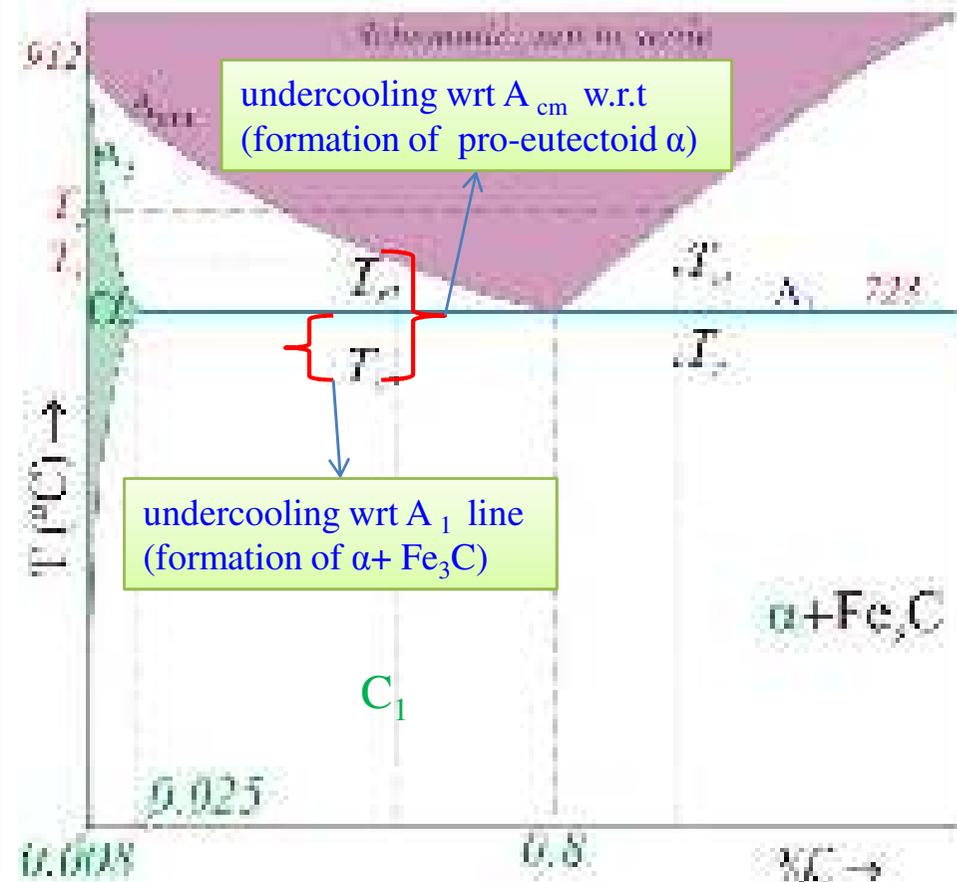
TTT diagram for Hypo eutectoid steel

- ❑ 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*).

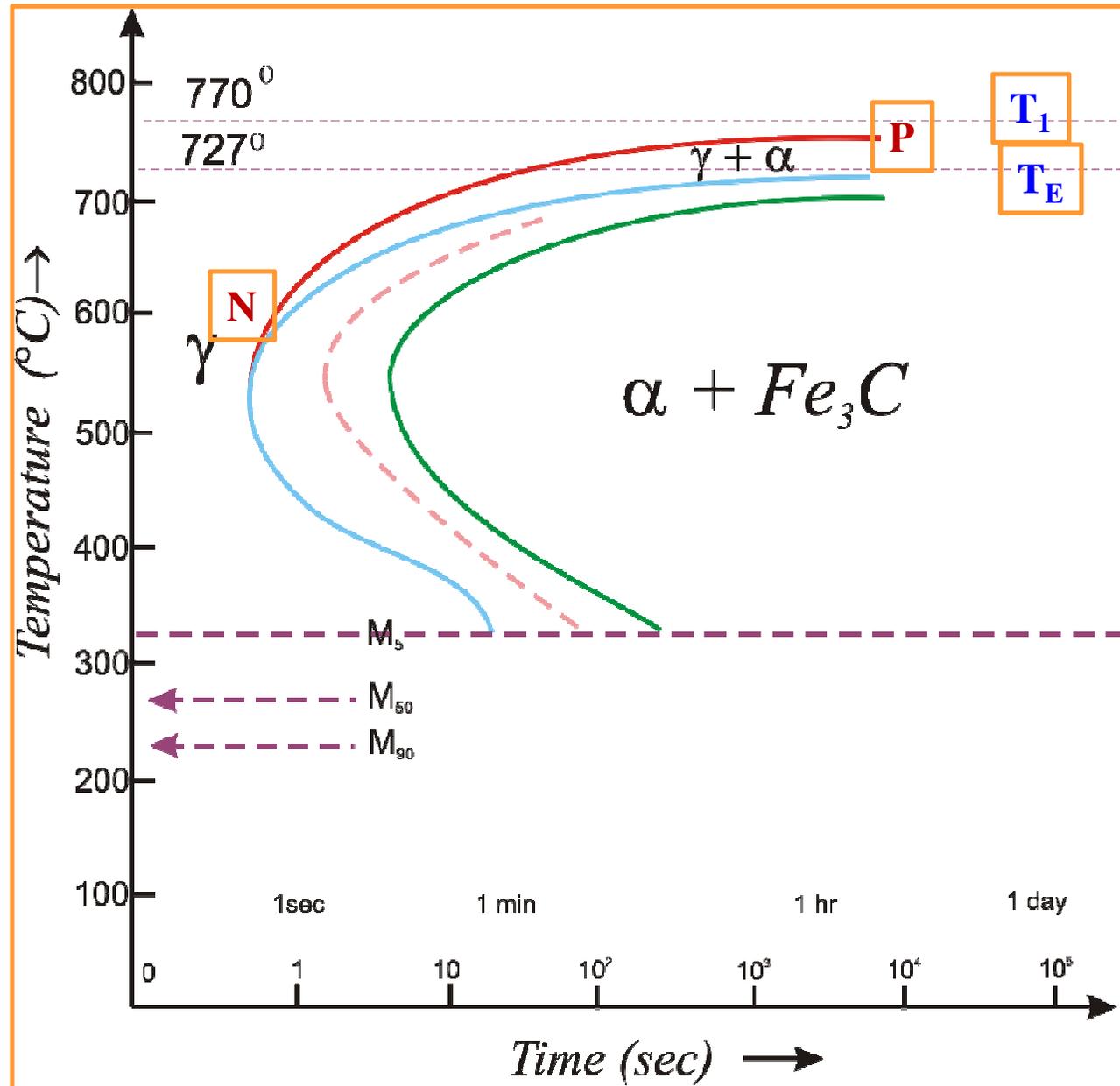
❑ The part of the curve below T_E is a bit of a 'mystery' (*since we are instantaneously cooling to below T_E , we should get a mix of $\alpha + Fe_3C$ → what is the meaning of a 'pro'-eutectoid phase in a TTT diagram? (remember 'pro-' implies 'pre-')*)

❑ Suppose we quench instantaneously an hypo-eutectoid composition C_1 to T_x we should expect the formation of $\alpha + Fe_3C$ (and not pro-eutectoid α first).

❑ The reason we see the formation of pro-eutectoid α first is that the undercooling w.r.t to A_{cm} is more than the undercooling w.r.t to A_1 . Hence, there is a higher propensity for the formation of pro-eutectoid α .

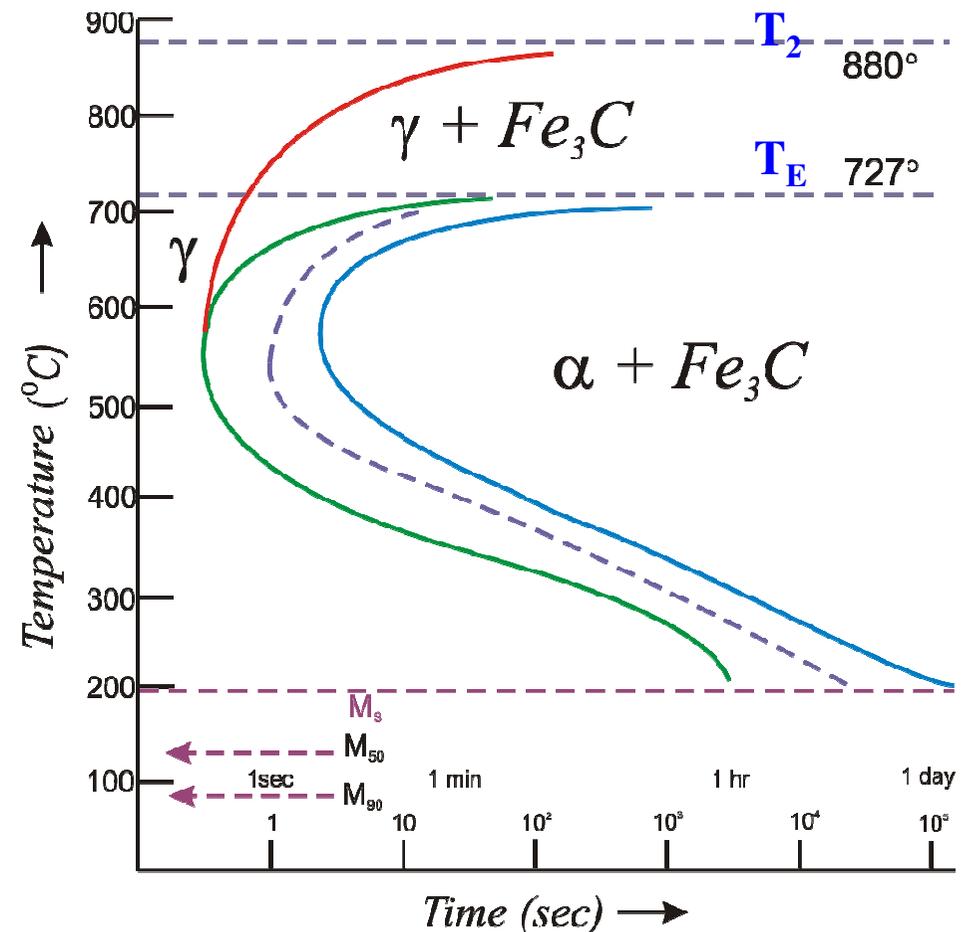
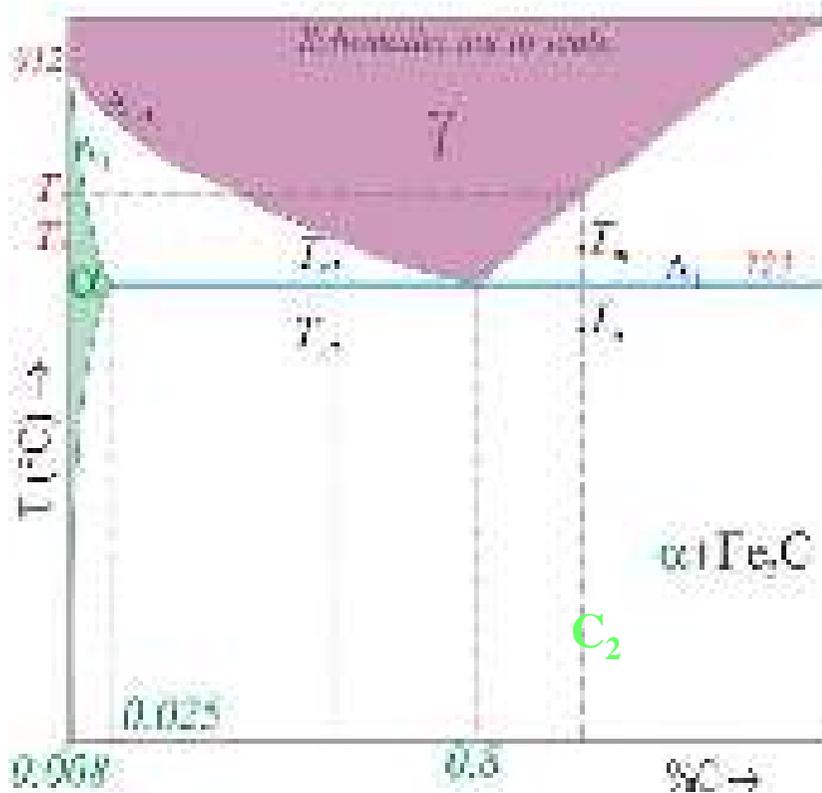


TTT diagram for Hypo eutectoid steel



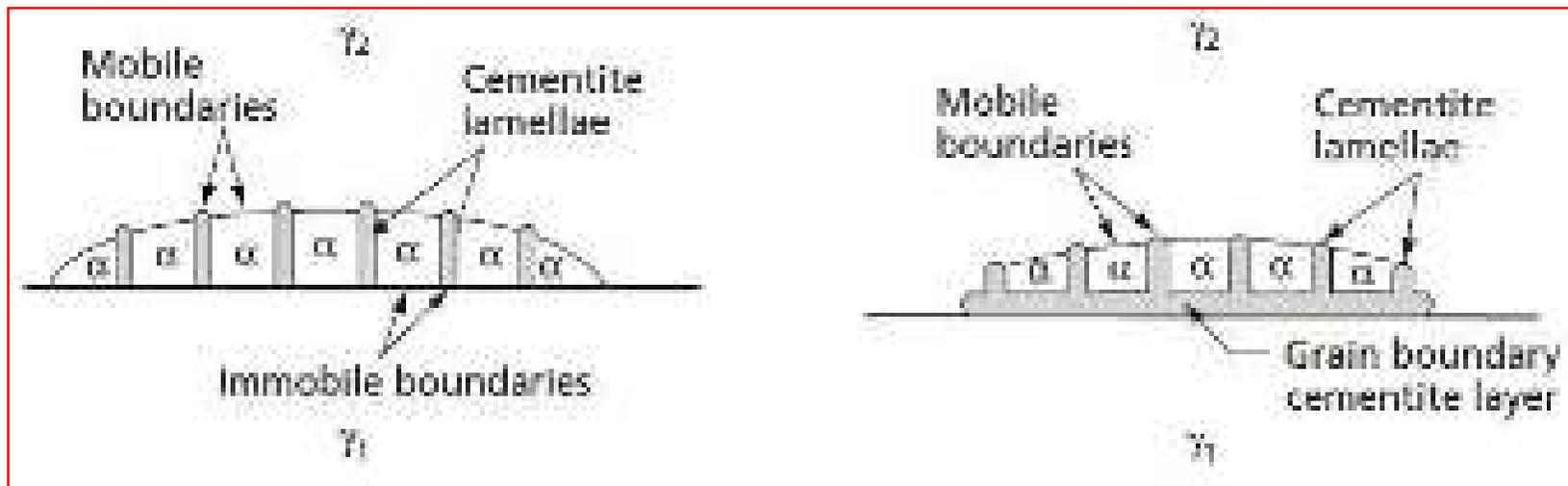
TTT diagram for Hyper eutectoid steel

- 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 $\gamma + Fe_3C$.

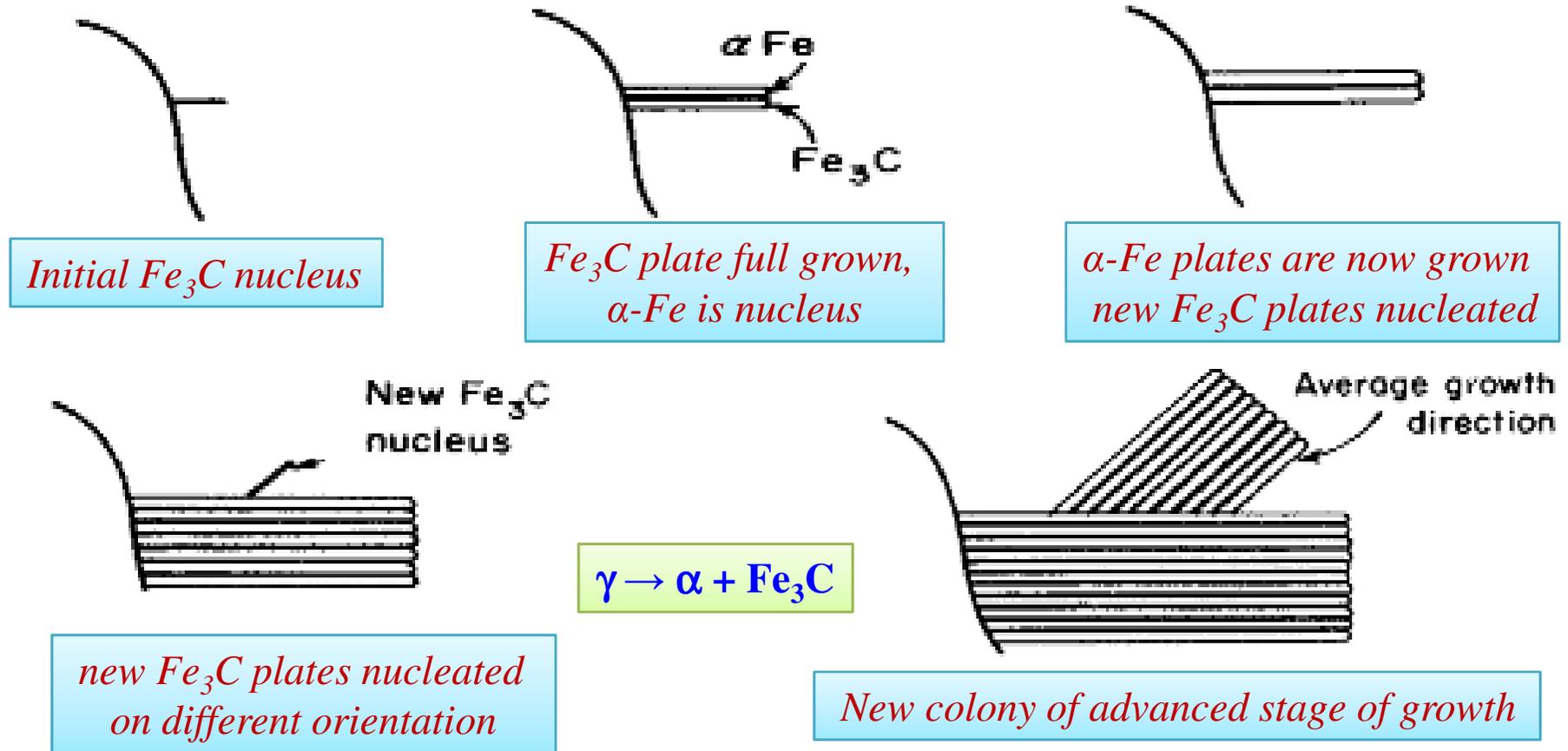


Transformation to Pearlite

- ❑ The transformation product above the nose region is pearlite. The pearlite microstructure is the characteristic lamellar structure of alternate layers of ferrite and cementite.
- ❑ As the transformation temperature decreases, the characteristic lamellar structure is maintained, but the spacing between the ferrite and carbide layers becomes increasingly smaller until the separate layers cannot be resolved with the light microscope.
- ❑ As the temperature of transformation and the fineness of the pearlite decreases, it is apparent that the hardness will increase.

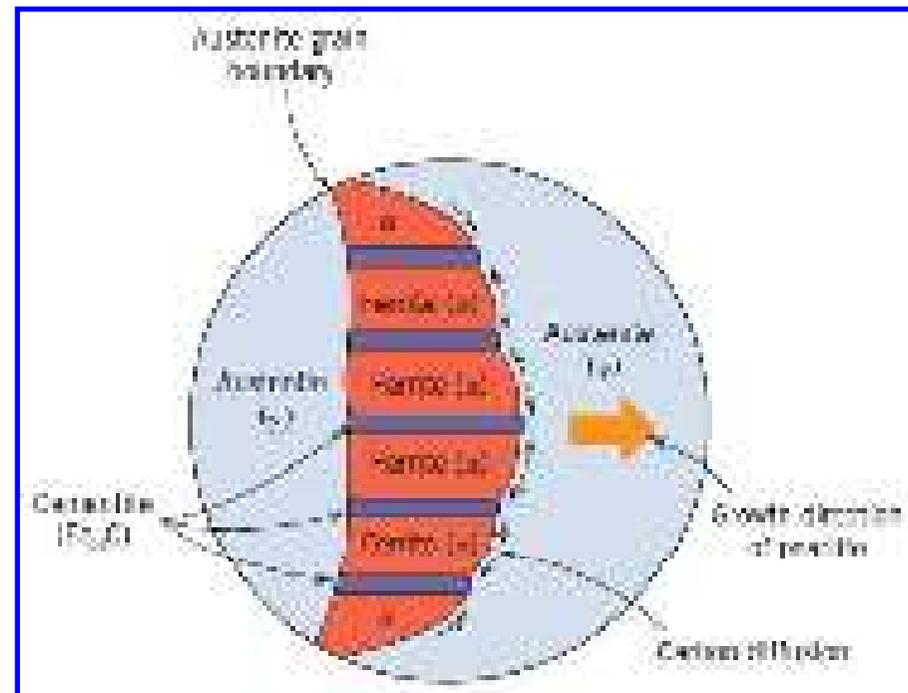
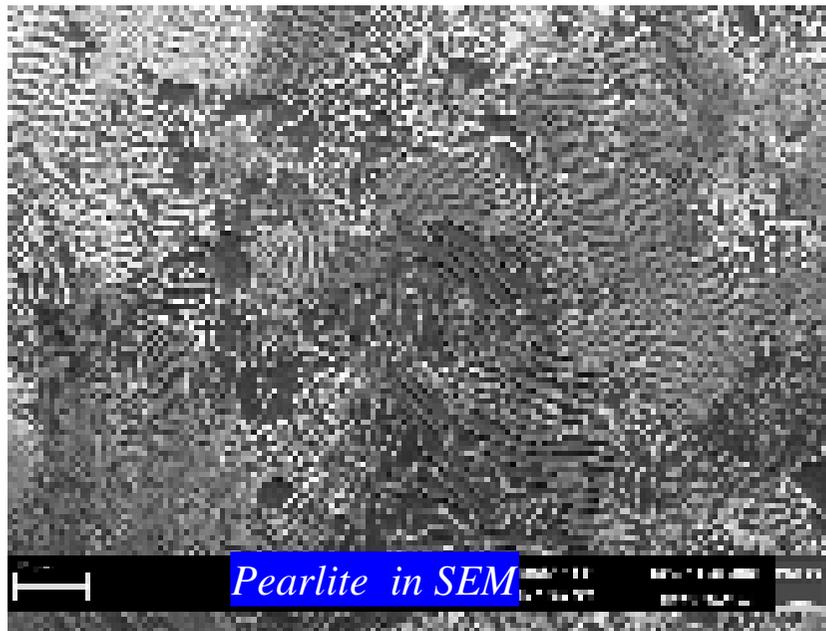


Transformation to Pearlite

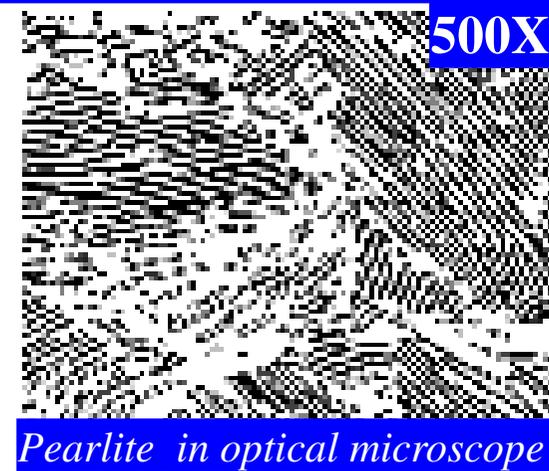
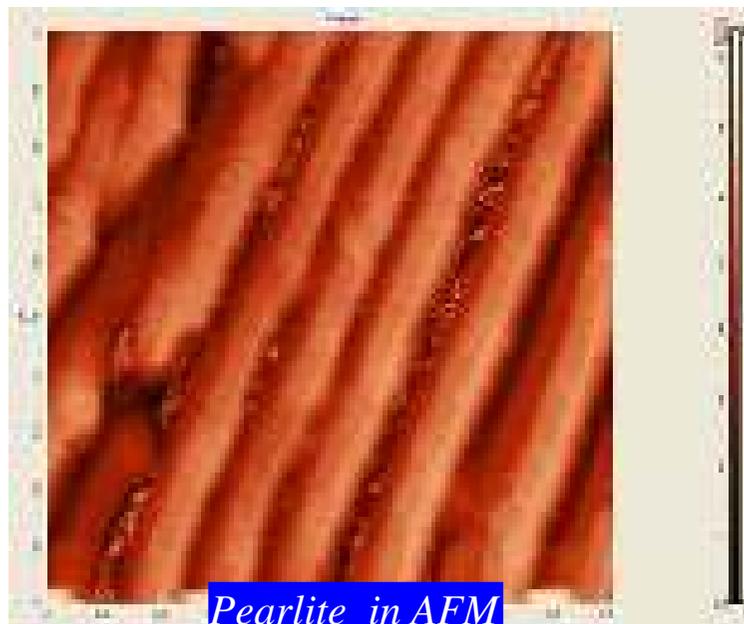


- Nucleation and growth
- Heterogeneous nucleation at grain boundaries
- Interlamellar spacing is a function of the temperature of transformation
- Lower temperature \rightarrow finer spacing \rightarrow higher hardness

Pearlitic structure

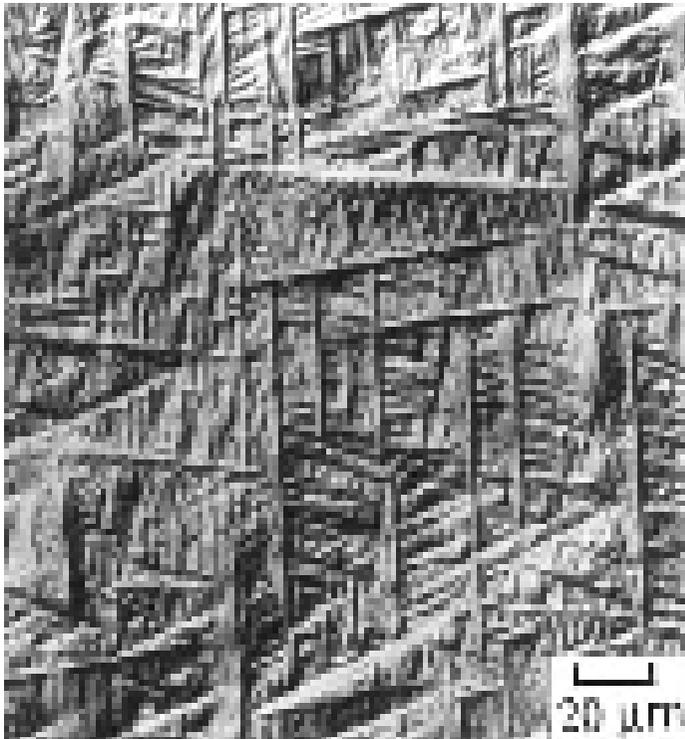


Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows



Transformation to Bainite

- ❑ In between the nose region of approximately 510°C and the M_s temperature, a new, dark-etching aggregate of ferrite and cementite appears. This structure, named after E.C.Bain, is called bainite.
- ❑ At upper temperatures of the transformation range, it resembles pearlite and is known as upper or feathery bainite. At low temperatures it appears as a black needlelike structure resembling martensite and is known as lower or acicular bainite.



Upper or Feathery bainite



Lower or Acicular bainite

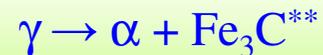
Transformation to Bainite



Bainite formed at 348°C

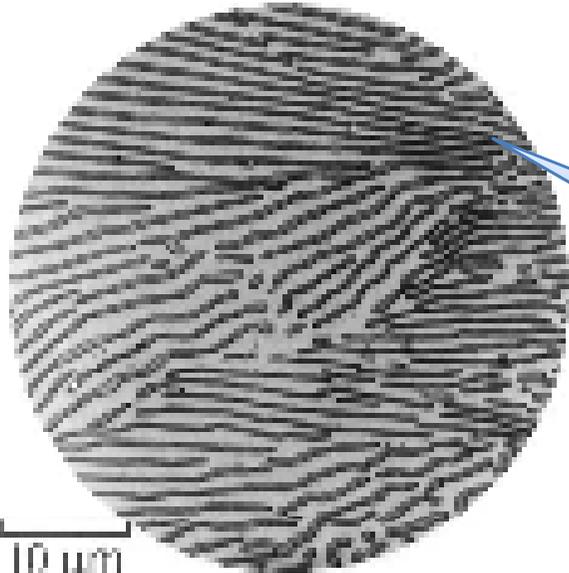


Bainite formed at 278°C



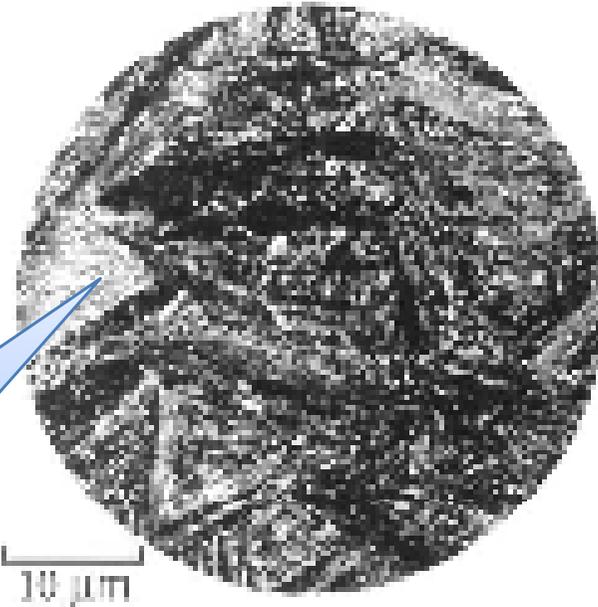
- ❑ Pearlite is nucleated by a carbide crystal, bainite is nucleated by a ferrite crystal, and this results in a different growth pattern.
- ❑ Acicular, accompanied by surface distortions
- ❑ ** Lower temperature → carbide could be ϵ carbide
- ❑ Bainite plates have irrational habit planes
- ❑ Ferrite in Bainite plates possess different orientation relationship relative to the parent Austenite than does the Ferrite in Pearlite

Microstructures in a eutectoid steel

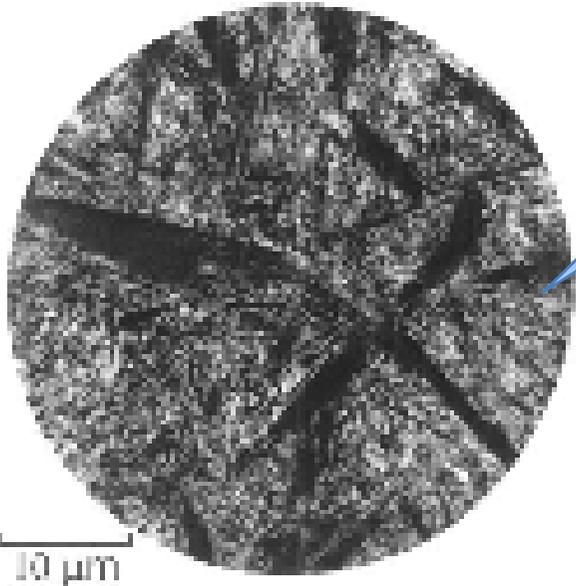


Pearlite formed at 720°C

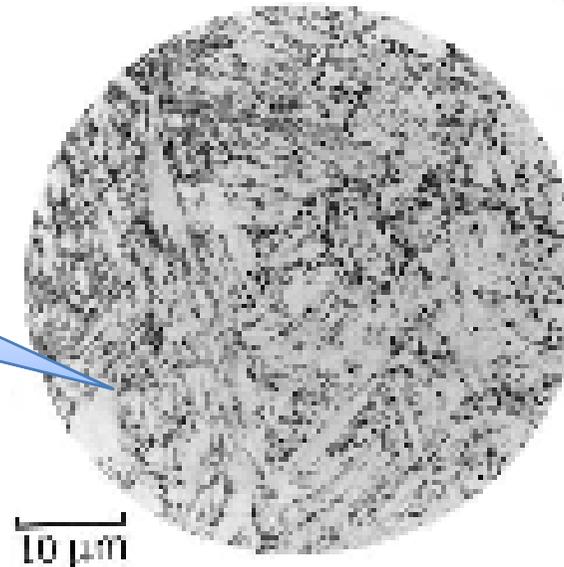
Bainite obtained by isothermal transformation at 290°C



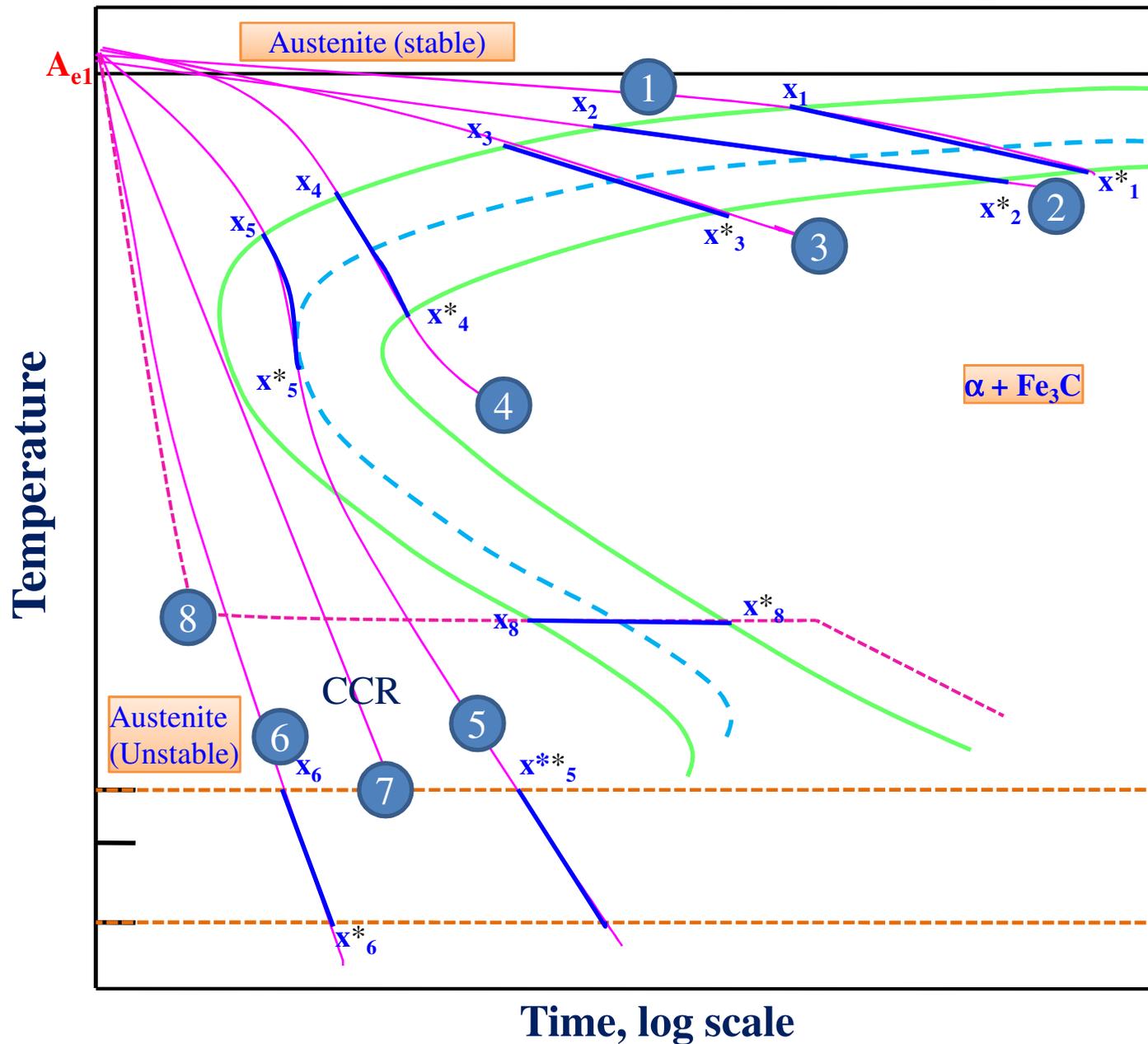
Bainite obtained by isothermal transformation at 180°C



Martensite



Cooling curves and the I-T diagram



Cooling curves and the I-T diagram

Curve 1

Cooling curve 1 shows a very slow cooling rate typical of conventional annealing. Transformation will start at x_1 , ends at x^*_1 , and there is a slight temperature difference in temperature between the beginning and end of transformation, there will be a slight difference in the fineness of pearlite formed at the beginning and at the end.

Curve 2

Cooling curve 2 shows 'isothermal' cooling and was developed directly from the IT diagram. The process is carried out by cooling the material rapidly from above the critical range to a predetermined temperature in the upper portion of the I-T diagram and holding for the time indicated to produce complete transformation. In contrast to conventional annealing, this treatment produces a more uniform microstructure and hardness.

Curve 3

Cooling curve 3 is a faster cooling rate than annealing and may be considered typical of normalizing. The diagram indicates that transformation will start at x_3 , with the formation of coarse pearlite, and ends at x^*_3 , with the formation of medium pearlite. Here, we are clearly observing the temperature difference between $x_3 - x^*_3$ and $x_1 - x^*_1$, so that microstructure will show a greater variation in fineness of pearlite.

Cooling curves and the I-T diagram

Curve 4

Cooling curve 4, typical of a slow oil quench, is similar to the one just described, and the microstructure will be a mixture of medium and fine pearlite.

Curve 5

Cooling curve 5, typical of an intermediate cooling rate, will start to transform at x_5 to fine pearlite in a relative short time. After some temperature, the cooling curve is going in a direction of decreasing percent transformed. Since pearlite cannot form austenite on cooling, the transformation must stop at x^*_5 . The microstructure at this point will consist, fine pearlite surrounding with austenitic grains. It will remain in this condition until the M_s line is crossed x^{**}_5 . The remaining austenite now transforms to martensite. The final microstructure consists, martensite and fine nodular pearlite largely concentrated along the original austenite grain boundaries.

Curve 6

Cooling curve 6, typical of drastic quench, is rapid enough to avoid transformation in the nose region. It remains austenitic until the M_s line is reached at x_6 . Transformation to martensite will take place between the M_s and M_F lines. The final microstructure will be entirely martensite of high hardness.

Cooling curves and the I-T diagram

Curve 7

Cooling curve 7, which is tangent to the nose, would be the approximate critical cooling rate (CCR) for the steel. Any cooling rate slower than the one indicated will cut the curve above the nose and form some softer transformation product. Any cooling rate faster than the one illustrated will form only martensite. To obtain a fully Martensitic structure it is necessary to avoid transformation in the nose region.

Curve 8

It is possible to form 100 % pearlite or 100% martensite by continuous cooling, but it is not possible to form 100% bainite. A complete bainitic structure may be formed only by cooling rapidly enough to miss the nose of the curve and then holding in the temperature range at which bainite is formed until transformation is complete. This is illustrated by cooling curve 8. It is apparent that continuously cooled steel samples will contain only small amounts of bainite, and this is probably the reason why this structure was not recognized until the isothermal study.

Factors affecting on TTT diagram

- ❖ Composition of steel
 - carbon wt%,
 - alloying element wt%
- ❖ Grain size of austenite
- ❖ Heterogeneity of austenite

Composition

- ❑ With some limitations, an increase in carbon or alloy content or in grain size of the austenite always retards transformation (*moves curves to the right*), at least at temperatures at or above the nose region. This in turn slows up the critical cooling rate, making it easier to form martensite.
- ❑ This retardation is also reflected in the greater hardenability, or depth of penetration of hardness, of steel with higher alloy content or larger austenitic grain size.

Continuous Cooling Transformation diagrams

- ❑ The TTT diagrams are also called Isothermal Transformation Diagrams, because the transformation times are representative of isothermal hold treatment (following a instantaneous quench).
- ❑ In practical situations we follow heat treatments (T-t procedures/cycles) in which (typically) there are steps involving cooling of the sample. The cooling rate may or may not be constant. The rate of cooling may be slow (as in a furnace which has been switch off) or rapid (like quenching in water).
- ❑ Hence, in terms of practical utility TTT curves have a limitation and we need to draw separate diagrams called Continuous Cooling Transformation diagrams (CCT), wherein transformation times (also: products & microstructure) are noted using constant rate cooling treatments. A diagram drawn for a given cooling rate (dT/dt) is typically used for a range of cooling rates (thus avoiding the need for a separate diagram for every cooling rate).
- ❑ However, often TTT diagrams are also used for constant cooling rate experiments-keeping in view the assumptions & approximations involved.
- ❑ The CCT diagram for eutectoid steel is considered next.
- ❑ *Important difference between the CCT & TTT transformations is that in the CCT case Bainite cannot form.*

Determination of CCT diagram for eutectoid steel

- ❑ CCT diagrams are determined by measuring some physical properties during continuous cooling. Normally these are specific volume and magnetic permeability. However, the majority of the work has been done through specific volume change by dilatometric method. This method is supplemented by metallography and hardness measurement.
- ❑ In dilatometry the test sample is austenitised in a specially designed furnace and then controlled cooled. Sample dilation is measured by dial gauge/sensor. Slowest cooling is controlled by furnace cooling but higher cooling rate can be controlled by gas quenching



Sample and fixtures
for dilatometric measurements



Dilatometer equipment

Determination of CCT diagram for eutectoid steel

- ❑ Cooling data are plotted as temperature versus time (Fig. a). Dilation is recorded against temperature (Fig. b). Any slope change indicates phase transformation. Fraction of transformation roughly can be calculated based on the dilation data as explained below.

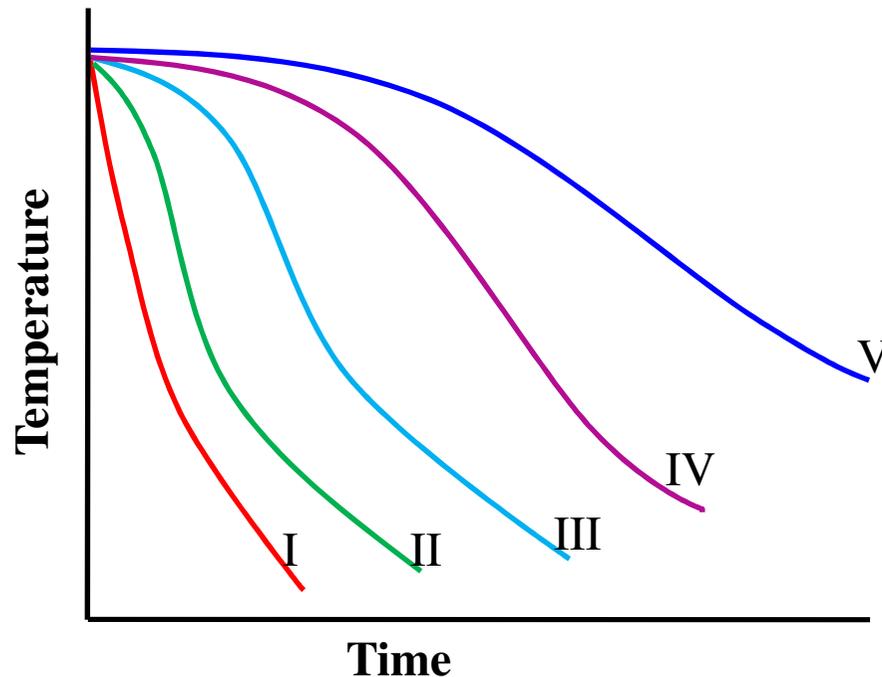


Fig. a : Schematic cooling curves

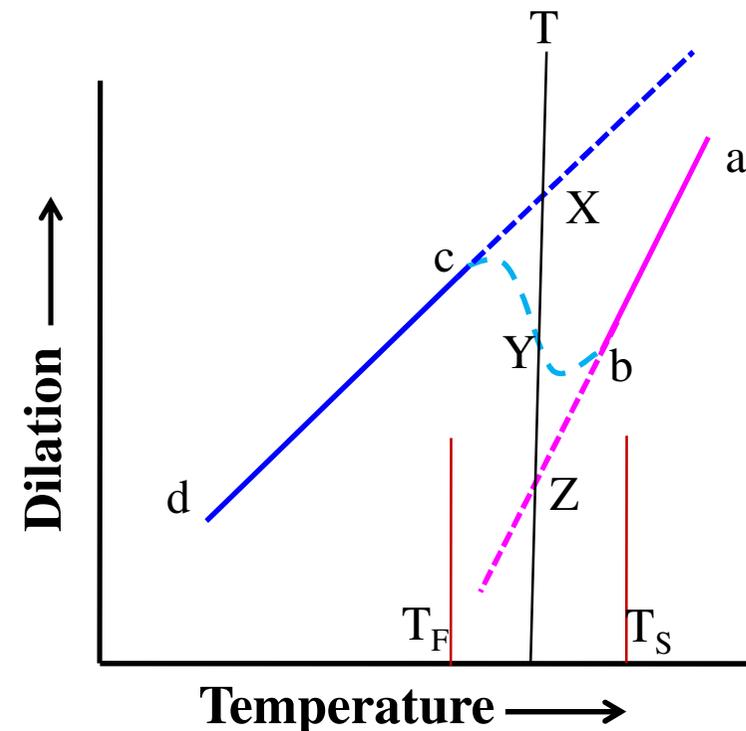


Fig. b : Dilation-temperature plot for a cooling curve

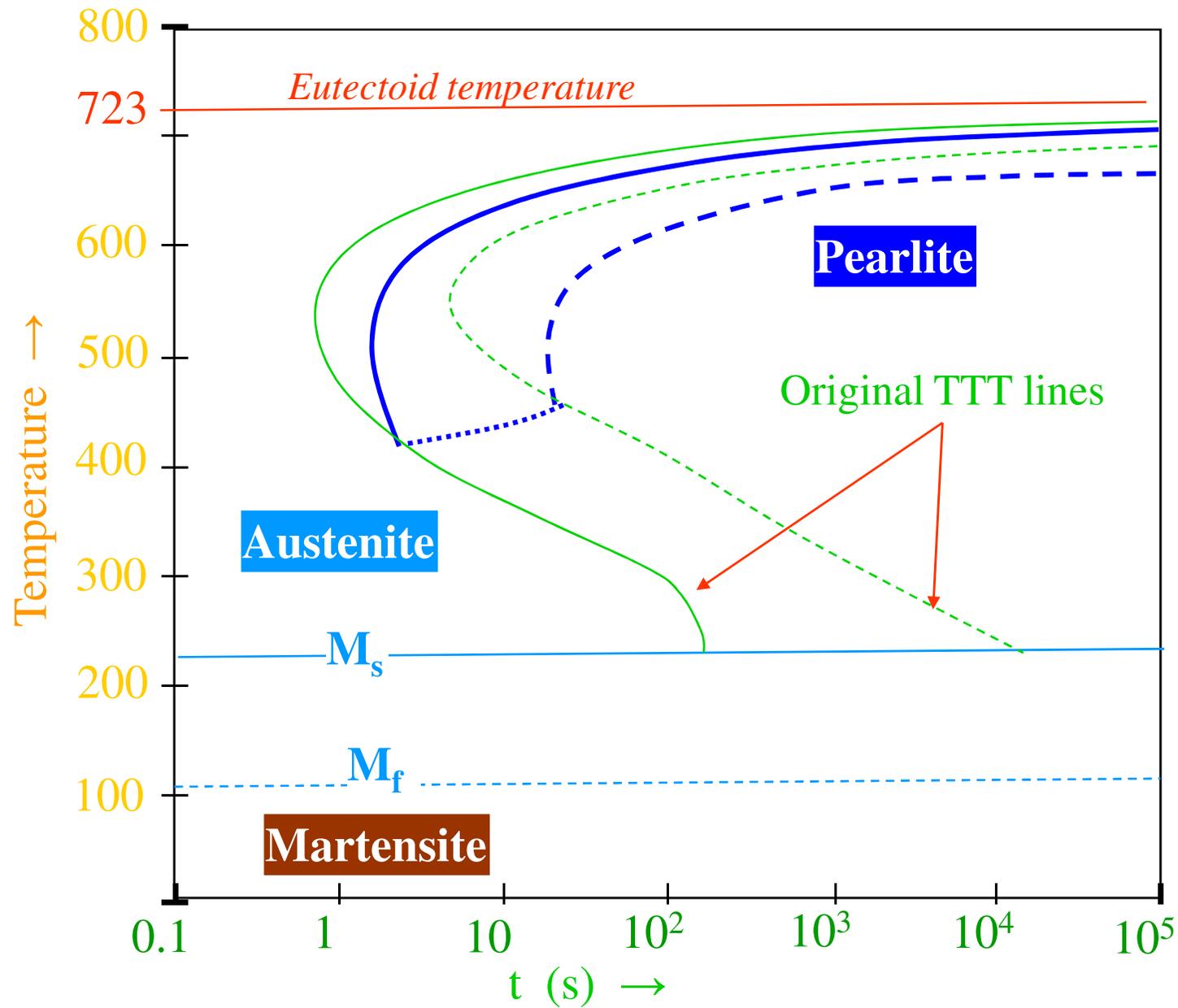
Determination of CCT diagram for eutectoid steel

- ❑ In **Fig. a** curves I to V indicate cooling curves at higher cooling rate to lower cooling rate respectively. **Fig. b** gives the dilation at different temperatures for a given cooling rate/schedule.
- ❑ In general slope of dilation curve remains unchanged while amount of phase or the relative amount of phases in a phase mixture does not change during cooling (or heating) however sample shrink or expand i.e. dilation takes place purely due to thermal specific volume change because of change in temperature.
- ❑ Therefore in **Fig. b** dilation from a to b is due to specific volume change of high temperature phase austenite. But at T_s slope of the curve changes. Therefore transformation starts at T_s . Again slope of the curve from c to d is constant but is different from the slope of the curve from a to b. This indicates there is no phase transformation between the temperature from c to d but the phase/phase mixture is different from the phase at a to b.
- ❑ Slope of the dilation curve from b to c is variable with temperature. This indicates the change in relative amount of phase due to cooling. The expansion is due to the formation of low density phase(s). Some part of dilation is compensated by purely thermal change due to cooling. Therefore dilation curve takes complex shape. i.e first slope reduces and reaches to a minimum value and then increases to the characteristic value of the phase mixture at c.

Determination of CCT diagram for eutectoid steel

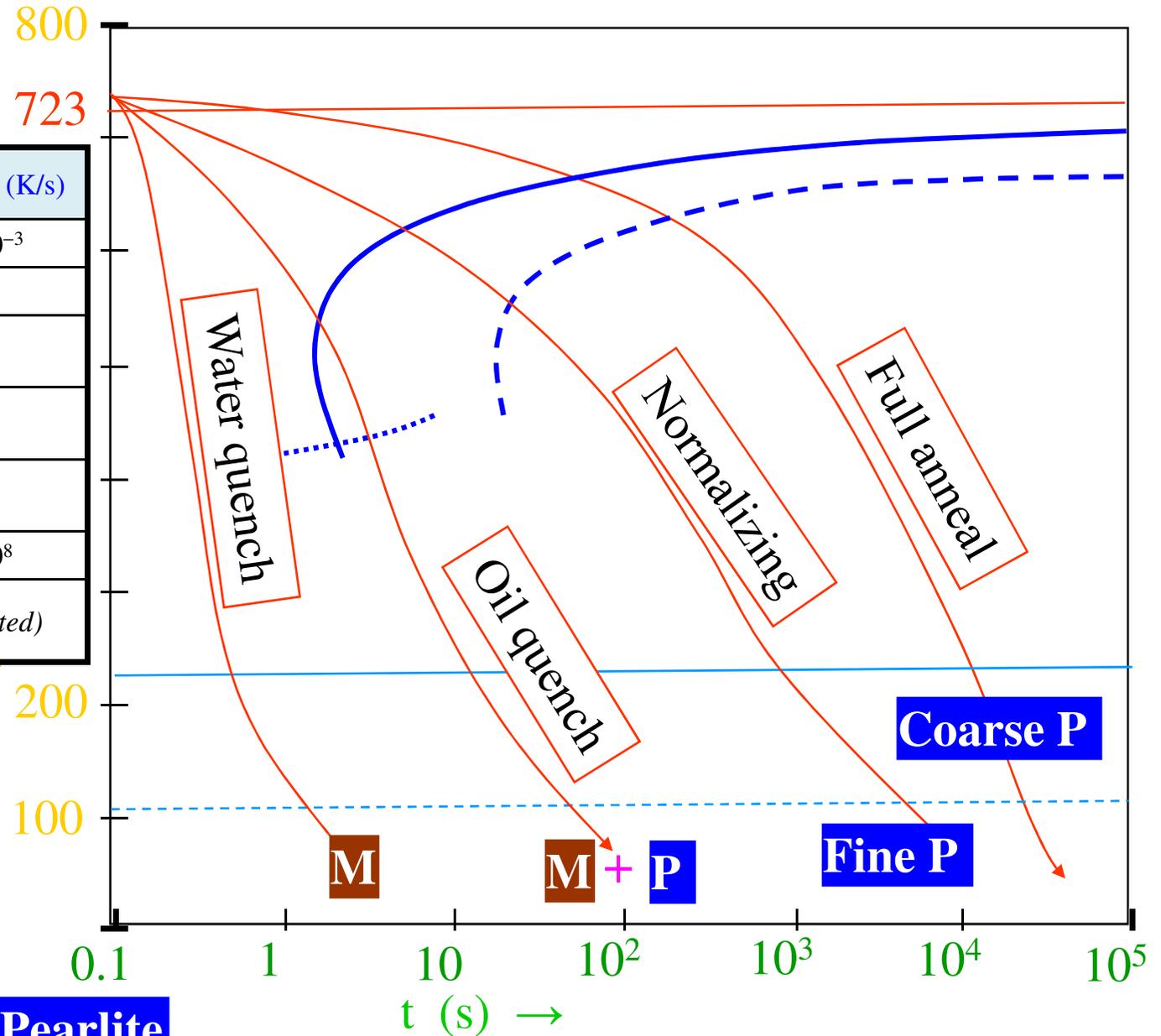
- ❑ Therefore phase transformation start at b i.e. at temperature T_S and transformation ends or finishes at c or temperature T_F . The nature of transformation has to be determined by metallography. When austenite fully transforms to a single product then amount of transformation is directly proportional to the relative change in length. For a mixture of products the percentage of austenite transformed may not be strictly proportional to change in length, however, it is reasonable and generally is being used.
- ❑ Cumulative percentage of transformation at in between temperature T is equal to $YZ/XZ*100$ where X, Y and Z are intersection point of temperature T line to extended constant slope curve of austenite (ba), transformation curve (bc) and extended constant slope curve of low temperature phase (cd) respectively.
- ❑ So at each cooling rate transformation start and finish temperature and transformation temperature for specific amount (10 %, 20%, 30% etc.) can also be determined. For every type of transformation, locus of start points, isopercentage points and finish points give the transformation start line, isopercentage lines and finish line respectively and that result CCT diagram. Normally at the end of each cooling curve hardness value of resultant product at room temperature and type of phases obtained are shown.

CCT curves for eutectoid steel



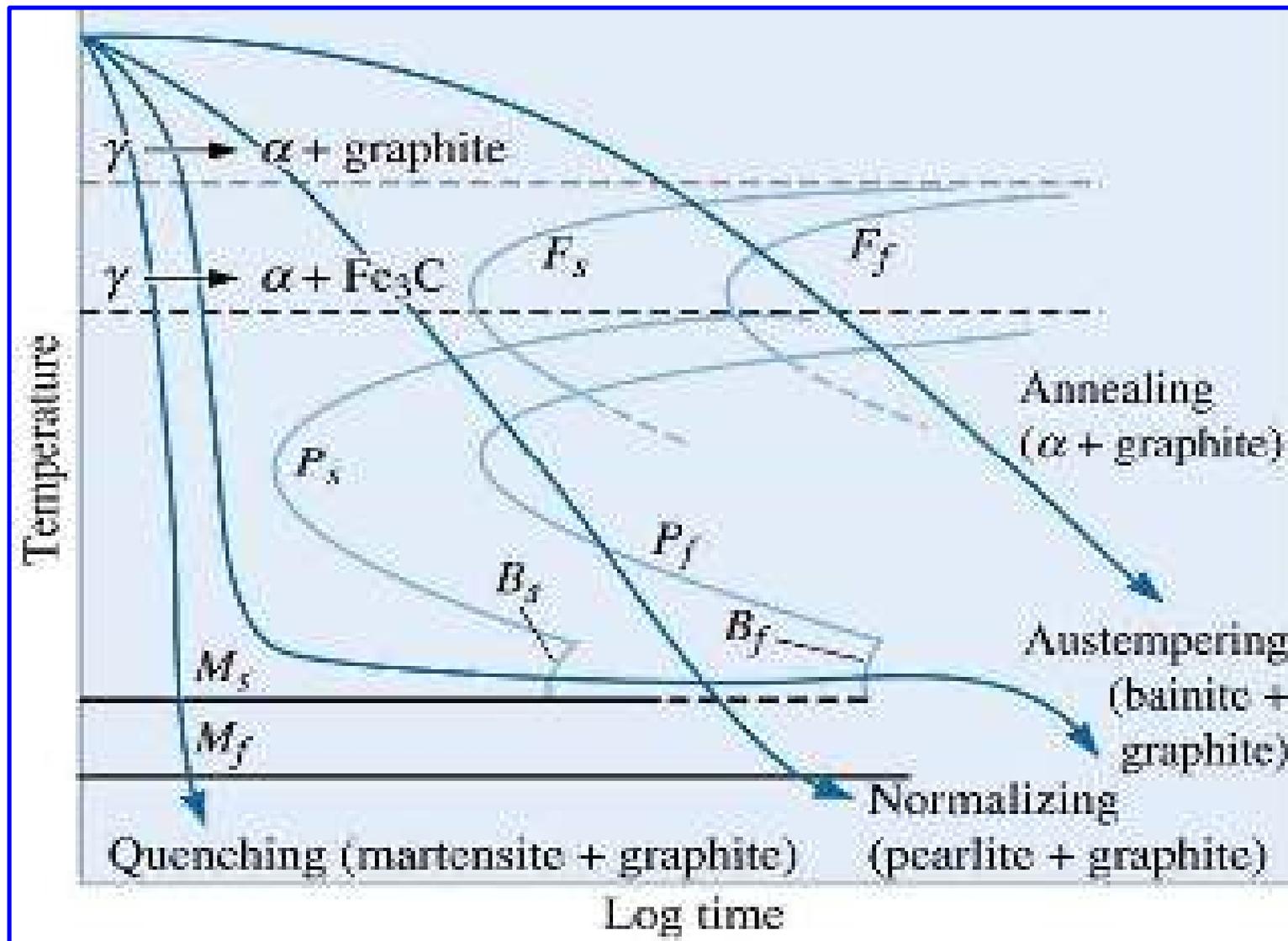
Different cooling treatments for eutectoid steel

Process	Cooling rate (K/s)
Annealing	$10^{-5} - 10^{-3}$
Air Cooling	1 - 10
Oil Quenching	~100
Water Quenching	~500
Splat Quenching	10^5
Melt-Spinning	$10^6 - 10^8$
Evaporation, sputtering	10^9 (expected)



M = Martensite **P = Pearlite**

Transformation diagram for cast iron



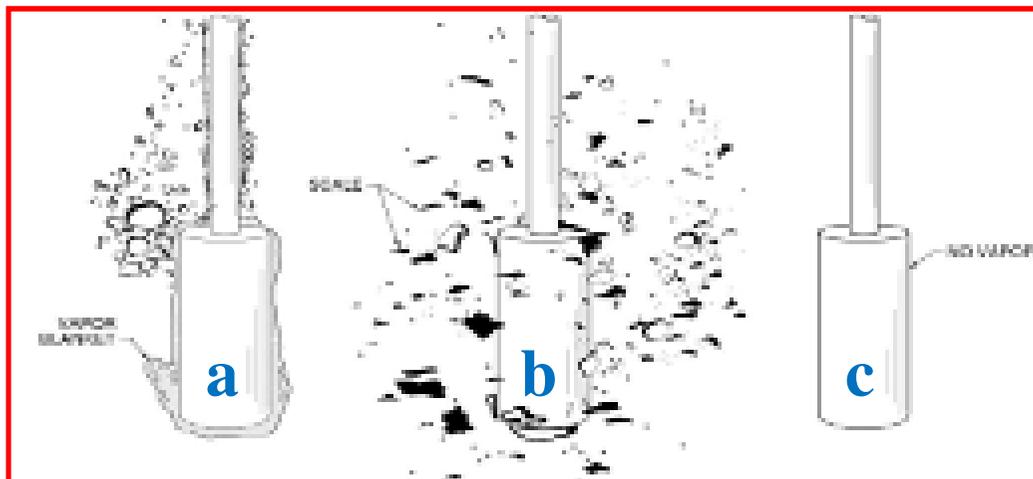
Homogeneity of austenite

- ❑ This refers to the uniformity in carbon content of the austenite grains. If a hypo-eutectoid steel is heated for hardening, when the A_1 line is crossed, the austenite grains formed from pearlite will contain 0.8 percent carbon.
- ❑ With continued heating, the austenite grains formed from pro-eutectoid ferrite will contain very little carbon, so that when the A_3 line is crossed, the austenite grains will not be uniform in carbon content.
- ❑ Upon quenching, the austenite grains leaner in carbon, having a fast critical cooling rate, tend to transform to nonmartensitic structures, while those richer in carbon, having a slower critical cooling rate, tend to form martensite. This results a non uniform microstructure with variable hardness . This condition may be avoided by very slow heating, so that uniformity is established by carbon diffusion during heating. *It is recommended that the material be held at the austenitizing temperature 1 hour for each inch of thickness or diameter*
- ❑ The recommended austenitizing temperature for hypo-eutectoid steels is about 30°C above the A_3 line. This same as the recommended annealing temperature.
- ❑ For hyper-eutectoid steels the recommended austenitizing temperature is usually between the A_{cm} and $A_{3,1}$ lines.
- ❑ The A_{cm} line rises so steeply that an excessively high temperature may be required to dissolve all the proeutectoid cementite in the austenite. This tends to develop undesirable coarse austenitic grain size, with danger of cracking on cooling.

Quenching

Mechanism

- ❑ The properties of materials alter by different heat treating processes by varying the cooling rate followed by quenching. If the actual cooling rate (ACR) exceeds the critical cooling rate, only martensite will result. If the actual cooling rate is less than the critical cooling rate (CCR), the part will not completely harden. So that, difference in cooling rates leads to variation in properties. *At this point, it is necessary to understand the mechanism of heat removal during quenching.*
- ❑ A cooling curve shows the variation of temperature with time during quenching. A cooling rate, however, shows the rate of change of temperature with time.
- ❑ The cooling rate at any temperature may be obtained from the cooling curve by drawing a tangent to the curve at that temperature and determining the slope of the tangent. It is apparent that the cooling rate is constantly changing with time.



- a- Vapor-blanket cooling stage
- b- Vapor-transport cooling stage
- c- Liquid cooling stage

Quenching

Vapor-blanket cooling stage

- ❑ In this stage, quenching medium is vaporized at the surface of the metal and forms a thin stable layer.
- ❑ Cooling is by conduction and radiation.
- ❑ Cooling rate is relatively slow



Vapor-transport cooling stage

- ❑ This stage starts when the metal has cooled to a temperature at which the vapor film is no longer stable. Wetting of the metal surface by the quenching medium and violent boiling occur. Heat is removed from the metal very rapidly as the latent heat of vaporization. This is the fastest stage of cooling.

Liquid cooling stage

- ❑ This stage starts when the surface temperature of the metal reaches the boiling point of the quenching liquid.
- ❑ Vapor no longer forms, so cooling is by conduction and convection through the liquid. The rate of cooling is slowest in this stage.

Factors affecting on Quenching

Many factors determine the actual cooling rate. The most important are the type of quenching medium, the temperature of the quenching medium, the surface condition of the part, and the size and mass of the part.

Quenching Medium

- Brine solution (Water solution of 10% sodium chloride)
- Tap water
- Fused or liquid salts
- Soluble oil and water solutions
- Oil
- Air

Temperature of Quenching Medium

- Generally, as the temperature of the medium rises, the cooling rate decreases. This is due to the increase in persistence of the vapor-blanket stage. This is particular true of water and brine.
- In another case, an increase in cooling rate with a rise in temperature of the medium. In the case of oil, as the temperature of the oil rises there is a tendency for the cooling rate to decrease due to the persistence of the vapor film. However, as the temperature of the oil rises it also become more fluid, which increase the rate of heat conduction through the liquid.

Factors affecting on Quenching

Severity of quench values of some typical quenching conditions

Process	Variable	H Value
Air	No agitation	0.02
Oil quench	No agitation	0.2
"	Slight agitation	0.35
"	Good agitation	0.5
"	Vigorous agitation	0.7
Water quench	No agitation	1.0
"	Vigorous agitation	1.5
Brine quench (saturated Salt water)	No agitation	2.0
"	Vigorous agitation	5.0
Ideal quench		∞

If the increase in rate of heat conduction is greater than the decrease due to persistence of the vapor film, the net result will be an increase in the actual cooling rate. However if the reverse is true, then the result will be decrease in cooling rate.

Severity of Quench as indicated by the heat transfer equivalent H

$$H = \frac{f}{K} \quad [m^{-1}]$$

$f \rightarrow$ heat transfer factor

$K \rightarrow$ Thermal conductivity

Note that apart from the nature of the quenching medium, the vigorousness of the shake determines the severity of the quench. When a hot solid is put into a liquid medium, gas bubbles form on the surface of the solid (interface with medium). As gas has a poor conductivity the quenching rate is reduced. Providing agitation (shaking the solid in the liquid) helps in bringing the liquid medium in direct contact with the solid; thus improving the heat transfer (and the cooling rate). The H value/index compares the relative ability of various media (gases and liquids) to cool a hot solid. Ideal quench is a conceptual idea with a heat transfer factor of ∞ ($\Rightarrow H = \infty$)

Factors affecting on Quenching

Surface condition

- ❑ When the steel is exposed to an oxidizing atmosphere, because of the presence of water vapor or oxygen in the furnace a layer of iron oxide called *scale* is formed. Experiments have shown that a thin layer of scale has very little effect on the actual cooling rate, but that a thick layer of scale (0.005 inch in deep) retards the actual cooling rate.
- ❑ There is also the tendency for parts of the scale to peel off the surface when the piece is transferred from the furnace to the quench tank, thus giving rise to a variation in cooling rate at different points on the surface. *The presence of scale is need to be considered only if the actual cooling rate is very close to critical cooling rate.*
- ❑ To minimize the formation of scale, we have different methods depend upon part being heat treated, type of furnace used, availability of equipment and cost.
 - ✓ Copper plating
 - ✓ Protective atmosphere
 - ✓ Liquid salt pots
 - ✓ Cast iron chips

Factors affecting on Quenching

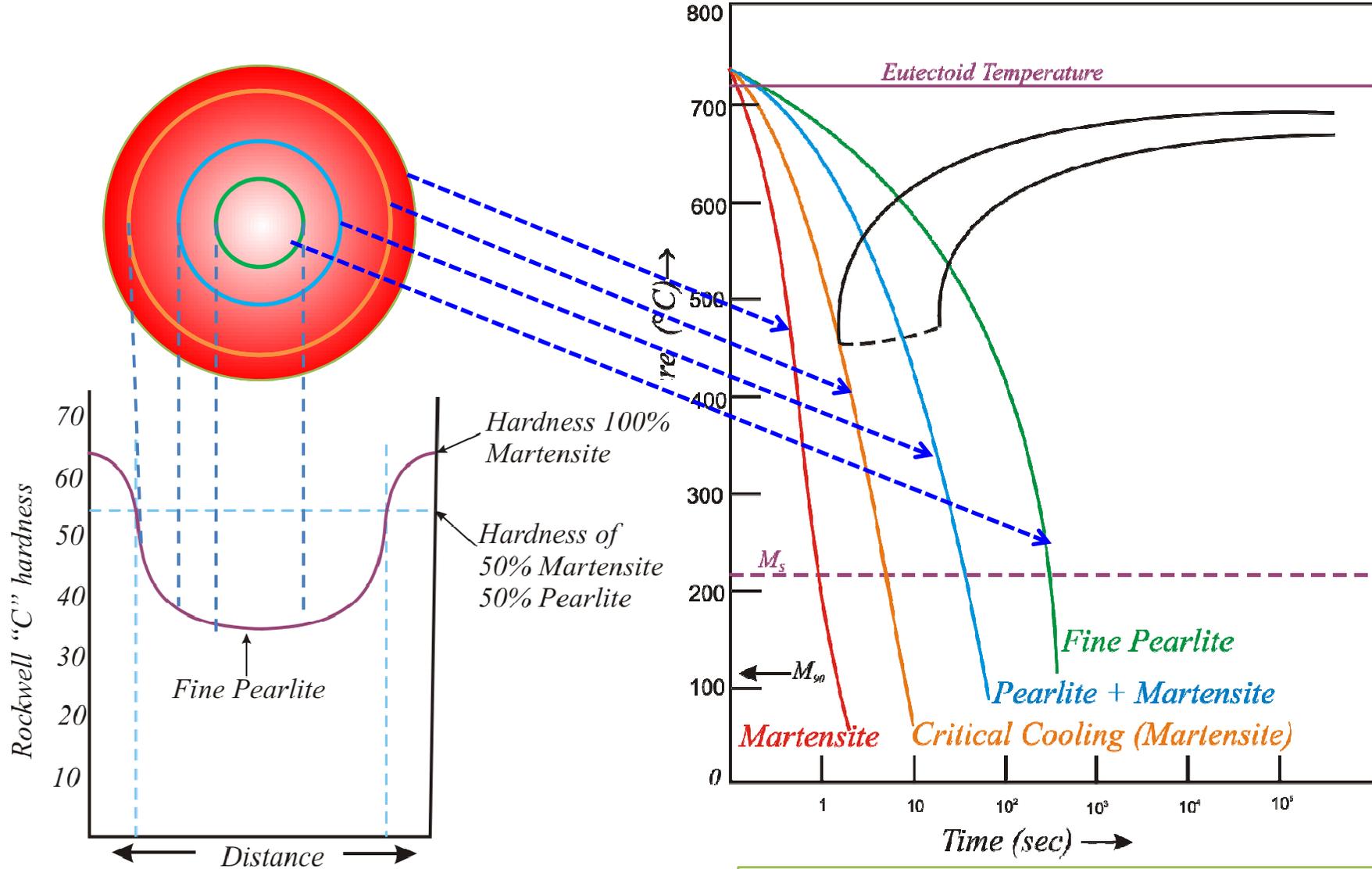
Size and mass

- ❑ The ratio of surface area to mass is an important factor in determining the actual cooling rate, because only the surface of a part which is in contact with the quenching medium.
- ❑ Thin plates and small diameter wires have a large ratio of surface area to mass and therefore rapid cooling rates.

$$\text{For Cylinder} \quad \frac{\text{Surface area}}{\text{Mass}} = \left(\frac{\pi DL}{(\pi/4)D^2 L \rho} \right)$$

- ❑ The calculation shows that the ratio is inversely proportional to diameter if the diameter is increased, the ratio of surface area to mass decreases, and the cooling rate decreases.
- ❑ The heat in the interior of the piece must be removed by conduction, through the body of the piece, eventually reaching the surface and the quenching medium. Therefore the cooling rate in the interior is less than that at the surface.
- ❑ If such variation in cooling rates exists across the radius of a bar during cooling, it is to be anticipated that variations in hardness would be evident when the bars are cut and hardness surveys made on the cross section. A considerable temperature difference between the surface and the center during quenching (*see in next slide*).
- ❑ This temperature difference will give rise to stresses during heat treatment called residual stresses, which may result in distortion and cracking of the piece.

Hardness profile in a cylinder from surface to interior

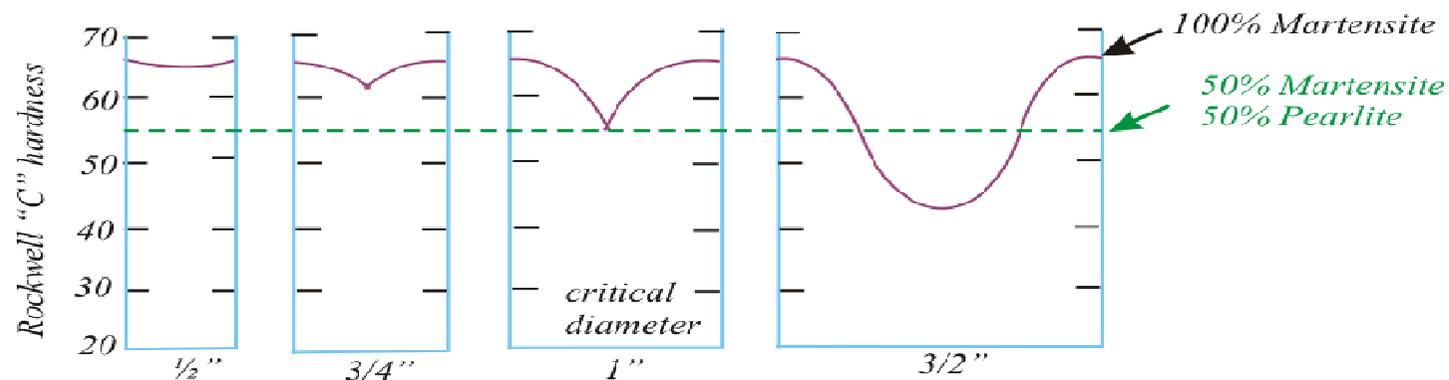


Typical hardness test survey made along a diameter of a quenched cylinder

Schematic showing variation in cooling rate from surface to interior leading to different microstructures

Hardenability

- ❑ From the earlier study, we seen that, hardness profile various from case to core. It leads to an important conclusion that, by varying the diameter of cylinder with same composition will give the different hardness profiles, i.e., depth of hardness is different from different size of samples. Generally this diagrams called as hardness-penetration diagrams or hardness-traverse diagrams.
- ❑ Hardenability is the ability of a steel to partially or completely transform from austenite to some fraction of martensite at a given depth below the surface, when cooled under a given condition.
- ❑ For example, a steel of a high hardenability can transform to a high fraction of martensite to depths of several millimeters, under relatively slow cooling, such as an oil quench, whereas a steel of low hardenability may only form a high fraction of martensite to a depth of less than a millimeter, even under rapid cooling such as a water quench. *Hardenability therefore describes the capacity of the steel to harden in depth under a given set of conditions.*

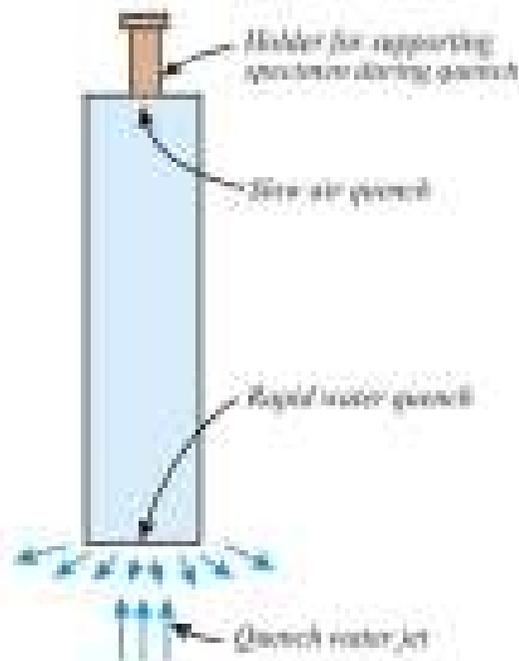


Hardenability

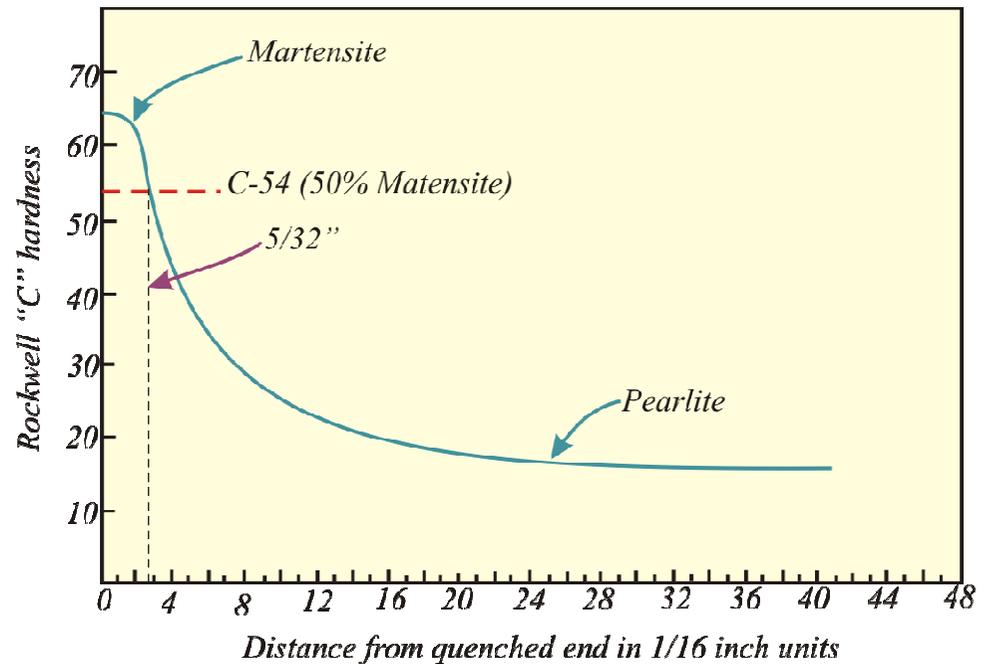
- ❑ Increase in the hardenability or depth of penetration of the hardness may be accomplished by either of two methods:
 1. With the actual cooling rates fixed, slow up the critical cooling rate (shift the I-T curve to the right) by adding alloying elements or coarsening the austenitic grain size.
 2. With the I-T curve fixed, increase the actual cooling rates by using a faster quenching medium or increasing circulation.
- ❑ *Since increasing cooling rates increase the danger of distortion or cracking, the addition of alloying elements is the more popular method of increasing hardenability.*
- ❑ Steels with high hardenability are needed for large high strength components, such as large extruder screws for injection moulding of polymers, pistons for rock breakers, aircraft undercarriages etc.
- ❑ Steels with low hardenability may be used for smaller components, such as chisels and gears etc.
- ❑ The most widely used method of determining hardenability is the end-quench hardenability test or the Jominy test, commonly called as Jominy End Quench test.

Jominy End Quench Test

- ❑ In conducting this test, a 1 inch round specimen 4 inch long is heated uniformly to the proper austenising temperature. It is then removed from the furnace and placed on a fixture where a jet of water impinges on the bottom face of the sample.
- ❑ After 10 min. on the fixture, the specimen is removed, and to cut along the longitudinal direction. And then Rockwell C scale hardness readings are taken at 1/16 inch, intervals from the quenched end. The results are expressed as a curve of hardness values Vs. distance from the quenched end. A typical hardenability curve shown below for eutectoid steel.



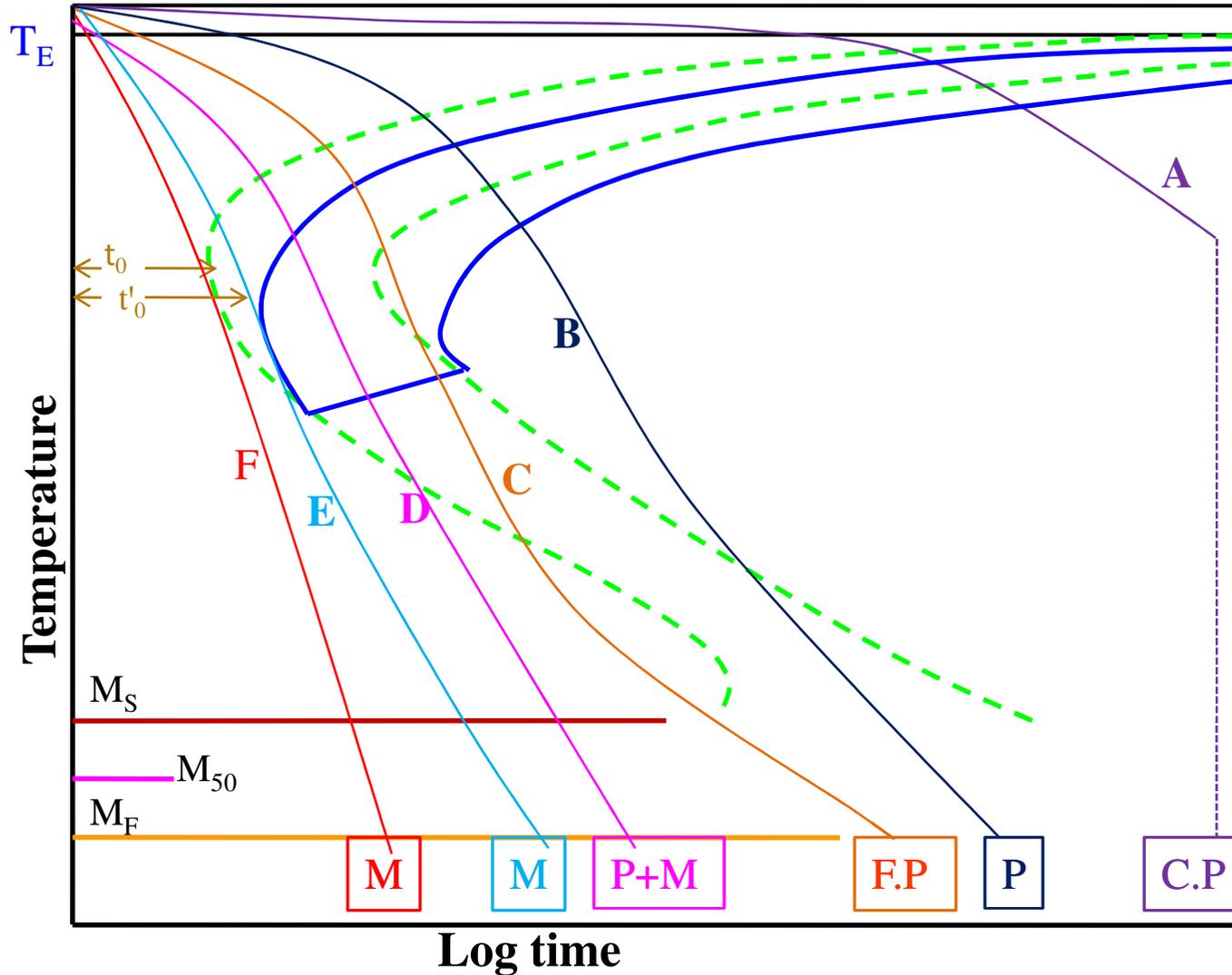
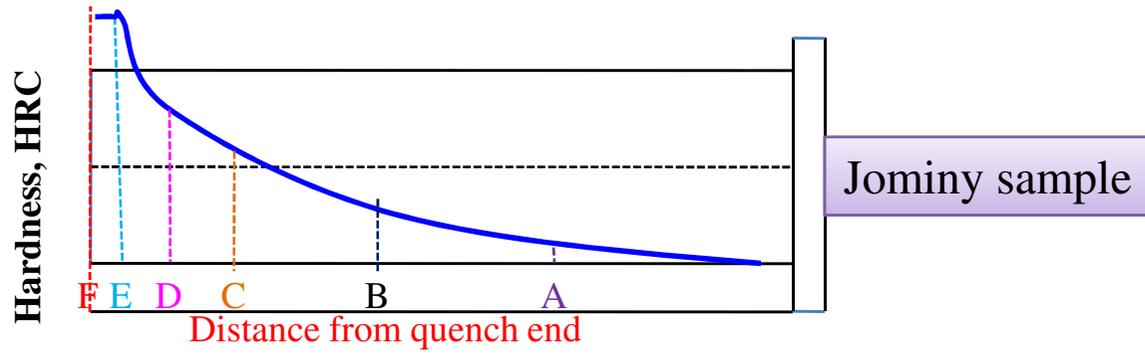
Jominy Sample



Variation of hardness along a Jominy bar

Jominy End Quench Test

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



t_0 = Minimum incubation period at the nose of the TTT diagram,
 t'_0 = minimum incubation period at the nose of the CCT diagram

M – Martensite
 P – Pearlite
 F.P – Fine pearlite
 C.P – Coarse pearlite
 M_S – Martensite start
 M_F – Martensite finish
 T_E – Eutectoid temp.

Tempering

- ❑ Tempering is the re-heat treatment processes, to relieve the residual stresses and improve the ductility and toughness of steel. In other words, tempering is a processes to optimize the strength and toughness of steel.
- ❑ With the increase in temperature, carbon diffusion becomes appreciable and the metastable martensite decomposes to more stable products. Four stages of tempering are known.

Stage I

- ❑ Stage I of temperature extends from room temperature to 200°C. During this stage, the martensite decomposes to two phases: a low carbon martensite with 0.2% C some times known as black martensite, and ϵ (HCP, $\text{Fe}_{2.4}\text{C}$), a transition carbide.
- ❑ With increase in the carbon content of the steel, more ϵ -carbide forms. It precipitates very fine form and resolves only under the electron microscope. The hardening effect due to this precipitation is usually offset by the softening effect associated with the loss of carbon in martensite.

Tempering

Stage II

- ❑ Stage II tempering occurs in the range of 250-400°C changes the epsilon carbide to orthorhombic cementite, the low-carbon martensite becomes BCC ferrite, and any retained austenite is transformed to lower bainite as a function of time. The carbide are too small to be resolved by the optical microscope, and the entire structure etches rapidly to a black mass formerly called troostite.

Stage III

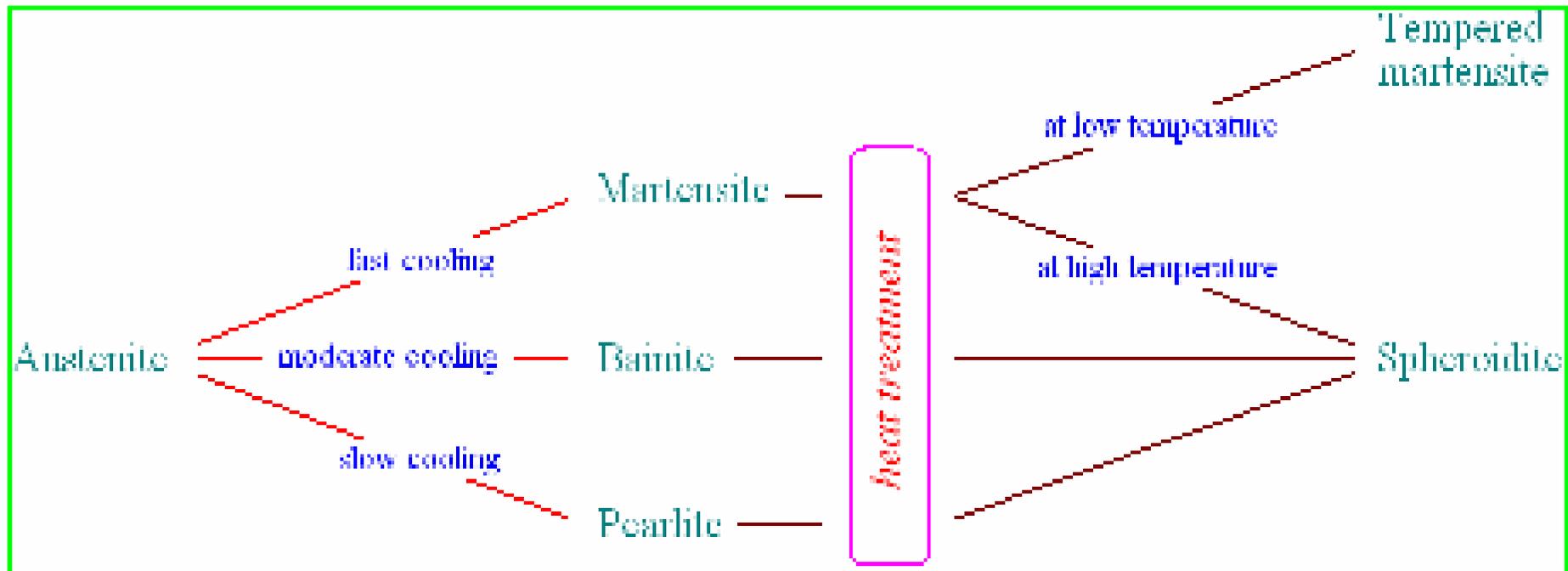
- ❑ Stage III tempering in the range of 400-650°C continues the growth of the cementite particles. This coalescence of the carbide particles allows more of the ferrite matrix to be seen, causing the sample to etch lighter than the low temperature product. In this structure formerly known as sorbite, it is resolvable above 500X, under electron microscopy it is clearly visible.

Stage IV

- ❑ Stage IV tempering in the range from 650-720°C produces large, globular cementite particles. This structure is very soft and tough and is similar to the spheroidized cementite structure. Spheroidite is the softest yet toughest structure that steel may have.

Tempering

- ❑ For many years , metallurgists divided the tempering processes into definite stages. For microstructures appearing in these stages was given names like Black Martensite, troostite and sorbite. However, the changes in microstructures are so gradual that it is more realistic to call the product of tempering at any temperature simply tempered martensite.

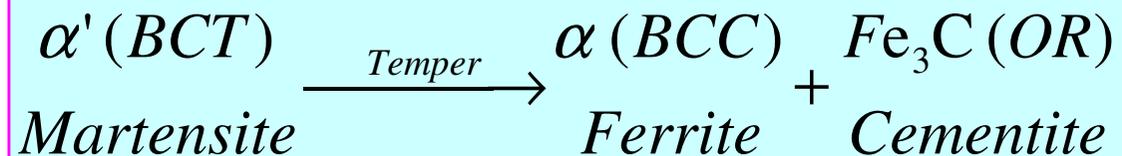


A schematic of possible transformations involving austenite decomposition

Tempering

- ❑ Tempering of some steels may result in a reduction of toughness what is known as temper embrittlement.
- ❑ This may be avoided by (1) compositional control, and/or (2) tempering above 575°C or below 375°C, followed by quenching to room temperature.
- ❑ The effect is greatest in Martensite structures, less severe in bainite structures and least severe in pearlite structures.
- ❑ It appears to be associated with the segregation of solute atoms to the grain boundaries lowering the boundary strength.
- ❑ Impurities responsible for temper brittleness are: P, Sn, Sb and As. Si reduces the risk of embrittlement by carbide formation. Mo has a stabilizing effect on carbides and is also used to minimize the risk of temper brittleness in low alloy steels.

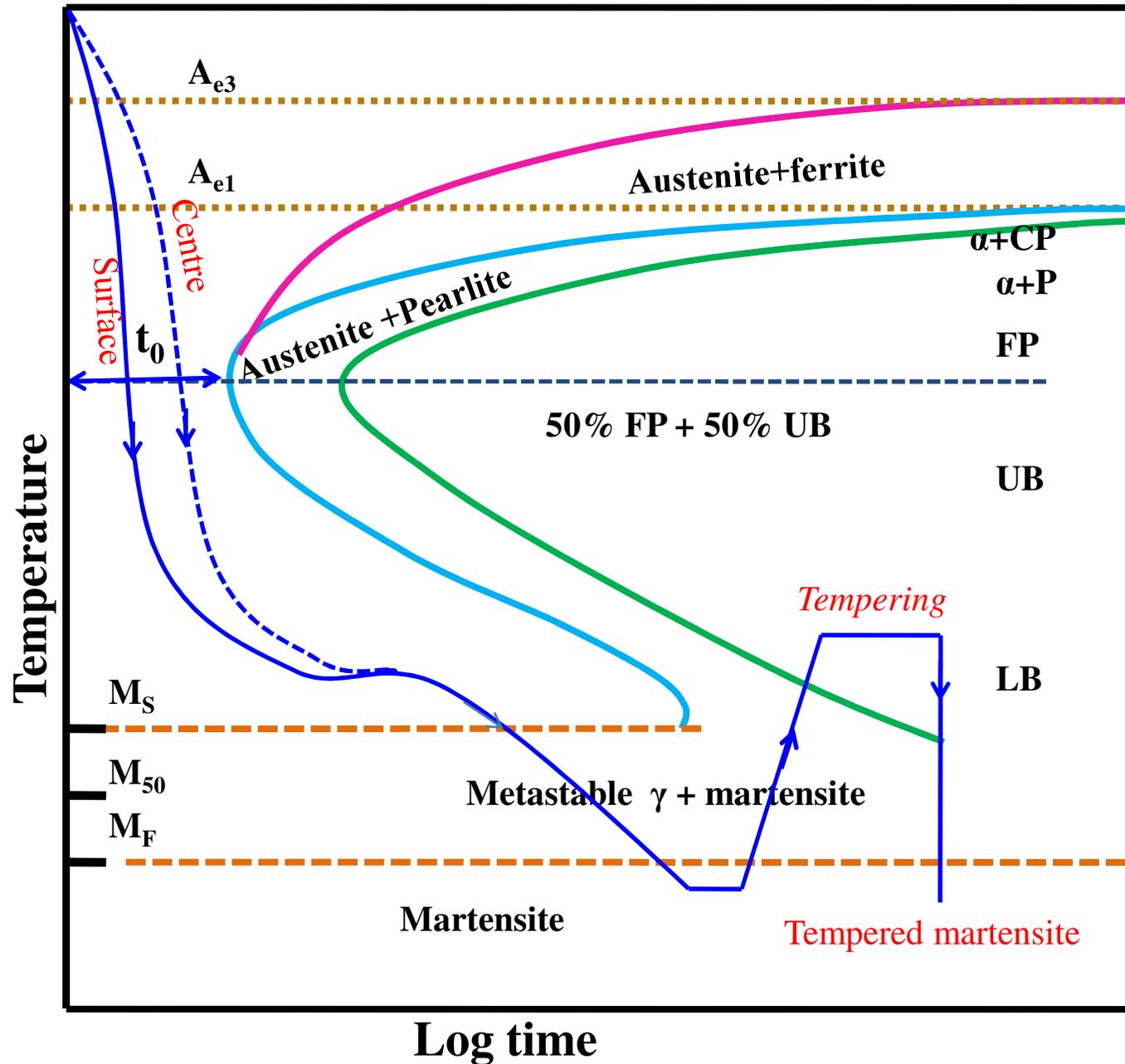
Summary



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.

Martempering

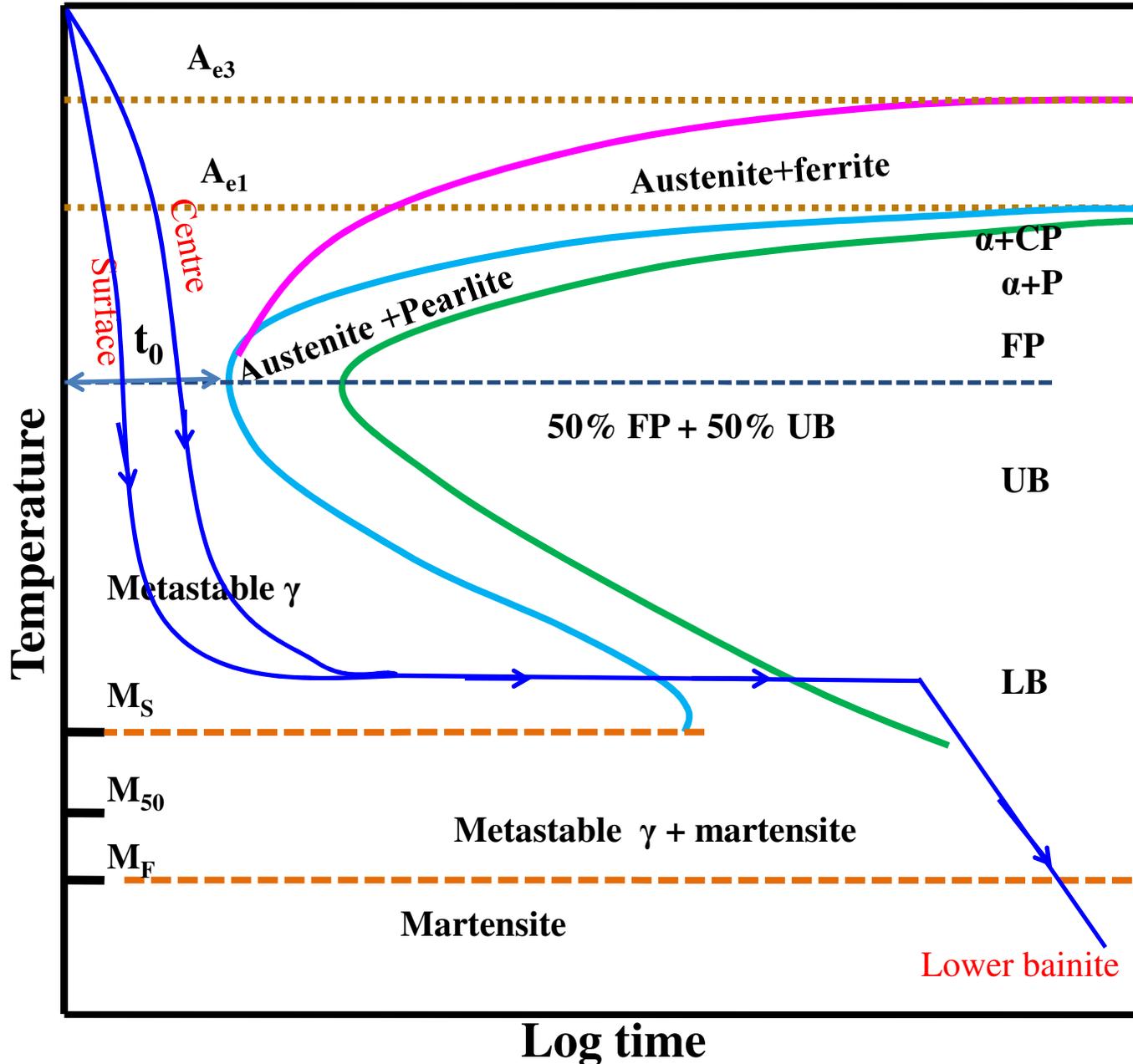


γ =austenite
 α =ferrite
 CP=coarse pearlite
 P=pearlite
 FP=fine pearlite
 t_0 =minimum incubation period
 UB=upper bainite
 LB=lower bainite
 M=martensite
 M_s =Martensite start temperature
 M_{50} =temperature at which 50% martensite is obtained
 M_f = martensite finish temperature

Austempering

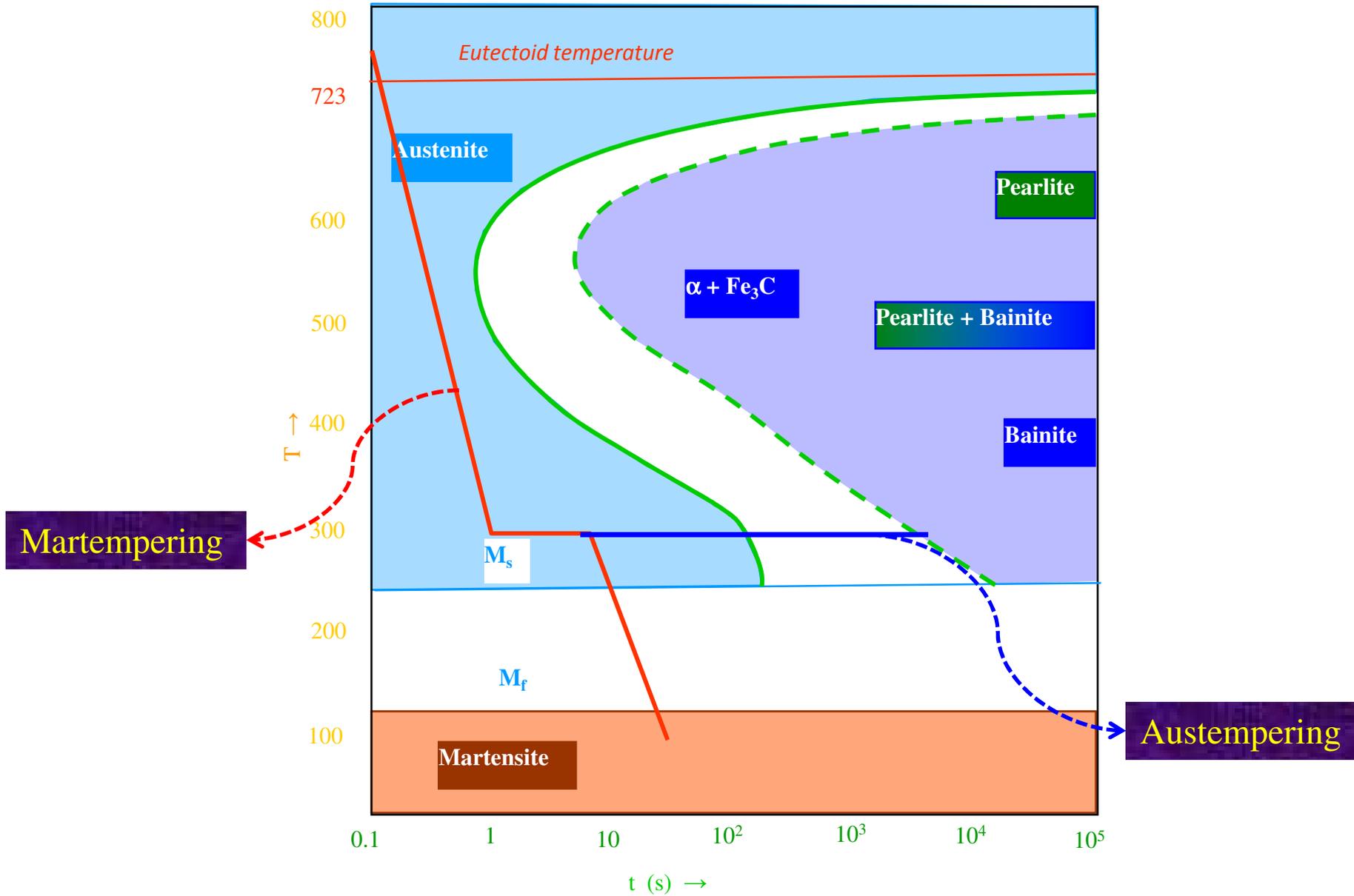
- ❑ Austempering heat treatment is given to steel to produce lower bainite in high carbon steel without any distortion or cracking to the sample.
- ❑ The heat treatment is cooling of austenite rapidly in a bath maintained at lower bainitic temperature (above M_s) temperature (avoiding the nose of the 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 required to be tempered.

Austempering



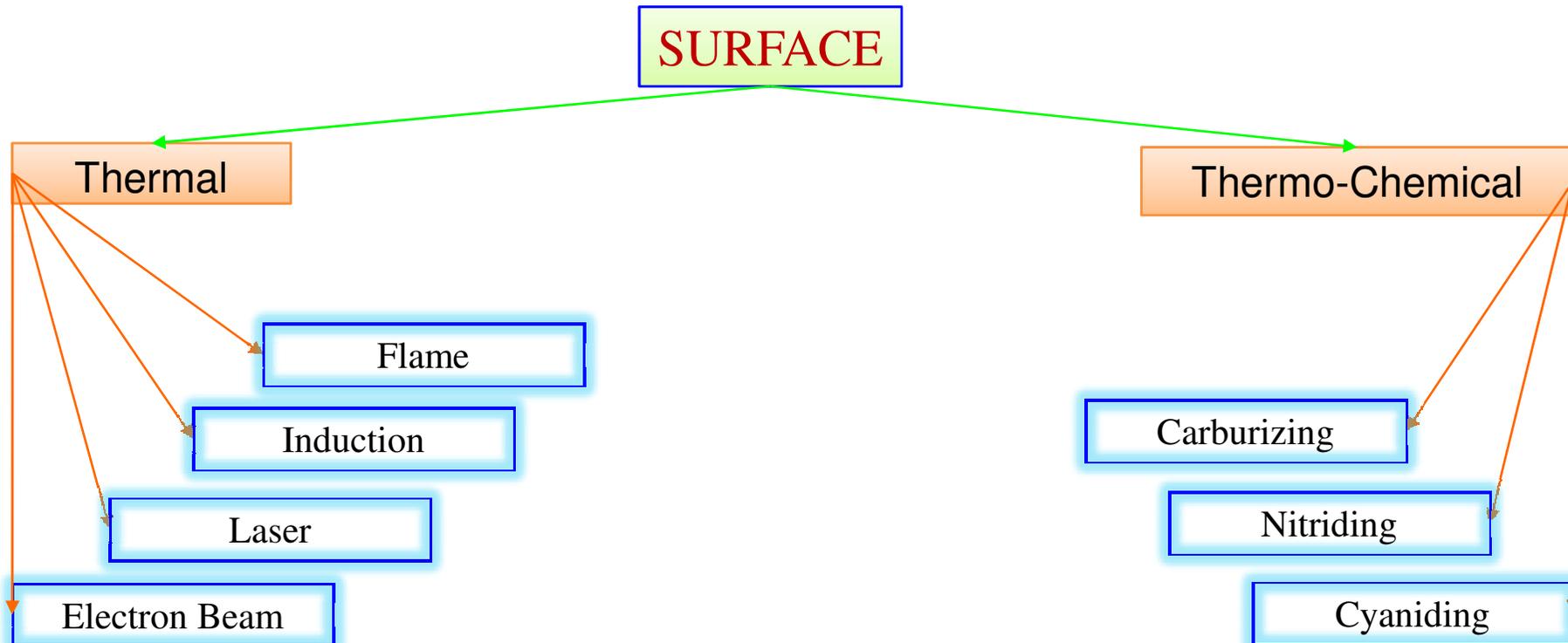
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Comparison between Martempering & Austempering



Surface Hardening Treatments

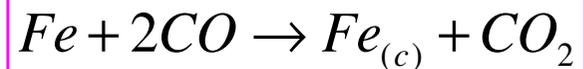
- ❑ Numerous industrial applications require a hard wear resistant surface called the *case*, and a relatively soft, tough inside called the *core*. Example: Gears
- ❑ They are two different categories. They are thermo chemical and thermo mechanical treatments. Thermo chemical treatment is related to change in chemical composition and In Thermo mechanical treatment, there is no change of chemical composition of the steel and are essentially shallow- hardening methods.
- ❑ A detailed flow chart is given below related to surface hardening treatments.



Thermo Chemical Treatments

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



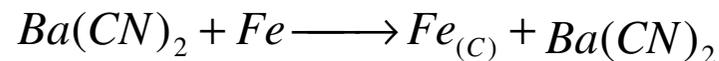
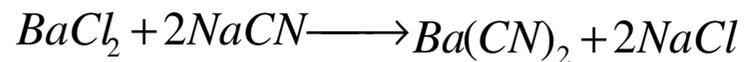
- ❑ Where $Fe_{(c)}$ represents carbon dissolved in austenite. the rate of diffusion of carbon in austenite, at a given temperature is dependent upon the diffusion coefficient and the carbon concentration gradient.
- ❑ The carburizing equation given previously, $Fe+2CO \rightarrow Fe_{(c)} + CO_2$ is 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.

Carburizing

- ❑ 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.

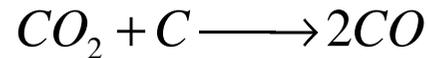
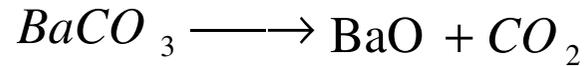
Liquid Carburizing

- ❑ Liquid carburizing is a method of case hardening steel by placing it in a bath (8% NaCN, 82% BaCl₂ and 10% NaCl) of molten cyanide so that carbon will diffuse from the bath into the metal and produce a case comparable to one resulting from pack or gas carburizing.
- ❑ Liquid carburizing may be distinguished from cyaniding by the character and composition of the case produced. The cyanide case is higher in nitrogen and lower in carbon; the reverse is true of liquid carburized cases.

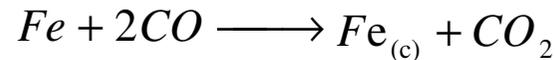


Pack Carburizing

- ❑ In *pack carburizing*, the articles to be carburized are packed in a box, embedding them in a powdery mixture of 85% charcoal and 15% of energizers such as $BaCO_3$. The box is sealed with fireclay and loaded into the furnace kept at $930^\circ C$. The residual air in the box combines with carbon to produce CO. The energizer decomposes as below :



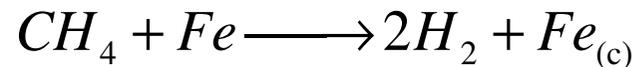
- ❑ The carbon enters the steel through the following reaction:



- ❑ If selective carburization is to be done, copper is electroplated to a thickness of ~ 0.05 mm in regions where carburization is not desired. Alternatively, a refractory paste of fireclay mixed with asbestos can be applied. Control of temperature and penetration depth is less in pack carburizing as compared to liquid and gas carburizing. Also, direct quench from the carburizing temperature to harden the surface is not possible.

Gas Carburizing

- ❑ The steel is heated in contact with carbon monoxide and/or a hydrocarbon which is readily decomposed at the carburizing temperature.
- ❑ A mixture consisting of 5-15% methane (or propane) in a neutral carrier gas is used. The methane decomposes according to the following reaction:

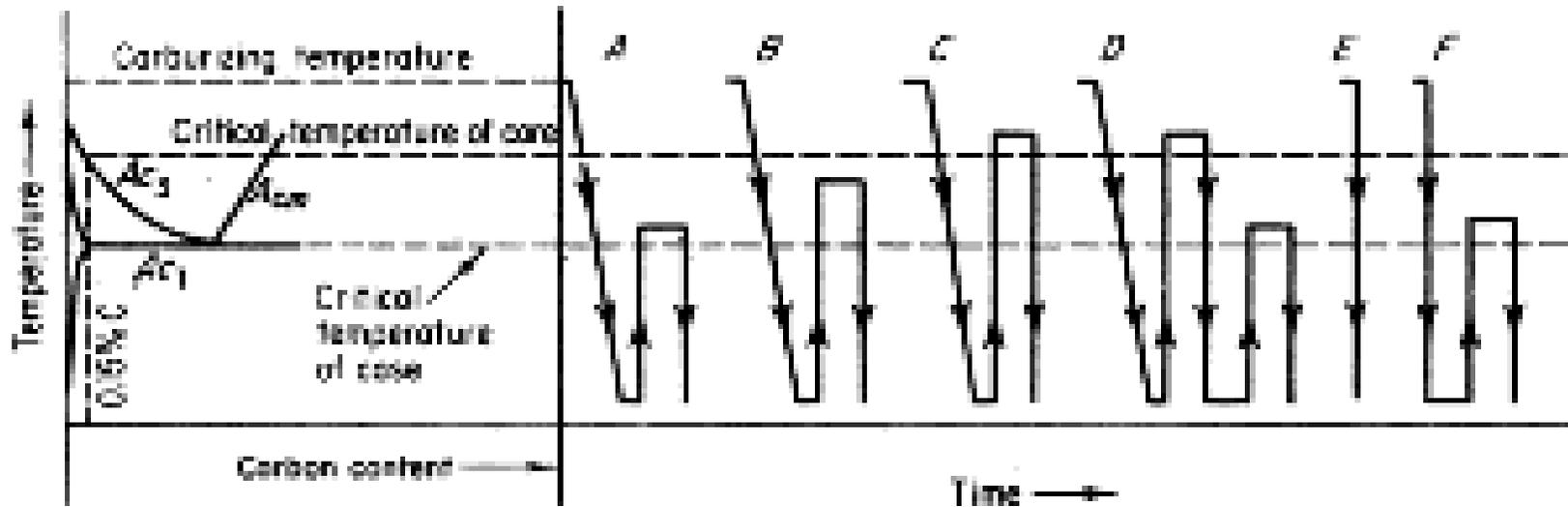


- ❑ The carbon potential of the gas mixture increases with increasing concentration of methane. Too large a concentration or too high a gas velocity releases carbon faster than it can be absorbed and may result in soot formation on the surface.
- ❑ Closer control of temperature and case depth is possible in gas carburizing, as compared to pack carburizing. Also, post quenching can be done directly.

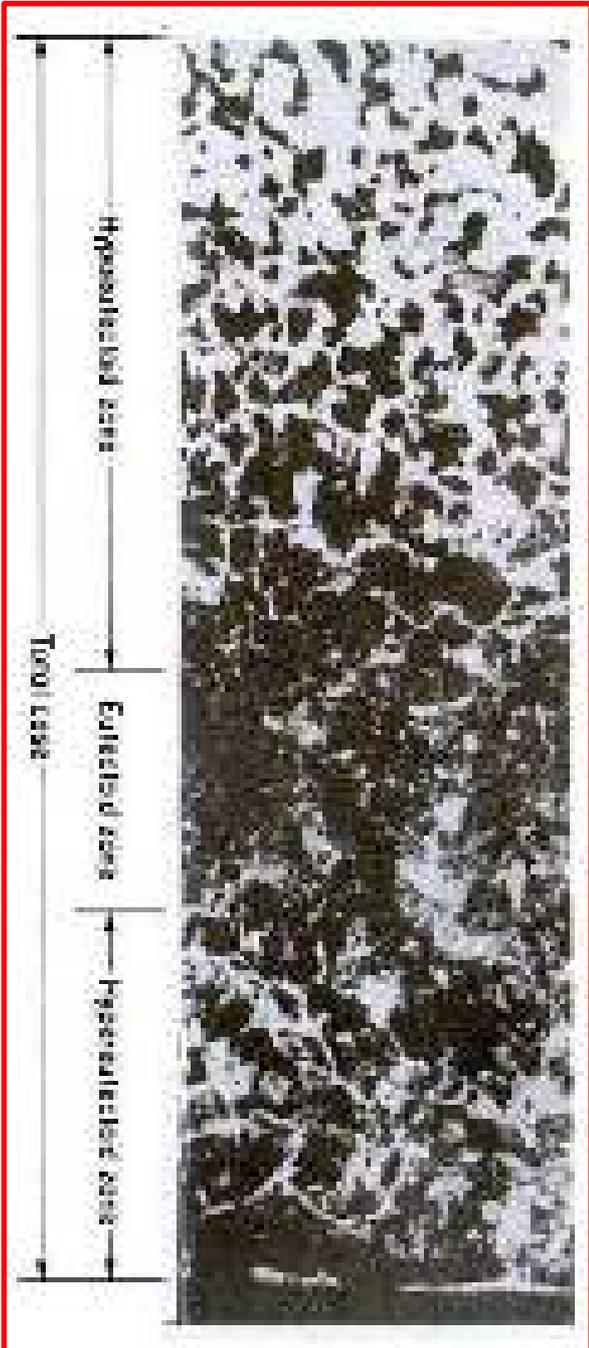
Heat treatment after carburizing

- ❑ Since steel is carburized in the austenite region, direct quenching from the carburizing temperature will harden both the case and core will harden both the case and core if the cooling rate is greater than the critical cooling rate. Direct quenching of coarse grained steels often leads to brittleness and distortion, so that this treatment should be applied only to fine grained steels. *A diagrammatic representation of various hardening treatments for carburized steels shown in next slide.*

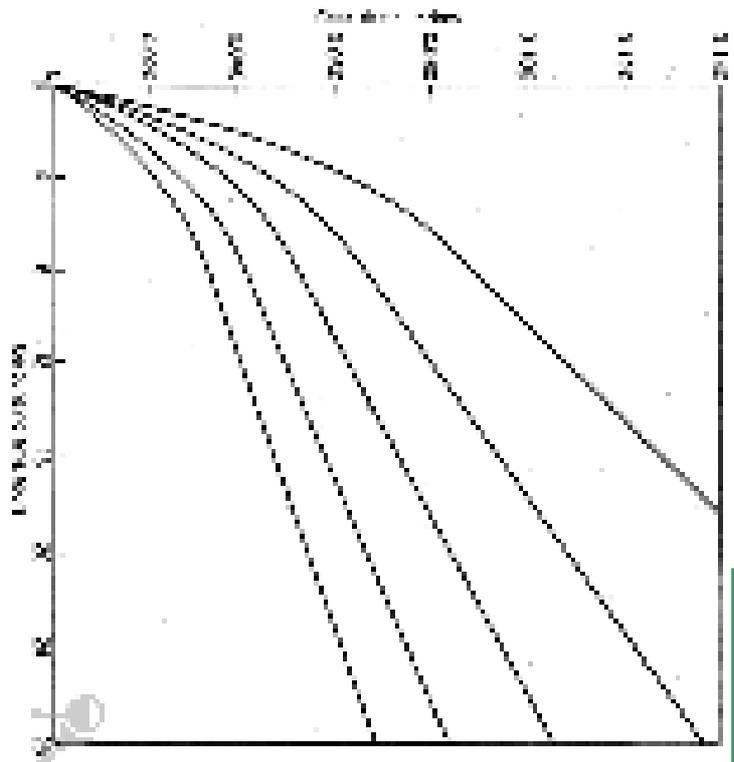
Heat treatment after carburizing



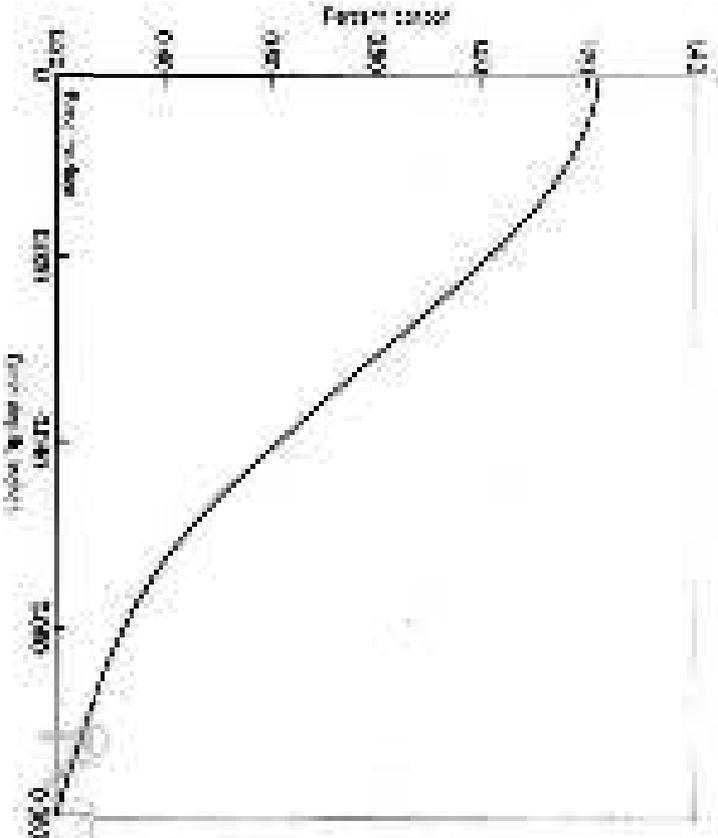
TREATMENT	CASE	CORE
A – best adapted to fine grained steels	Refined; Excess carbide not dissolved	Unrefined; soft and machinable
B-best adapted to fine grained steels	Slightly coarsened; some solution of excess carbide	Partially refined; stronger and tougher than A
C-best adapted to fine grained steels	Somewhat coarsened; solution of excess carbide favored; austenite retention promoted in highly alloyed steels.	Refined: maximum core strength and hardness; better combination of strength and ductility than B
D-best treatment for coarse grained steels	Refined solution of excess carbide favored; austenite retention minimized	Refined; soft and machinable; maximum toughness and resistance to impact
E-adapted to fine grained steels only	Unrefined with excess carbide dissolved; austenite retained; distortion minimized	Unrefined but hardened
F-adapted to fine grained steels only	Refined; solution of excess carbide favored; austenite retention minimized	Unrefined; fair toughness



Relation of time and temperature to case depth



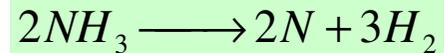
Carburizing



Carbon-concentration gradient in a carburized steel

Nitriding

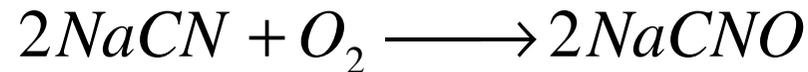
- ❑ In contrast to the processes described before, nitriding is carried out in the ferrite region. Consequently, no phase change occurs after nitriding .
- ❑ This part to be nitrided should possess the required core properties prior to nitriding. Pure ammonia decomposes to yield nitrogen which enters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



- ❑ The solubility of nitrogen in ferrite is small. Most of the nitrogen that enters the steel forms hard nitrides (e.g. Fe₃N). A typical nitriding steel contains alloying elements of 1%Al, 1.5%Cr and 0.2%Mo. Al, Cr, and Mo form very hard and wear resistant nitrides.
- ❑ The temperature of nitriding is 500-590°C. the time for a case depth of 0.02mm is about 2 hour. In addition with wear resistance, it also increases the resistance of a carbon steel to corrosion in moist atmospheres.
- ❑ A common problem encountered in nitriding is the formation of γ' nitride (Fe₄N) on the outer layers of the case , known as the “white layer”, as it looks white under the microscope. This layer is very brittle and tends to crack. It must be removed by final grinding operation. Its formation can be minimized by maintaining the correct ratio of NH₃/ H₂ in the gas mixture during the heat treatment.

Cyaniding and Carbonitriding

- ❑ 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:



- ❑ 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 and Carbonitriding

- ❑ **Carbonitriding** 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

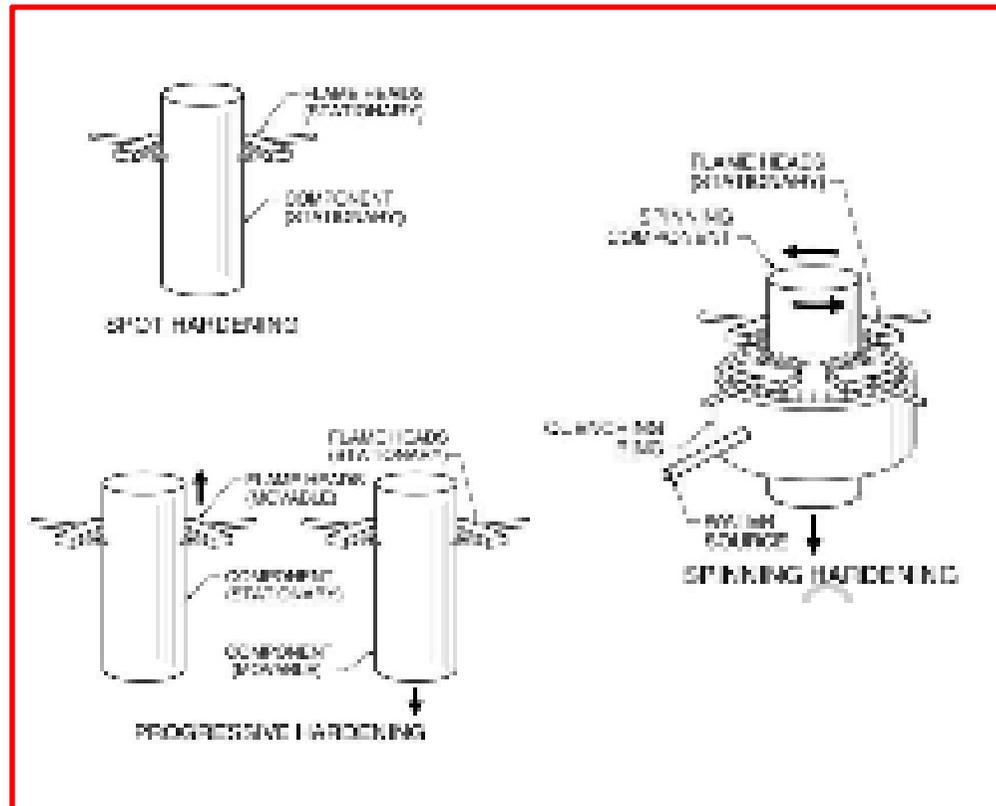
Thermal Energy Treatments

Flame Hardening

❑ For large work pieces, such as mill rolls, large gears and complicated cross sections, in such cases, flame hardening is done by means of an oxyacetylene torch. Heating should be done rapidly by the torch and the surface quenched, before appreciable heat transfer to the core occurs.

❑ Four methods are generally use for Flame Hardening

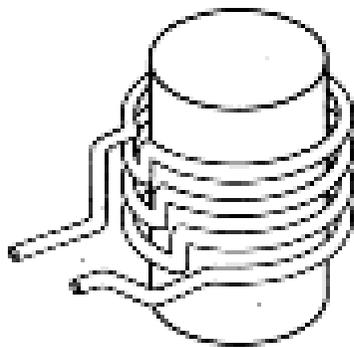
- ✓ Stationary (Spot): Torch and work is stationary
- ✓ Progressive: Torch moves over a work piece
- ✓ Spinning: Torch is stationary while work piece rotates
- ✓ Progressive-spinning: Torch moves over a rotating work piece.



Induction Hardening

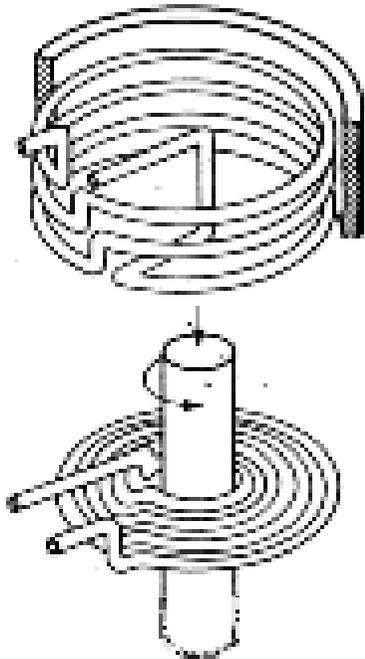
- ❑ Here, an alternating current of high frequency passes through an induction coil enclosing the steel part to be heat treated. The induced emf heats the steel. the depth up to which the heat penetrates and rises the temperature above A_{c3} is inversely proportional to the square root of the AC frequency.
- ❑ 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



A Simple Solenoid for
external heating

Induction Hardening



Heating pattern

A coil to be used internally for heating bores

Heating pattern

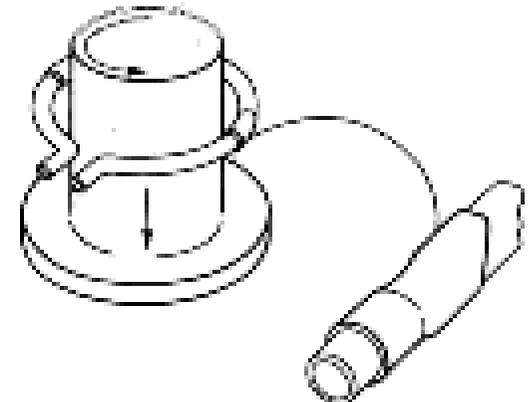


A "pie-plate" type of coil designed to provide high current densities in a narrow band for scanning applications.

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

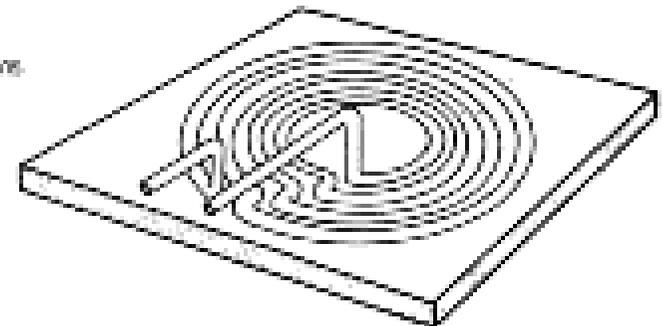
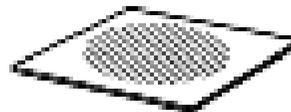


Heating pattern



A 'Pancake' coil for spot heating.

Heating pattern



Laser Hardening

- ❑ Laser hardening treatment is widely used to harden localized areas of steel and cast iron machine components. This process is sometimes referred to as laser transformation hardening to differentiate it from laser surface melting phenomena.
- ❑ There is no chemistry change produced by laser transformation hardening, and the process, like induction and flame hardening, provides an effective technique to harden ferrous materials selectively.
- ❑ As laser beams are of high intensity, a lens is used to reduce the intensity by producing a defocused spot of size ranging from 0.5 to 25 mm. proper control of energy input is necessary to avoid melting.
- ❑ Laser transformation hardening produces thin surface zones that are heated and cooled very rapidly, resulting in very fine Martensitic microstructures, even in steels with relatively low hardenability. High hardness and good wear resistance with less distortion result from this process.
- ❑ Laser hardening has the advantage of precise control over the area to be hardened, an ability to harden reentrant surfaces, very high speed of hardening and no separate quenching step (the quench is effected by the mass of the unheated material).
- ❑ The disadvantage is that the hardening is shallower than in induction and flame hardening.

Electron Beam (EB) Hardening

- ❑ Electron Beam (EB) hardening is like laser treatment, is used to harden the surfaces of steels. The EB heat treating process uses a concentrated beam of high-velocity electrons as an energy source to heat selected surface areas of ferrous parts. Electrons are accelerated and are formed into a directed beam by an EB gun.
- ❑ After exiting the gun, the beam passes through a focus coil, which precisely controls beam density levels (spot size) at the work piece surface and then passes through a deflection coil.
- ❑ To produce an electron beam, a high vacuum of 10^{-5} torr is needed in the region where the electrons are emitted and accelerated. This vacuum environment protects the emitter from oxidizing and avoids scattering of the electrons while they are still traveling at a relatively low velocity.
- ❑ Like laser beam hardening, the EB process eliminates the need for quenchants but requires a sufficient work piece mass to permit self quenching.
- ❑ A mass of up to eight times that of the volume to be EB hardened is required around and beneath the heated surfaces. Electron beam hardening does not require energy absorbing coatings, as does laser beam hardening.

Relative benefits of common surface-hardening processes

PROCESS	BENEFITS
Carburizing	Hard, highly wear-resistant surface (medium case depths); excellent capacity for contact load; good bending fatigue strength; good resistance to seizure; excellent freedom from quench cracking; low-to-medium cost steels required; high capital investment required
Nitriding	Hard, highly wear-resistant surface (shallow case depths); fair capacity for contact load; good bending fatigue strength; excellent resistance to seizure; excellent dimensional control possible; good freedom from quench cracking (during pretreatment); medium-to-high-cost steels required; medium capital investment required; improved salt corrosion resistance
Induction hardening	Hard, highly wear-resistant surface (deep case depths); good capacity for contact load; good bending fatigue strength; fair resistance to seizure; fair dimensional control possible; fair freedom from quench cracking; low-cost steels usually satisfactory; medium capital investment required
Flame hardening	Hard, highly wear-resistant surface (deep case depths); good capacity for contact load; good bending fatigue strength; fair resistance to seizure; fair dimensional control possible; fair freedom from quench cracking; low-cost steels usually satisfactory; low capital investment required

