

# Module 3

Phase diagrams: - Limitations of pure metals and need of alloying - classification of alloys, solid solutions, Hume Rothery's rule - equilibrium diagram of common types of binary systems: five types. Coring - lever rule and Gibb's phase rule - Reactions: -monotectic, eutectic, eutectoid, peritectic, peritectoid. Detailed discussion on Iron-Carbon equilibrium diagram with microstructure and properties changes in austenite, ledeburite, ferrite, cementite, special features of martensite transformation, bainite, spheroidite etc. Heat treatment: - Definition and necessity – TTT for a eutectoid iron-carbon alloy, CCT diagram, applications - annealing, normalizing, hardening, spheroidizing. Tempering:- austempering, martempering and ausforming - Comparative study on ductility and strength with structure of pearlite, bainite, spherodite, martensite, tempered martensite and ausforming. Hardenability, Jominy end quench test, applications-Surface hardening methods:- no change in surface composition methods :- Flame, induction, laser and electron beam hardening processes- change in surface

# Need for alloying

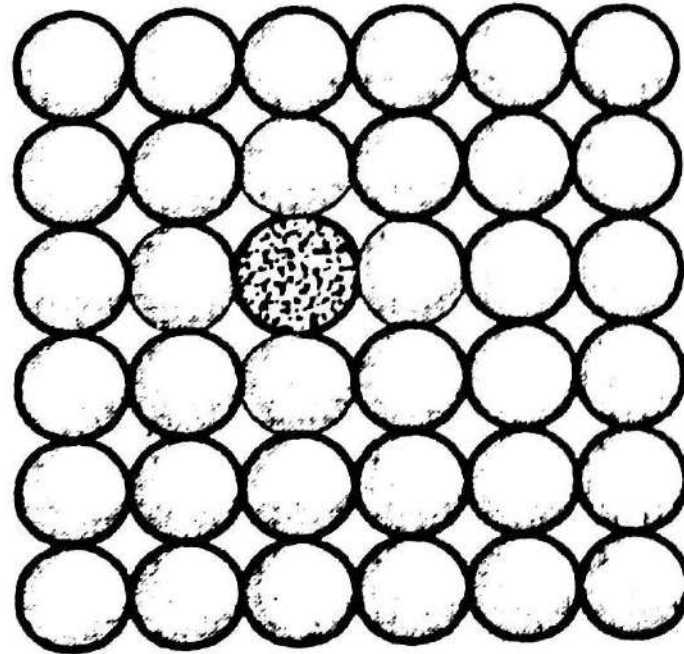
- Pure metals are ideal materials but due to higher cost, poor properties and lack of availability, it is desirable to have a certain level of impurity.
- Silver can be made stronger by adding a small amount of copper to it, without changing its appearance at a lower cost.
- Copper can be made stronger by adding zinc to it-brass
- Upon alloying infinite number of materials can be prepared with varied properties.
- Adding chromium to steel can increase the corrosion resistance.

# Alloy or solid solution

- **Alloys or solid solutions** are materials in which impurity atoms are added purposely to bring some special properties to the material.
- In the case of alloys, the terms *solute* and *solvent* are generally used.
- “*Solvent*” means the element or compound that is present in large quantity; sometimes solvent atoms are also called as *host* atoms. “*Solute*” is used to denote an element or compound present in a minor concentration.
- In alloys, the crystal structure is maintained, and no new structures are formed.
- If two liquids, soluble in each other (such as water and alcohol) are combined, a liquid solution is produced as the molecules intermix, and its composition is homogeneous throughout. A solid solution is also compositionally homogeneous; the impurity atoms are randomly and uniformly dispersed in the solid.

# A substitutional solid solution

- In the substitutional type, solute or impurity atoms replace or substitute for the host atoms.



# Hume Rothery's rules for Substitutional solid solutions

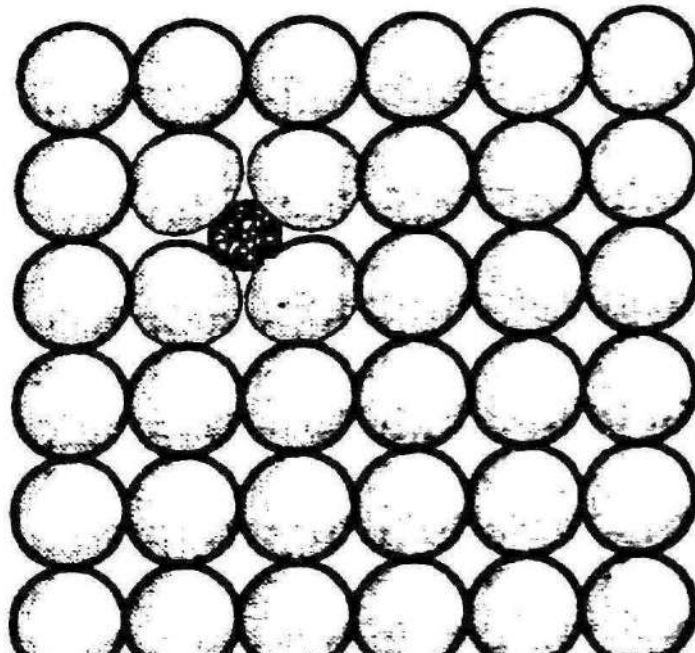
The features of the solute and solvent atoms that determine the degree to which the former dissolves in the latter, as follows:

- **Atomic size factor**. Large quantities of a solute may be accommodated in this type of solid solution only when the difference in atomic radii between the two atom types is less than about  $\sim 15\%$ . Otherwise the solute atoms will create lattice distortions and a new phase will form.
- **Crystal structure**. For a good solid solubility the crystal structures for metals of both atom types must be the same.
- **Electronegativity**. The more electropositive one element and the more electronegative the other, the greater is the likelihood that they will form an intermetallic compound instead of a substitutional solid solution.
- **Valences**. A metal will have more tendency to dissolve another metal of higher valency than one with lower valency.

An example of a substitutional solid solution is found for copper-nickel alloy. These two elements are completely soluble in one another at all proportions. With regard to the aforementioned rules that govern degree of solubility, the atomic radii for copper and nickel are 0.128 and 0.125 nm, respectively, both have the FCC crystal structure, and their

# Interstitial solid solution

- For interstitial solid solutions, impurity atoms fill the voids or interstices (vacant space between atoms) among the host atoms
- For metallic materials with high atomic packing factors, these interstitial positions are relatively small.



# Hume Rothery's rules for interstitial solid solutions

- Atomic diameter or atomic size factor of an interstitial impurity must be reasonably smaller than that of the host atoms.
  - Normally, the maximum allowable concentration of interstitial impurity atoms is low (less than 10%).
  - Even very small impurity atoms are larger than the interstitial sites of the host material, and as a result they impart some lattice strains on the adjacent host atoms.
- Crystal structure. Irrespective of the crystal structure the impurity atom can fit into the interstitial positions of both FCC and BCC crystal structures.

For example, carbon forms an interstitial solid solution when added to iron; the maximum soluble concentration of carbon is about 2%. The



# Alloys or Solid solutions

## Definitions

### Component

- Components are pure metals and/or compounds of which an alloy is composed. For example, in a copper–zinc brass, the components are Cu and Zn, *Solute* and *solvent*.

### System

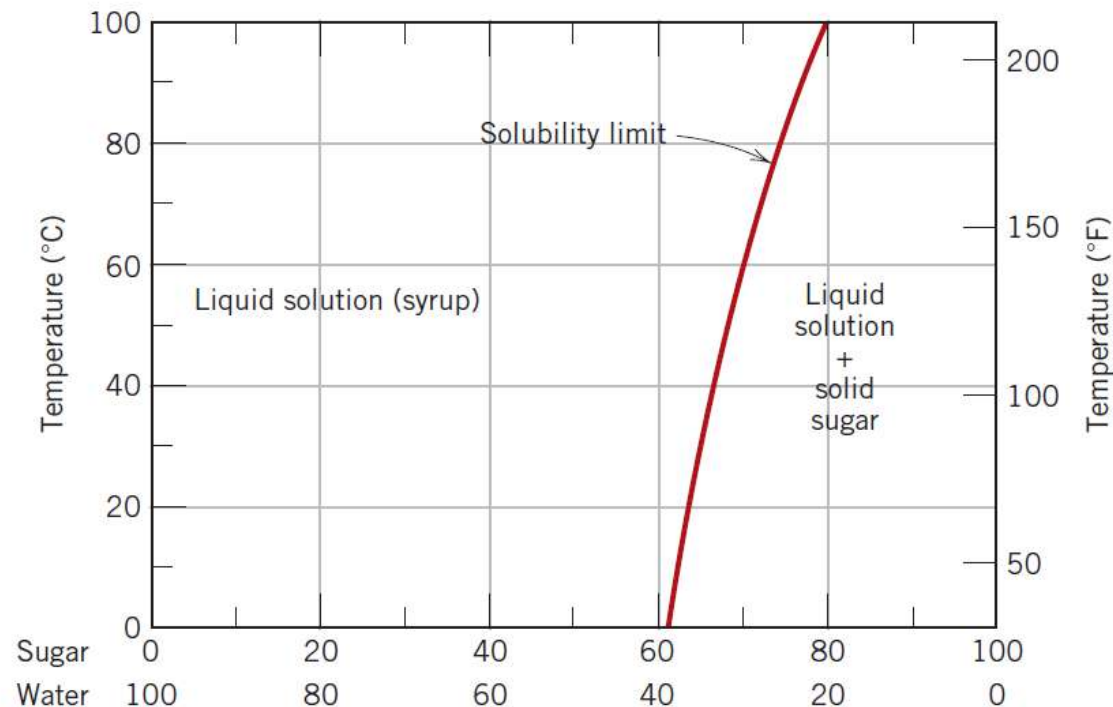
- “system” refers to a specific body of material under consideration (e.g., a ladle of molten steel).
- Or it may relate to the series of alloys consisting of the same components, but not to consider alloy composition (e.g., the iron–carbon system).

### Solid solution

- A solid solution consists of atoms of at least two different types; the solute atoms occupy either substitutional or interstitial positions in the

# Solubility limit

- In alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is called a solubility limit.
- The addition of solute in excess of this solubility limit results in the formation of another solid solution or compound that has a distinctly different composition.
- E.g., consider the sugar–water ( $C_{12}H_{22}O_{11}$ – $H_2O$ ) system.



## Phases

- A phase can be defined as a **homogeneous portion of a system that has uniform physical and chemical characteristics.**
- **Every pure material is considered to be a phase; so also is every solid, liquid, and gaseous solution.** For example, the sugar–water syrup solution is one phase, and solid sugar is another.
- If more than one phase is present in a given system, each will have its own distinct properties, and a boundary separating the phases will exist across which there will be a discontinuous and abrupt change in physical and/or chemical characteristics.
- When water and ice are present in a container, two separate phases exist; they are physically dissimilar (one is a solid, the other is a liquid) but identical in chemical makeup.
- Sometimes, a single-phase system is termed “*homogeneous*.” Systems composed of two or more phases are termed “mixtures” or “*heterogeneous systems*.” Most metallic alloys and, for that matter, ceramic, polymeric, and composite systems are heterogeneous.

## Microstructure

- Microstructure is subject to direct microscopic observation, using optical or electron microscopes;
- In metal alloys, microstructure is characterized by the number of phases present, their proportions, and the manner in which they are distributed or arranged.
- The microstructure of an alloy depends on such variables as the alloying elements present, their concentrations, and the heat treatment of the alloy

## Phase equilibria

- Equilibrium means that the characteristics of the system do not change with time but continue **indefinitely**; that is, the system is stable.
- A change in temperature, pressure, and/or composition for a system in equilibrium will result in a spontaneous change to another state.
- The term phase equilibrium, refers to equilibrium of systems in which more than one phase may exist.
- Phase equilibrium is reflected by a constancy with time in the phase characteristics of a system..

## Phase diagram

- The information about the control of the phase structure of a particular system (metal alloys) is conveniently and concisely displayed in what is called a phase diagram, also often termed an equilibrium diagram.
- There are three externally controllable parameters that will affect phase structure—viz. temperature, pressure, and composition—and phase diagrams are constructed when various combinations of these

# Gibbs phase rule

- The construction of phase diagrams as well as some of the principles governing the conditions for phase equilibria are dictated by laws of thermodynamics. One of these is the Gibbs phase rule, proposed by the nineteenth-century physicist J. Willard Gibbs.
- This rule represents a relationship between the number of phases, number of components and number of degrees of freedom that will coexist within a system at equilibrium, and is expressed by the simple equation;

$$F=C-P+2$$

- where F is termed the number of degrees of freedom, P is the number of phases present, and C represents the number of components in the system
- Degrees of freedom or the number of externally controlled variables (e.g., temperature, pressure, composition) which must be specified to completely define the state of the system and these variables that can be changed independently without altering the number of phases that coexist at equilibrium.
- Since pressure is ignored in the case of liquids and solids; and phase rule can be modified as

$$F=C-P+1$$

# Solution and mixture

- **Solution** is a phase with more than one component (liquid or solid).
- In a solution, the solvent does not alter the structural properties of the solvent.
- In a **mixture**, there will be more than one phases which are insoluble and distinct atomic arrangements in each phase present.
- E.g., sand and water.

# Classification of alloys

- All the metals used in structural applications are obtained by melting two or more metals together.
- While melting two or more metals, three different things can happen, they are;
  - A solid solution
  - A mixture with different phases
  - Inter metallic compound
- A solution is formed when X-Y bond strength is intermediate between X-X and Y-Y bonds.
- A multi phase mixture is formed when the X-Y bond is weaker than the X-X bond and Y-Y bond. The alloy solidifies by separating out into two distinct phases.
- An intermetallic compound is formed when the X-Y bond is stronger than the X-X bond and Y-Y bond.
- The term alloy system refers to all the different compositions of the particular alloy.

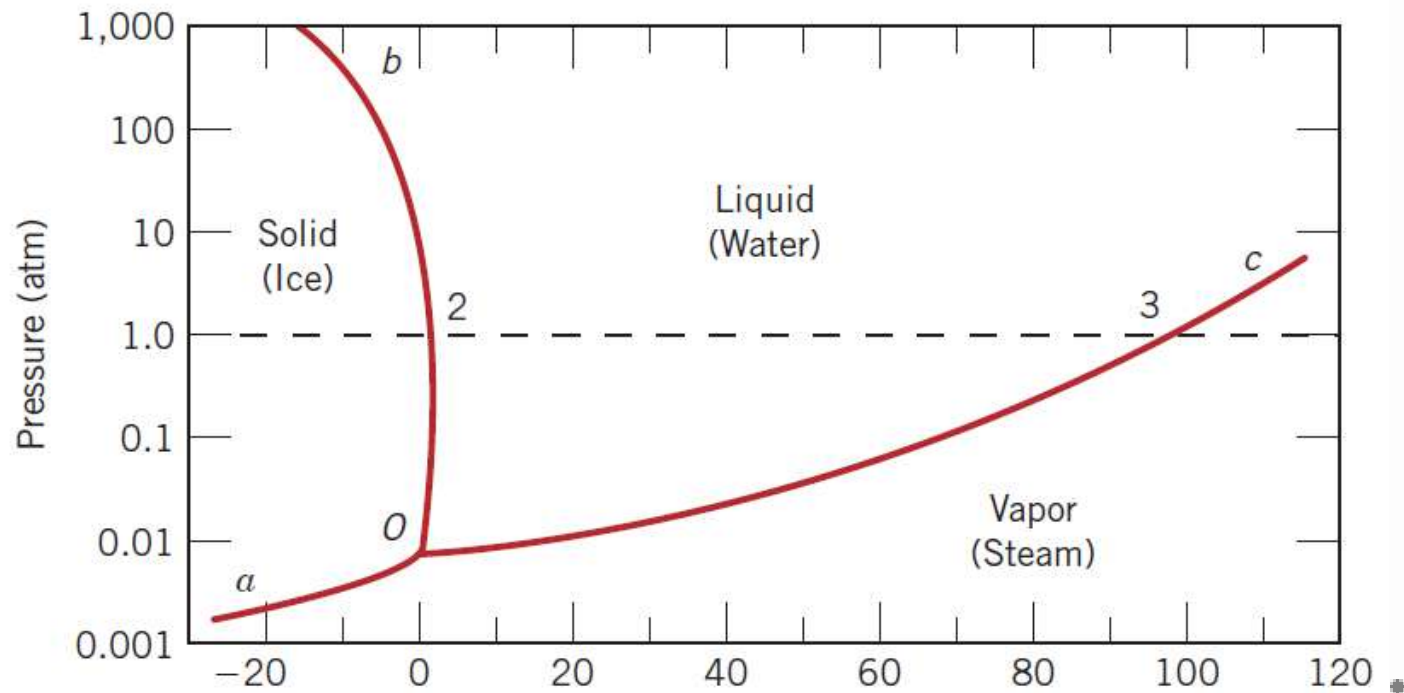
# Phase diagram

- The information about the control of the phase structure of a particular system (metal alloys) is conveniently and concisely displayed in what is called a phase diagram, also often termed an equilibrium diagram.
- There are three externally controllable parameters that will affect phase structure—viz. temperature, pressure, and composition—and phase diagrams are constructed when various combinations of these parameters are plotted against one another.



# One component or Unary phase diagram

- In a one-component system, composition is held constant; means that pressure and temperature are the variables.
- The one-component phase diagram (or unary phase diagram)[sometimes also called a pressure–temperature (or P–T ) diagram] is represented as a two-dimensional plot of pressure (ordinate, or vertical or y-axis) versus temperature (abscissa, or horizontal or x-axis).



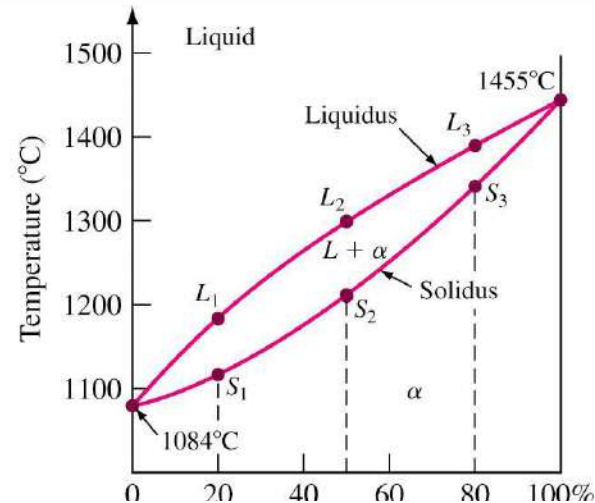
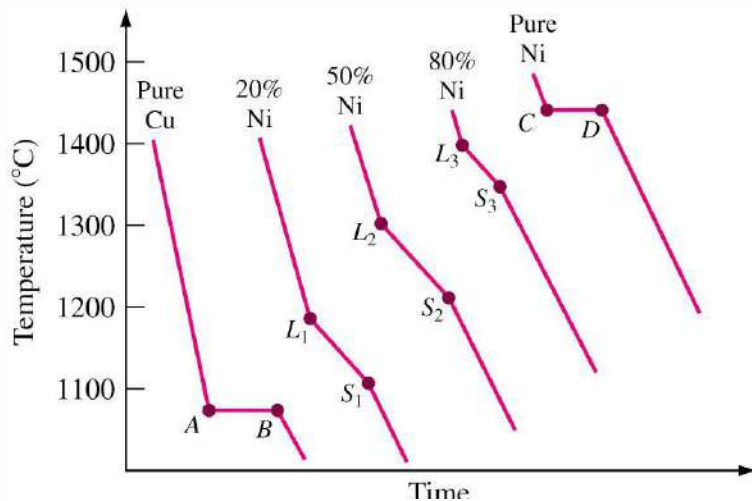
- In the phase diagram for  $\text{H}_2\text{O}$ , the regions for three different phases—solid, liquid, and will exist under equilibrium conditions over the temperature–pressure ranges.
- The three curves labeled aO, bO, and cO are phase boundaries; at any point on one of these curves, the two phases on either side of the curve are in equilibrium (or coexist) with one another.
- That is, equilibrium between solid and vapor phases is along curve aO—likewise for the solid-liquid, curve bO, and the liquid-vapor, curve cO.
- Upon crossing a boundary (as temperature and/or pressure is altered), one phase transforms to another.
- All three of the phase boundary curves intersect at a common point, which is labeled O (and for this  $\text{H}_2\text{O}$  system, at a temperature of 273.16 K and a pressure of  $6.04 \times 10^3 \text{ atm}$ ).
- This means that at this point only, all of the solid, liquid, and vapor phases are simultaneously in equilibrium with one another. Appropriately, this, and any other point on a P–T phase diagram where three phases are in equilibrium, is called a **triple point**; sometimes it is also termed an invariant point inasmuch as its position is distinct, or fixed by definite values of pressure and temperature.

# Binary phase diagram

- Another type of extremely common phase diagram is one in which temperature and composition are variable parameters, and *pressure is held constant—normally 1 atm.*
- Binary phase diagrams are maps that represent the relationships between temperature and the compositions and quantities of phases at equilibrium, which influence the microstructure of an alloy.
- Many microstructures develop from **phase transformations**, the changes that occur when the temperature is altered (ordinarily upon cooling).
- This may involve the transition from one phase to another, or the appearance or disappearance of a phase.
- Binary phase diagrams are helpful in predicting phase transformations and the resulting microstructures, which may have equilibrium or

# Construction of phase diagram

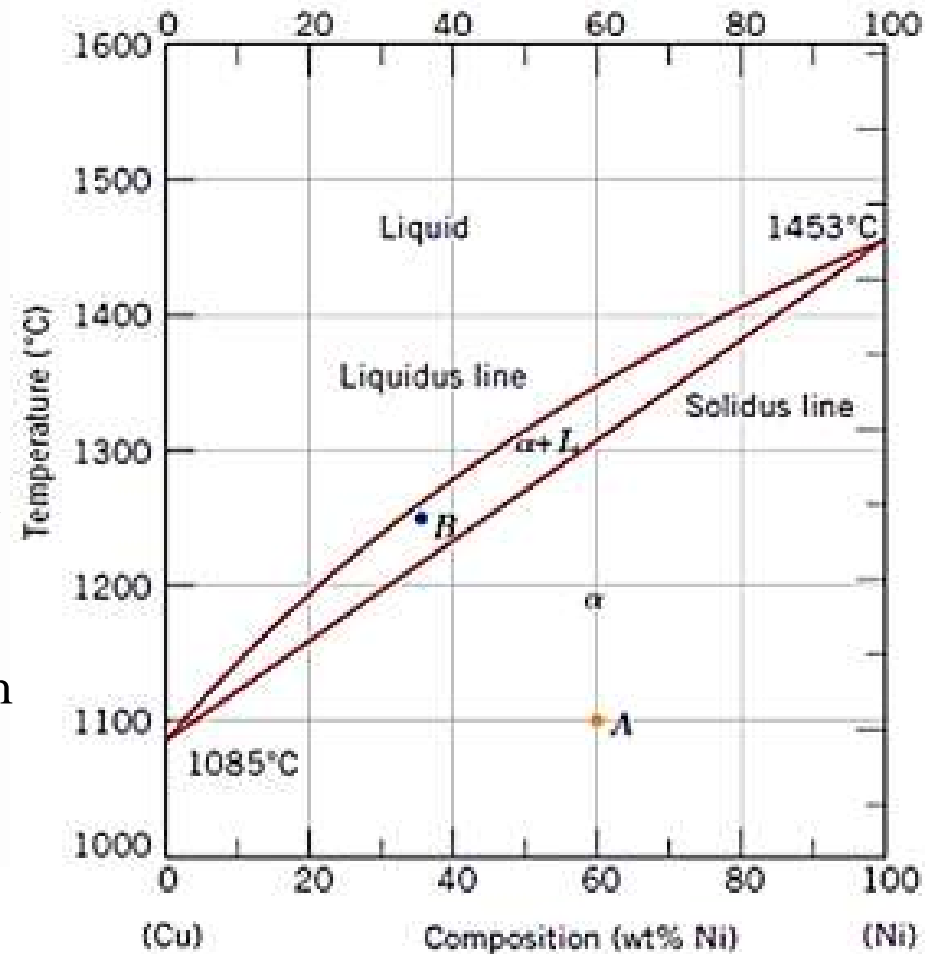
- Series of cooling curves with points corresponding to solid-liquid transition for different metal composition are first constructed.
- Points of change of slope of cooling curves (thermal arrests) are noted and phase diagram is constructed by joining these solid-liquid transition temperatures.
- More the number of cooling curves, more accurate is the phase diagram.
- The curve joining solidification start is called **liquidus** and curve joining all solidification end points is called **solidus** curve



# Classification of binary system

## Isomorphous system

- In alloys, when two components are mixed, they could be completely soluble in the liquid state and the solid state. Such a binary system is called *isomorphous system*.
- Cu-Ni, Ag-Cu, Ge-Si etc., are examples
- Cu-Ni is the simplest among to understand.
- Composition of Ni ranges from 0%-100% from left to right and *vice versa* for copper composition.
- There are three distinct phases which are liquid,  $\alpha$  (solid) phase and two ( $\alpha+L$ ) phase.

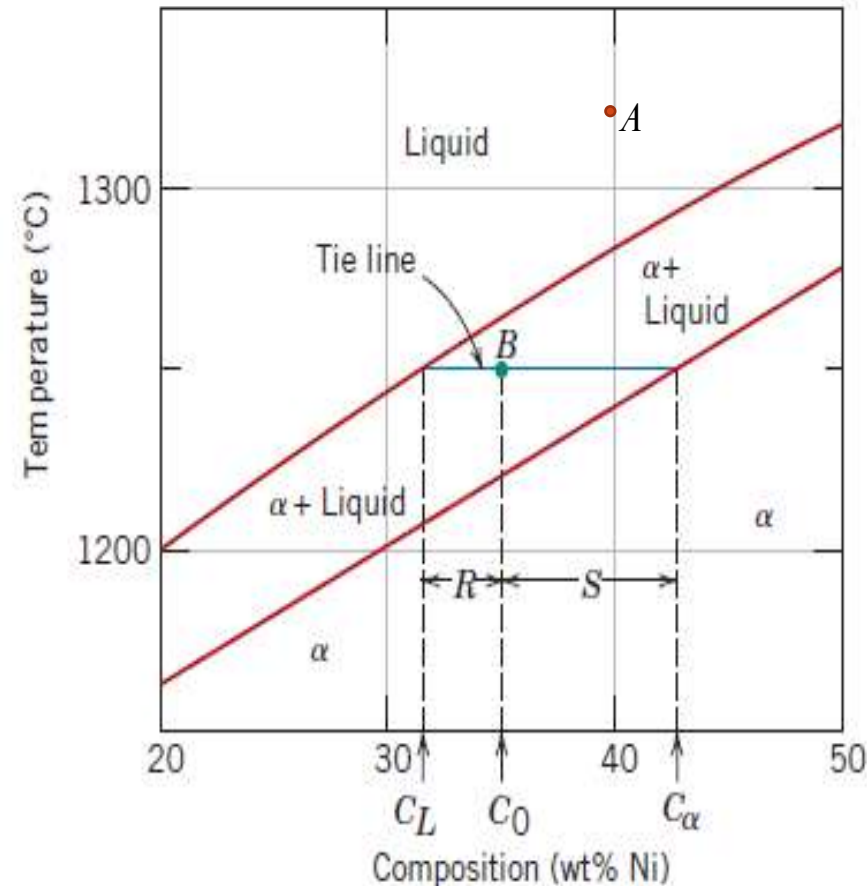


# Interpretation of phase diagrams

- For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available:
  1. The phases that are present,
  2. The compositions of these phases,
  3. The percentages or fractions of the phases.

# Phases Present

- The estimation of what phases are present in a phase diagram is simple.
- One has to locate the temperature–composition point on the diagram, composition of different phases (single or two phase) present can be determined.
- For example, an alloy of composition 60 wt% Ni–40 wt% Cu at 1100°C would be located at point A in **Figure** and only a single phase will be present.



# Determination of Phase Compositions

- The first step in the determination of phase compositions (in terms of the concentrations of the components) is to locate the temperature–composition point on the phase diagram.
- If only one phase is present, the procedure is simple: the composition of this phase is simply the same as the overall composition of the alloy.
- For two-phase regions one has to draw a horizontal line passing through the respective composition and temperature; each of these is line known as a *tie line*, or sometimes as an isotherm.
- These tie lines extend across the two-phase region and terminate at the phase boundary lines on either side.
- To compute the equilibrium concentrations of the two phases, the following procedure is used:
  1. A tie line is constructed across the two-phase region at the temperature of the alloy.
  2. The intersections of the tie line and the phase boundaries on either side are noted.
  3. Perpendiculars are dropped from these intersections to the horizontal composition axis from which the composition of each of the respective phases is



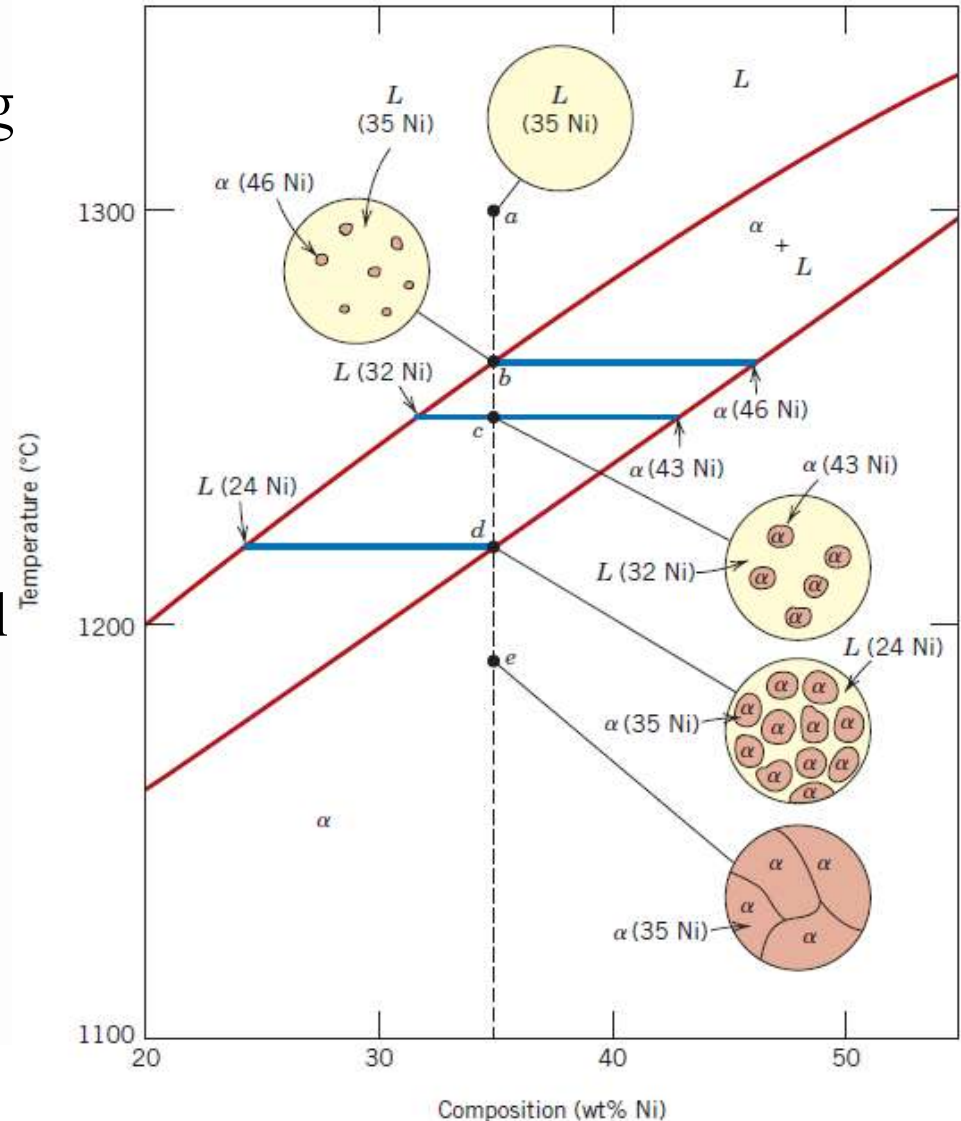
# Determination of Phase Amounts - lever rule

- The relative amounts (as fraction or as percentage) of the phases present at equilibrium can be computed with the help of phase diagrams.
- In a single-phase system: only one phase is present, therefore the phase fraction is 1.0, or as in percentage 100%.
- The tie line must be used, combining with a procedure; the step by step procedure is called the **lever rule** (or the **inverse lever rule**), which is applied as follows:
  1. The tie line is constructed across the two-phase region at the temperature of the alloy.
  2. The overall alloy composition is located on the tie line.
  3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the other phase, and dividing by the total tie line length.
  4. The fraction of the other phase is determined in the same manner.
  5. If phase percentages are desired, each phase fraction is multiplied by 100.
- The phase fractions computed using the lever rule are mass fractions—the mass (or

# Development of microstructure in isomorphous alloys

## Equilibrium Cooling

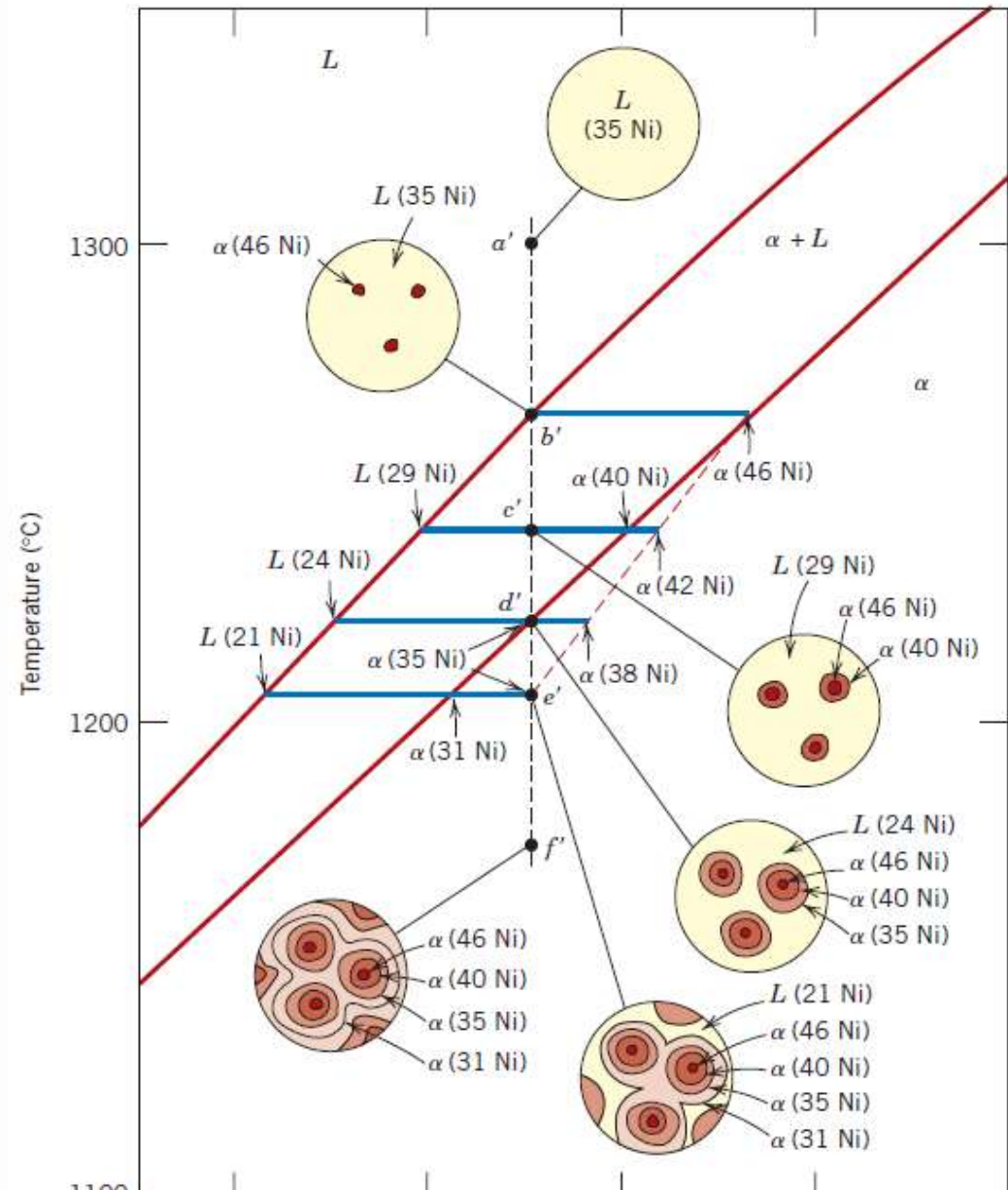
- During equilibrium, the cooling occurs very slowly, and phase equilibrium is continuously maintained.
- Consider the copper–nickel system of composition 35 wt% Ni–65 wt% Cu; and it is cooled from 1300°C.



- Cooling of an alloy of the above composition corresponds to moving down the vertical dashed line.
- At point *a*, the alloy is completely liquid (of composition 35 wt% Ni–65 wt% Cu) and has the microstructure represented by the circle inset in the figure.
- As cooling begins, no microstructural or compositional changes will be present until we reach the liquidus line (point *b*, ).
- At point *b*, the first solid begins to form, which has a composition dictated by the tie line drawn at this temperature [i.e., 46 wt% Ni–54 wt% Cu, noted as (46 Ni)];
- The composition of liquid is still approximately 35 wt% Ni–65 wt% Cu [*L*(35 Ni)], which is different from that of the solid .
- With continued cooling, both compositions and relative amounts of each of the phases will change. The compositions of the liquid and phases will follow the liquidus and solidus lines, respectively.
- Furthermore, the fraction of the phase will increase with continued cooling. Note that the overall alloy composition (35 wt% Ni–65 wt% Cu) remains unchanged during cooling even though there is a redistribution of copper and nickel between the phases.
- At point *c* in Figure 9.4, the compositions of the liquid and phases are 32 wt% Ni–68 wt% Cu [*L*(32 Ni)] and 43 wt% Ni–57 wt% Cu [ (43 Ni)], respectively.
- The solidification process is virtually complete at about point *d*; the composition of the solid is approximately 35 wt% Ni–65 wt% Cu (the overall alloy composition) while that of the last remaining liquid is 24 wt% Ni–76 wt% Cu.
- Upon crossing the solidus line, this remaining liquid solidifies; the final product then is a polycrystalline -phase solid solution that has a uniform 35 wt% Ni–65 wt% Cu composition (point *e*, Figure 9.4).

# Nonequilibrium Cooling

- During nonequilibrium solidification for isomorphous alloys; the distribution of the two elements within the grains is nonuniform.
- A phenomenon termed *segregation*; that is, concentration gradients are established across the grains that are represented by the insets of Figure.
- The center of each grain, which is the first part to freeze, is rich in the high-melting element.

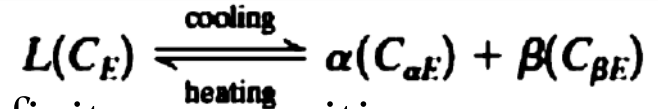


# Coring

- There are some important concerns for isomorphous alloys that have solidified under nonequilibrium conditions.
- As discussed above, the distribution of the two elements within the grains is nonuniform, a phenomenon termed *segregation*; that is, concentration gradients are established across the grains
- The center of each grain, which is the first part to freeze, is rich in the high-melting element (e.g., nickel for this Cu–Ni system), whereas the concentration of the low-melting element increases with position from this region to the grain boundary.
- This formation is called as **coring** and the structure is called as a **cored structure**, which gives rise to less than the optimal properties.
- A casting with a cored structure is reheated, grain boundary regions will melt first, as they are richer in the low-melting component.
- This produces a sudden loss in mechanical integrity due to the thin liquid film that separates the grains.
- Furthermore, this melting may begin at a temperature below the equilibrium solidus temperature of the alloy.
- **Coring** may be eliminated by a homogenization heat treatment carried out at a temperature below the solidus point for the particular alloy composition.

# Eutectic systems

- Binary systems do not show complete solubility.
- Hume-Rothery rules are not ideally obeyed by many pairs of elements.
- This results in two categories of binary systems;
  1. Simple eutectic system in which the components are completely soluble in liquid state while completely insoluble in solid state (simple eutectic).
  2. Eutectic system in which the components are completely soluble in liquid state but limited solubility in the solid state with two terminal solid solutions.



- In a eutectic reaction, a liquid solution with a definite composition solidifies at a fixed temperature to separate solid phases.
- This is an invariant reaction, meaning it occurs at a point having zero degree of freedom.
- In a eutectic system, there is always an alloy of specific composition which solidifies at a fixed lower temperature than the alloys of all other composition.

# Simple eutectic (Alloy insoluble in the solid state )

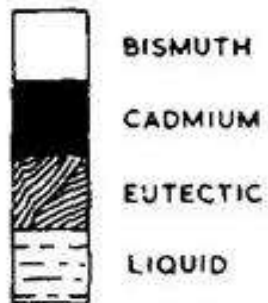
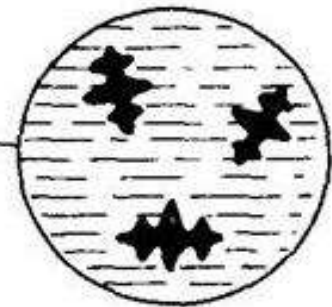
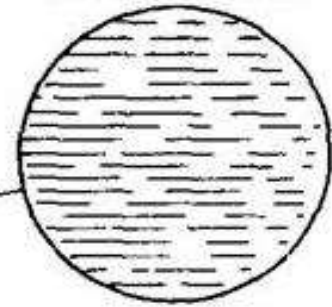
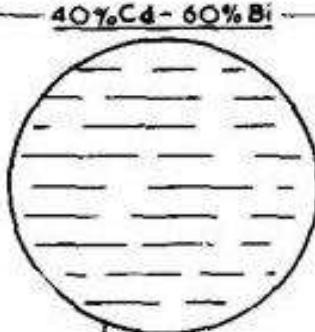
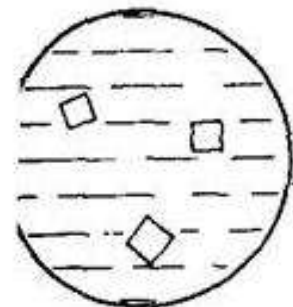
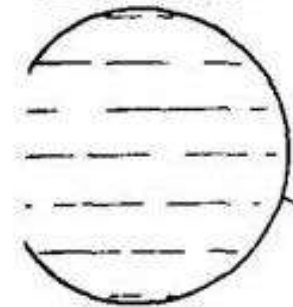
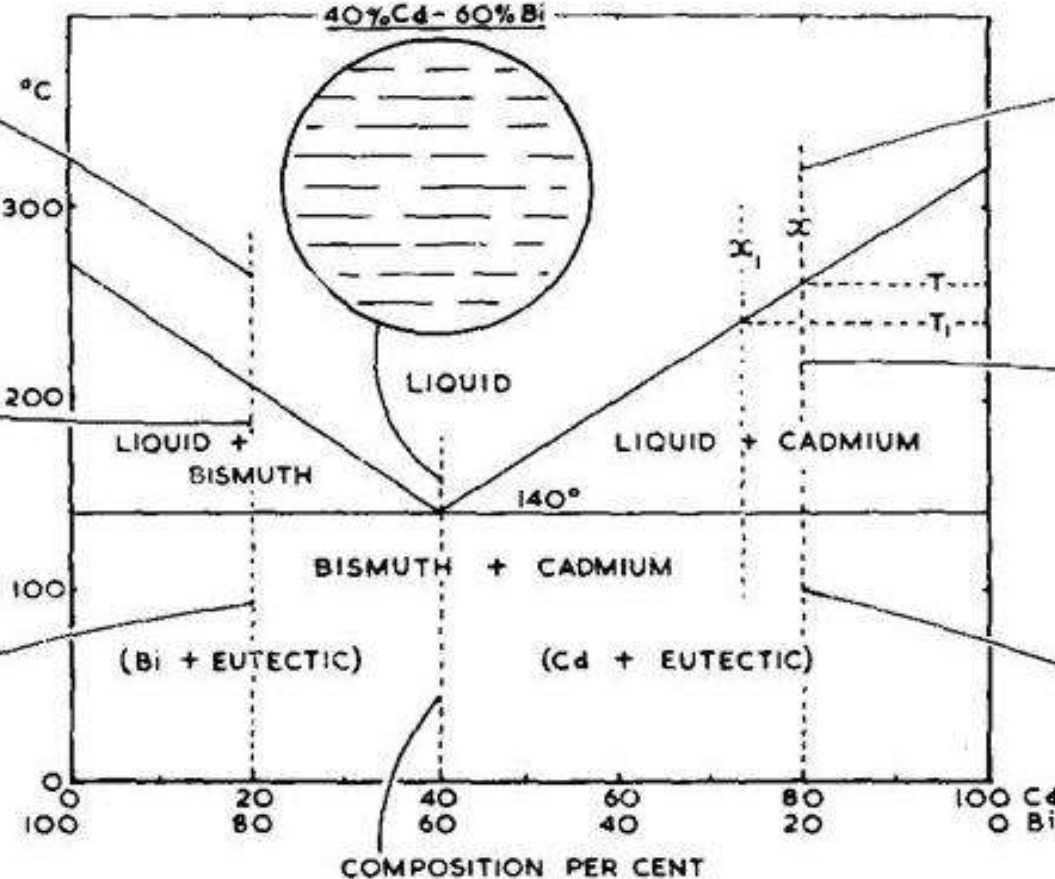
- Phase diagram of Cd-Bi system is an example of simple eutectic type.
- The melting point of Cd comes down with the addition of Bi and vice-versa.
- The liquidus line of both the components intersect at a point called *eutectic point*.
- The composition of alloy corresponding to this point is called as the eutectic composition.
- Eutectic alloy is cooled below eutectic temperature, microstructure consists of alternate solid layers of Cd and Bi.
- Solute concentration less than eutectic composition are called **hypoeutectic alloys** and those having other compositions are called as **hypereutectic alloys**.
- The microstructure development in all these cases is similar to that of alloy with limited solubility.



20% Cd - 80% Bi

80% Cd - 20% Bi

40% Cd - 60% Bi

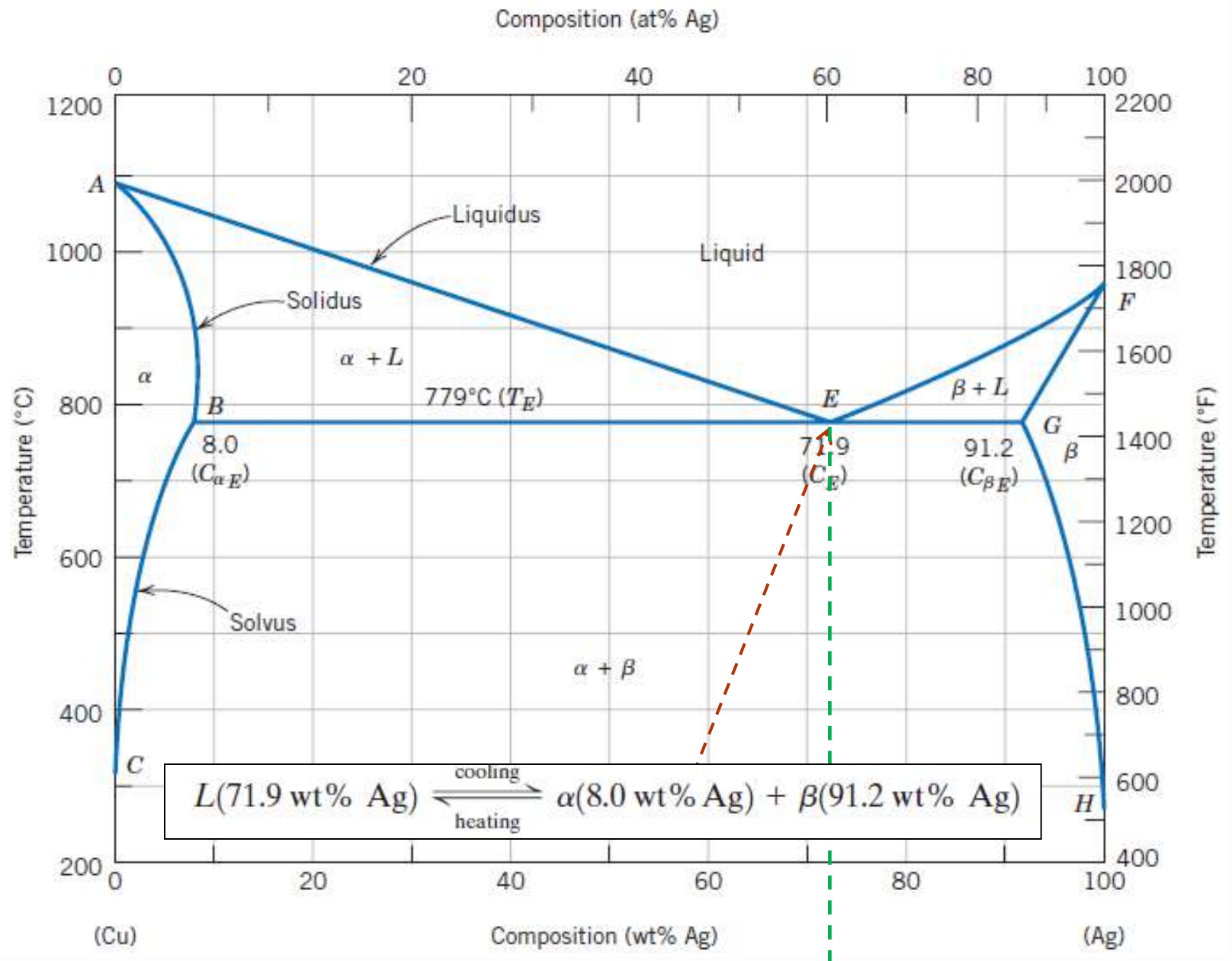


THE RELATIVE RICHNESS OF THE LIQUID PHASE IN CADMIUM IS INDICATED BY THE DISTANCE APART OF THE SHADING LINES.



# BINARY EUTECTIC SYSTEMS

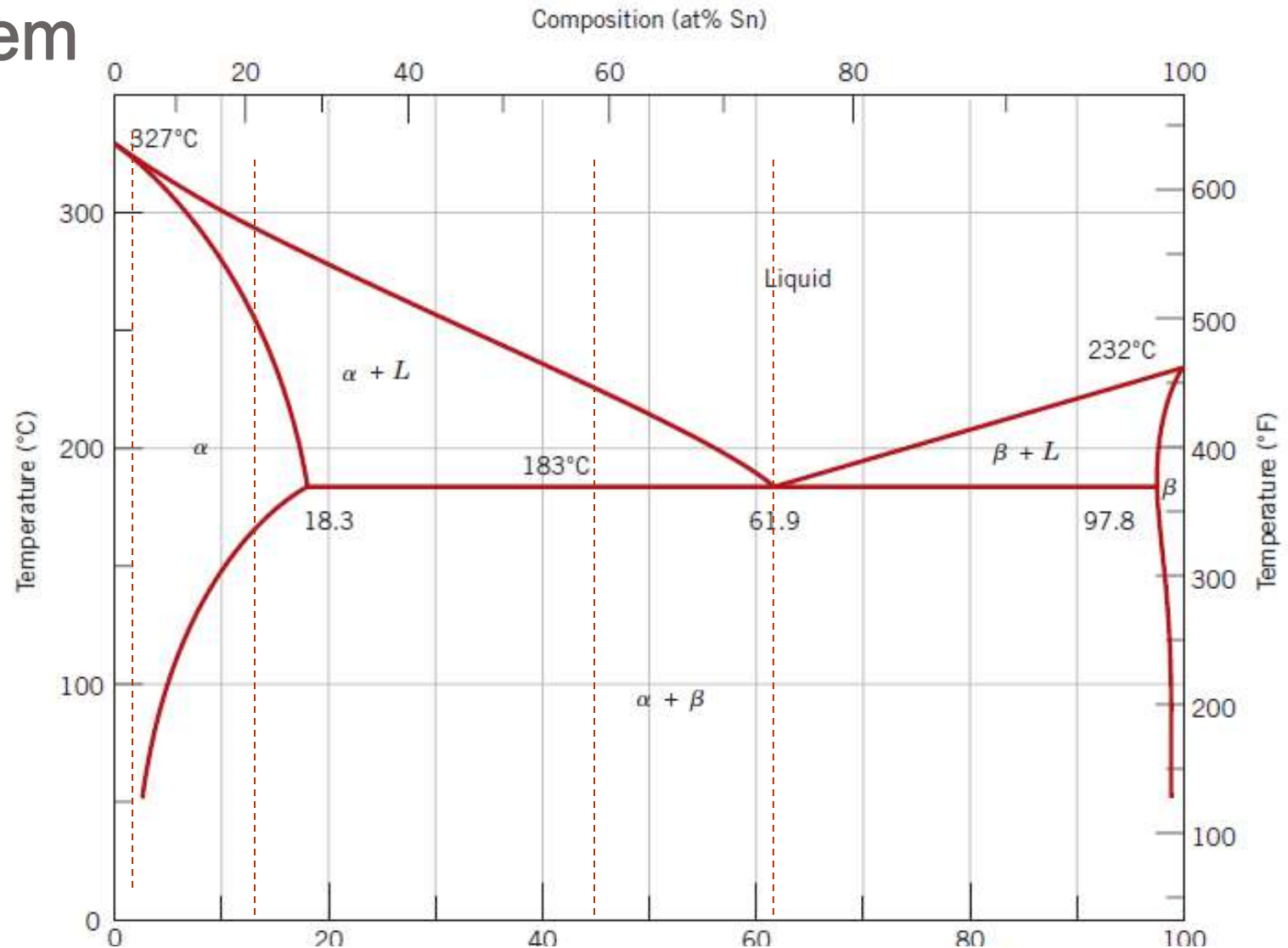
- Another type of common and relatively simple phase diagram found for binary alloys is observed for the copper–silver system; this is known as a binary eutectic phase diagram.
- A number of features of this phase diagram are important and worth noting. First, three single-phase regions are found on the diagram:  $\alpha$ ,  $\beta$  and liquid.
- The  $\alpha$  phase is a solid solution rich in copper; it has silver as the solute component and an FCC crystal structure.
- The  $\beta$ -phase solid solution also has an FCC structure, but copper is the solute. Pure copper and pure silver are also considered to be  $\alpha$  and  $\beta$  phases, respectively.
- Thus, the solubility in each of these solid phases is limited, in that at any temperature below line BEG only a limited concentration of silver will dissolve in copper (for the  $\alpha$  phase), and similarly for copper in silver (for the  $\beta$  phase).
- The solubility limit for the  $\alpha$  phase corresponds to the boundary line, labeled CBA, between  $\alpha$  and ( $\alpha + \beta$ ) and  $\alpha$  and ( $\alpha + L$ ) phase regions.

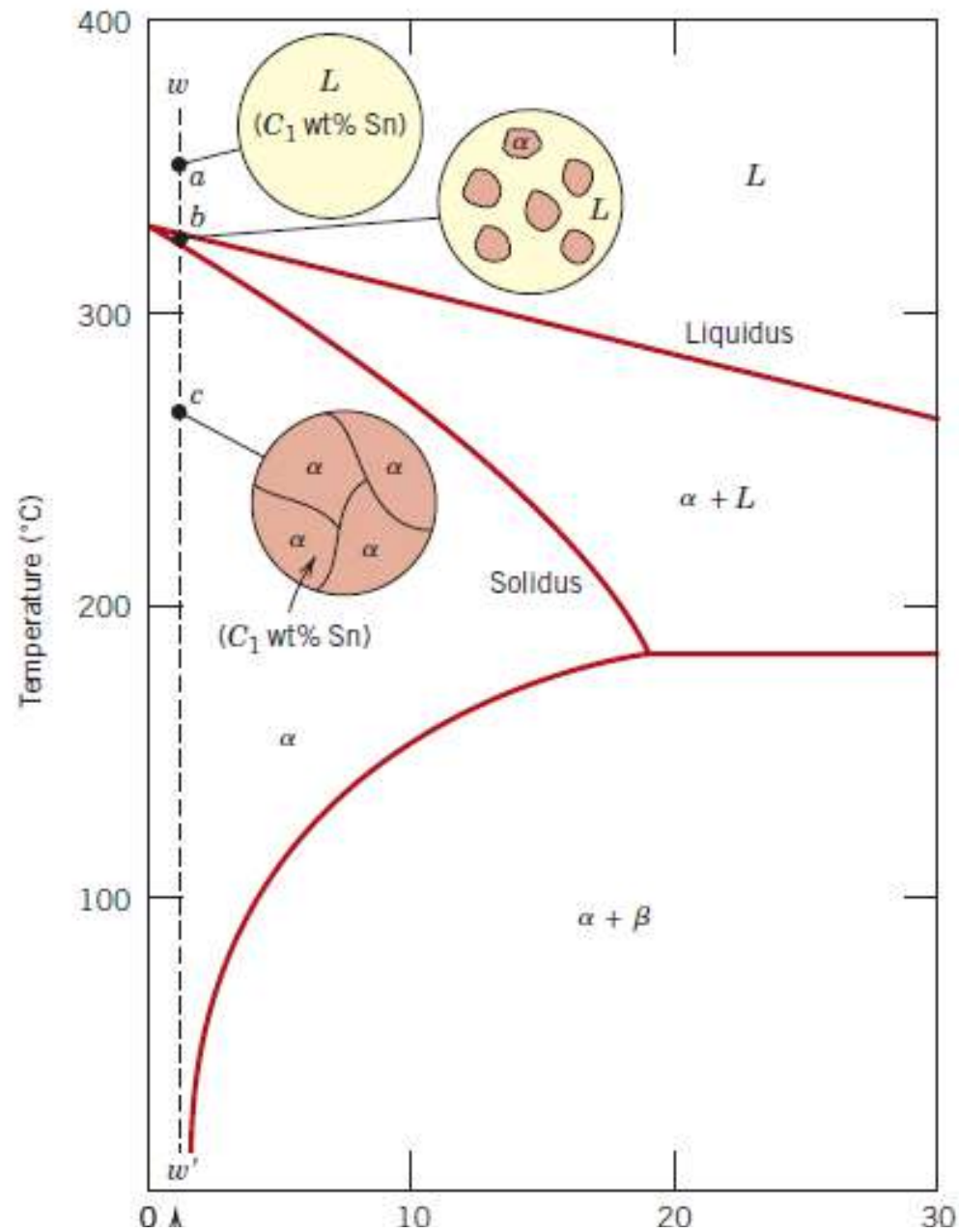


# BINARY EUTECTIC SYSTEMS

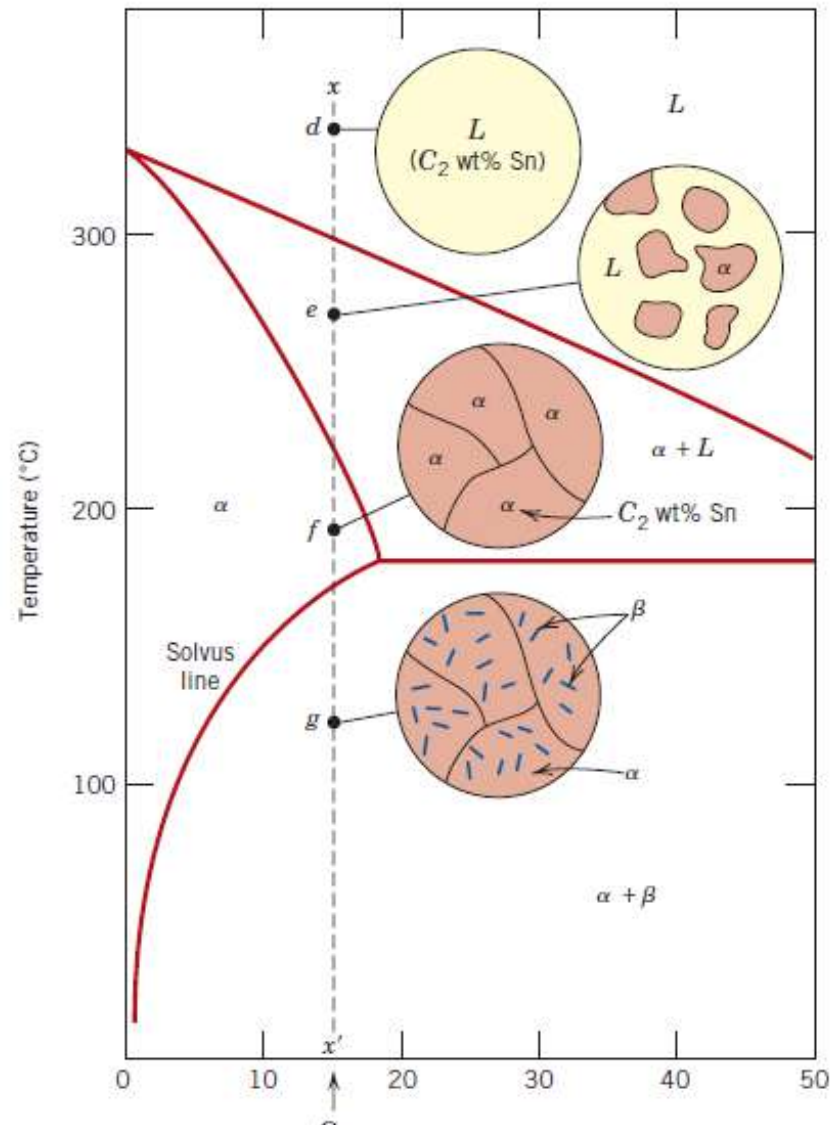
- Liquidus line shows that as the silver is added to copper, the melting temperature of the alloy decreases.
- The same is true for silver, as copper is added.
- The alloy with lowest melting point is the one where both the liquidus lines meet.

# Development of microstructure in eutectic system





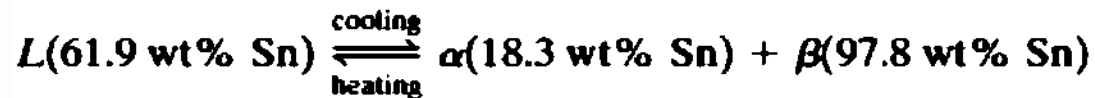
- The first case is for compositions ranging between a pure component and the maximum solid solubility for that component at room temperature [20°C].
- For the lead–tin system, this includes lead-rich alloys containing between 0 and about 2 wt% Sn (for the phase solid solution), and also between approximately 99 wt% Sn and pure tin (for the  $\beta$  phase).
- Consider an alloy of composition C1 as it is slowly cooled from a temperature within the liquid-phase region, say, 350°C this corresponds to moving down the dashed vertical line  $ww'$  in the figure.
- The alloy remains totally liquid and of composition until we cross the liquidus line at approximately at which time the solid  $\alpha$  phase begins to form.
- While passing through this narrow  $\alpha+L$  phase region solidification proceeds in the same manner as was described for the copper–nickel alloy in the preceding section; that is, with continued cooling more of the solid a forms.
- Furthermore, liquid- and solid-phase compositions are different, which follow along the liquidus and solidus phase boundaries, respectively.
- Solidification reaches completion at the point where  $ww'$  crosses the solidus line. The resulting alloy is polycrystalline with a uniform composition of C1, and no subsequent



- The second case considered is for compositions that range between the room temperature solubility limit and the maximum solid solubility at the eutectic temperature.
- For the lead–tin system, these compositions extend from about 2 wt% Sn to 18.3 wt% Sn (for lead-rich alloys) and from 97.8 wt% Sn to approximately 99 wt% Sn (for tin-rich alloys).
- Let us examine an alloy of composition as it is cooled along the vertical line  $xx'$ .
- Down to the intersection of  $xx'$  and the solvus line, changes that occur are similar to the previous case, as we pass through the corresponding phase regions (as demonstrated by the insets at points d, e, and f).
- Just above the solvus intersection, point f, the microstructure consist of  $\alpha$  grains of composition C2.
- Upon crossing the solvus line, the  $\alpha$  solid solubility is exceeded, which results in the formation of small  $\beta$ -phase particles; these are indicated in the microstructure inset at point g.
- With continued cooling, these particles will grow in size because the mass fraction of the  $\beta$  phase increases slightly with decreasing temperature.

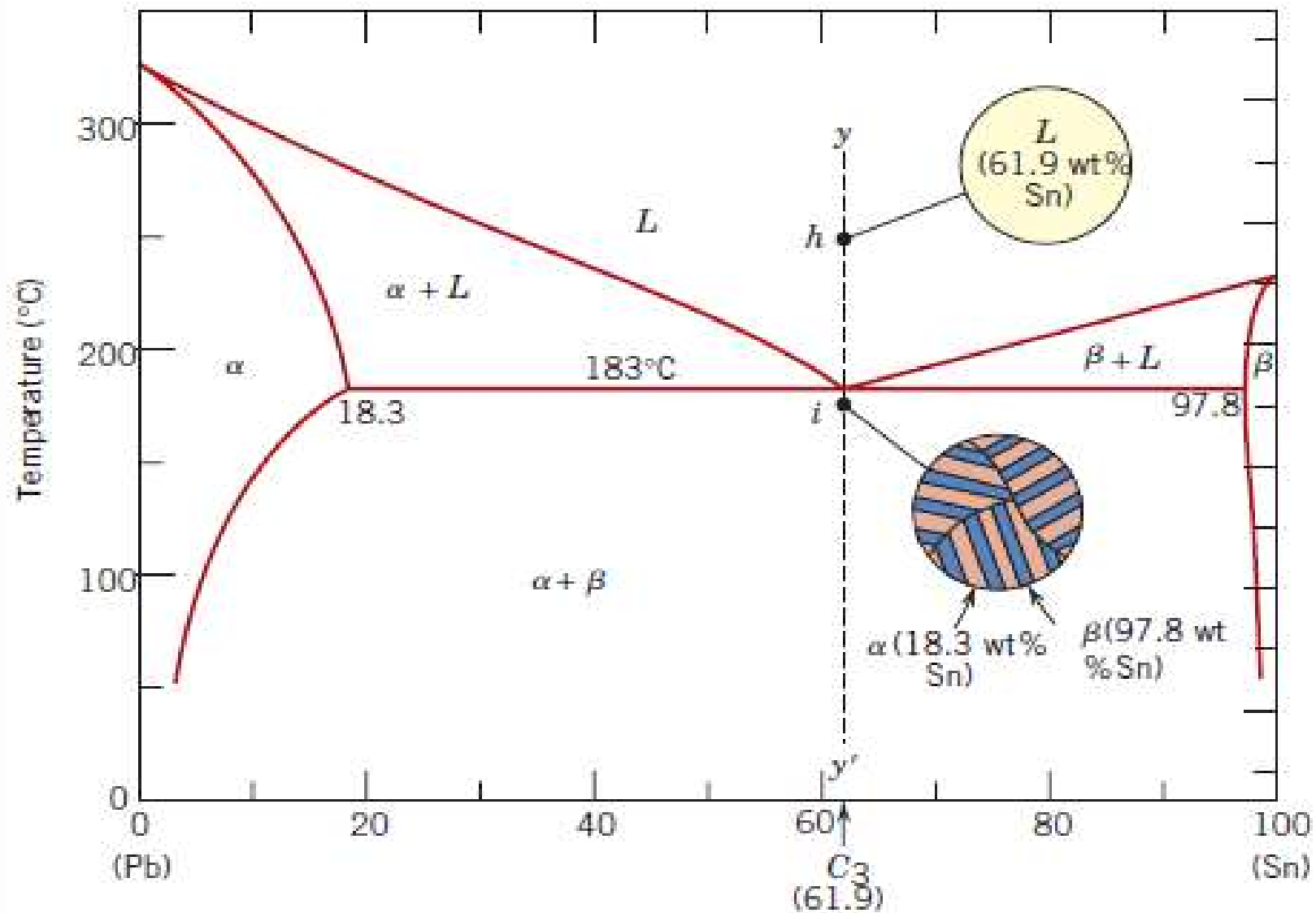


- The solidification at eutectic composition, 61.9 wt% Sn (C3).
- Consider an alloy having this composition that is cooled from a temperature within the liquid-phase region (e.g., 250°C) down the vertical line yy' in which the  $\alpha$ - and  $\beta$ -phase compositions are determined by the eutectic isotherm end points.
- During this transformation, there must necessarily be a redistribution of the lead and tin components, inasmuch as the  $\alpha$  and  $\beta$  phases have different compositions neither of which is the same as that of the liquid.
- This redistribution is accomplished by atomic diffusion.
- The microstructure of the solid that results from this transformation consists of alternating layers (sometimes called lamellae) of the  $\alpha$  and  $\beta$  phases that form simultaneously during the transformation.
- **This structure is called eutectic structure** and is characteristic of this reaction

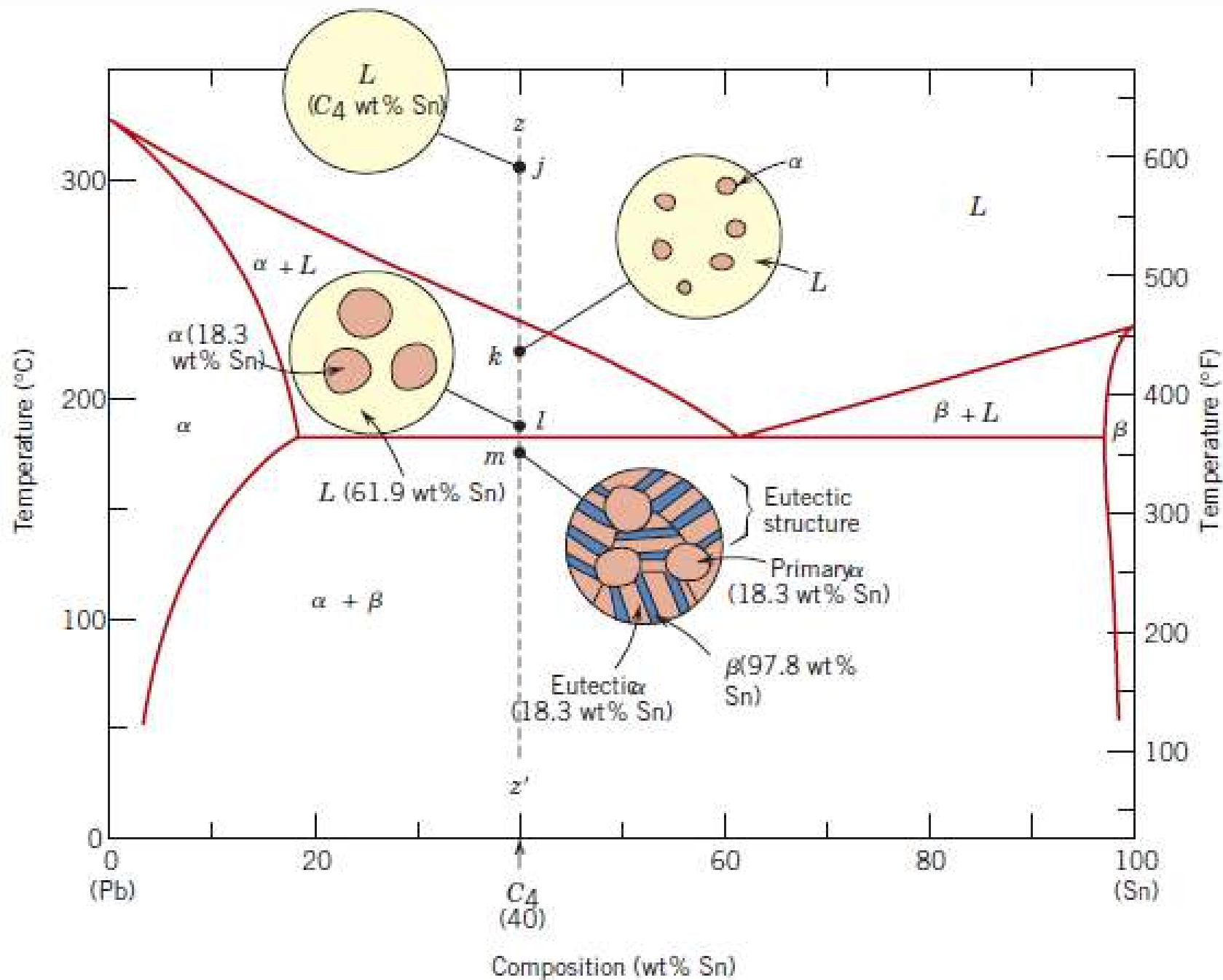


- In eutectic transformation,  $\alpha$ - $\beta$  layered eutectic growing into and replacing the liquid phase.
- The process of the redistribution of lead and tin occurs by diffusion in the liquid just ahead of the eutectic–liquid interface. T
- The eutectic structure forms in these alternating layers because, for this lamellar

61.9 wt% Sn 18.3 wt% Sn 97.8 wt% Sn



- The microstructural case for system with all compositions other than the eutectic that, when cooled, cross the eutectic isotherm.
- Consider, the composition C4 lies to the left of the eutectic; as the temperature is lowered, we move down the line  $zz'$ , beginning at point j.
- The microstructural development between points j and l is similar to that for the second case, such that just prior to crossing the eutectic isotherm (point l), the  $\alpha$  and liquid phases are present having compositions of approximately 18.3 and 61.9 wt% Sn, respectively, as determined from the appropriate tie line.
- As the temperature is lowered to just below the eutectic, the liquid phase, which is of the eutectic composition, will transform to the eutectic structure (i.e., alternating  $\alpha$  and  $\beta$  lamellae); insignificant changes will occur with the  $\alpha$  phase that formed during cooling.



# Invariant reaction

- This is an invariant reaction, meaning it occurs at a point having zero degree of freedom.
- Invariant reactions involve three phases; also known as three phase reactions.
- This type of reactions happen along horizontal lines
- These reactions take place at a constant composition and temperature.
  - Peritectic reaction
  - Eutectoid reaction
  - Peritectoid reaction
  - Monotectic reaction

# Peritectic reaction

- Peritectic reaction occurs when a **liquid and a solid react to form a solid** at a constant temperature.
- Peritectic reaction can lead to non-equilibrium solidification and segregation.
- Peritectic reaction occurs when there is a large difference in the melting point of the components.



# Peritectoid reaction

- The **peritectoid reaction** is another invariant reaction involving three phases at equilibrium.
- With this reaction, during cooling, two solid phases transform to a single another solid phase.



# Eutectoid reaction

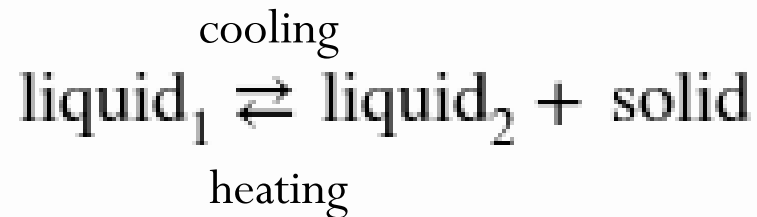
- A **eutectoid reaction** is a three-phase **reaction** by which, on cooling, a solid transforms into two other solid phases at the same time.
- It has the structure having alternate layers of phases resembles the eutectic structure.
- A complete solid state reaction; reverse on heating
- Observed in Fe-C, Cu-Zn and Al-Cu





# Monotectic reaction

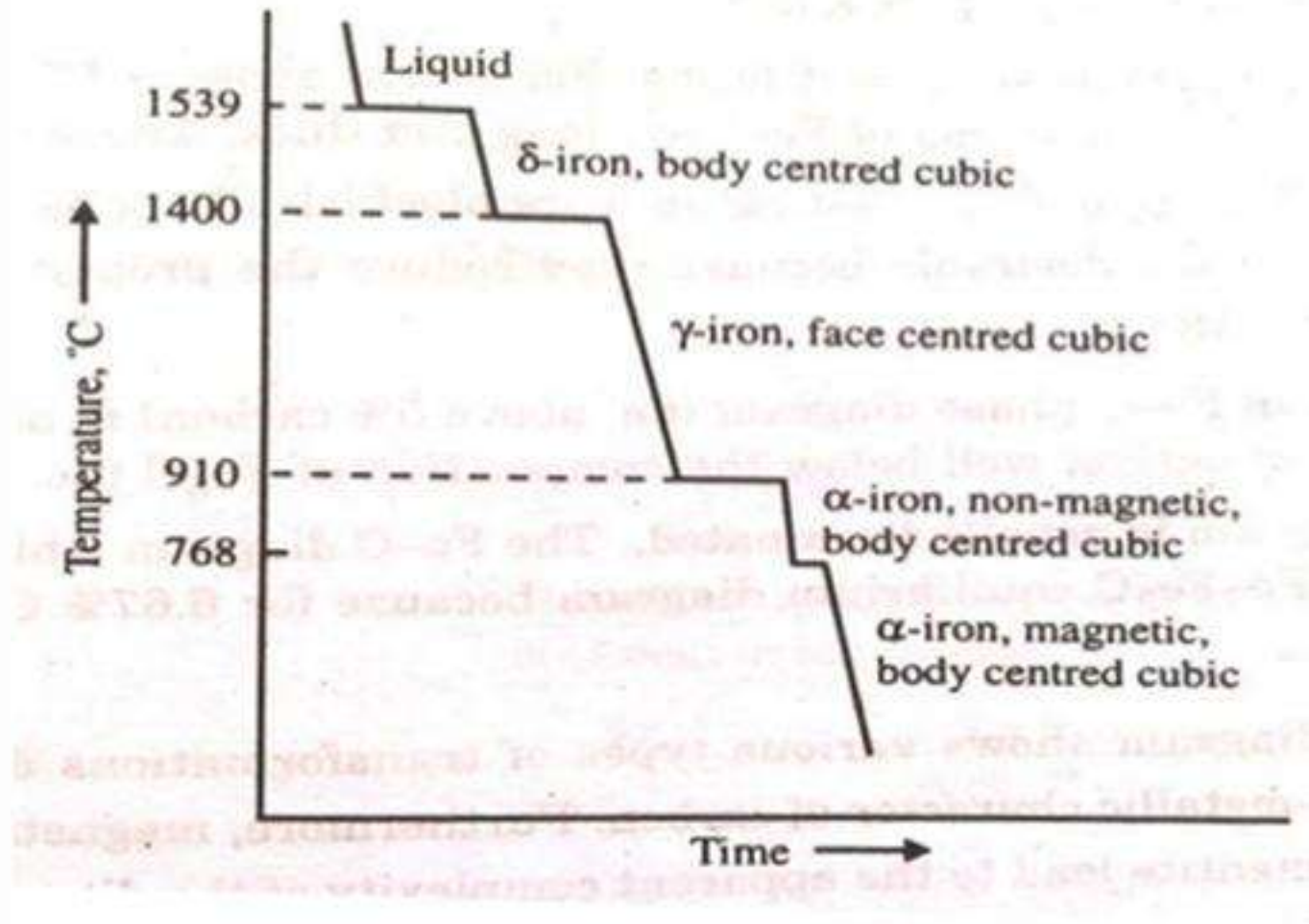
- A liquid phase transform into another liquid phase of a different composition and a new solid precipitates out.



# Iron-carbon phase diagram

- The most important binary alloy system is that of iron and carbon.
- The primary engineering materials; steel and cast iron are alloys of iron and carbon.
- The relative advantages of steel are;
  - Cheap and readily available
  - Provides a range of mechanical properties
  - Properties can be improved by the addition of other elements in small quantities.
  - It responds to heat treatment and any desired combination of strength and ductility can be obtained.
  - Good machinability and weldability.

# Allotropic forms of iron

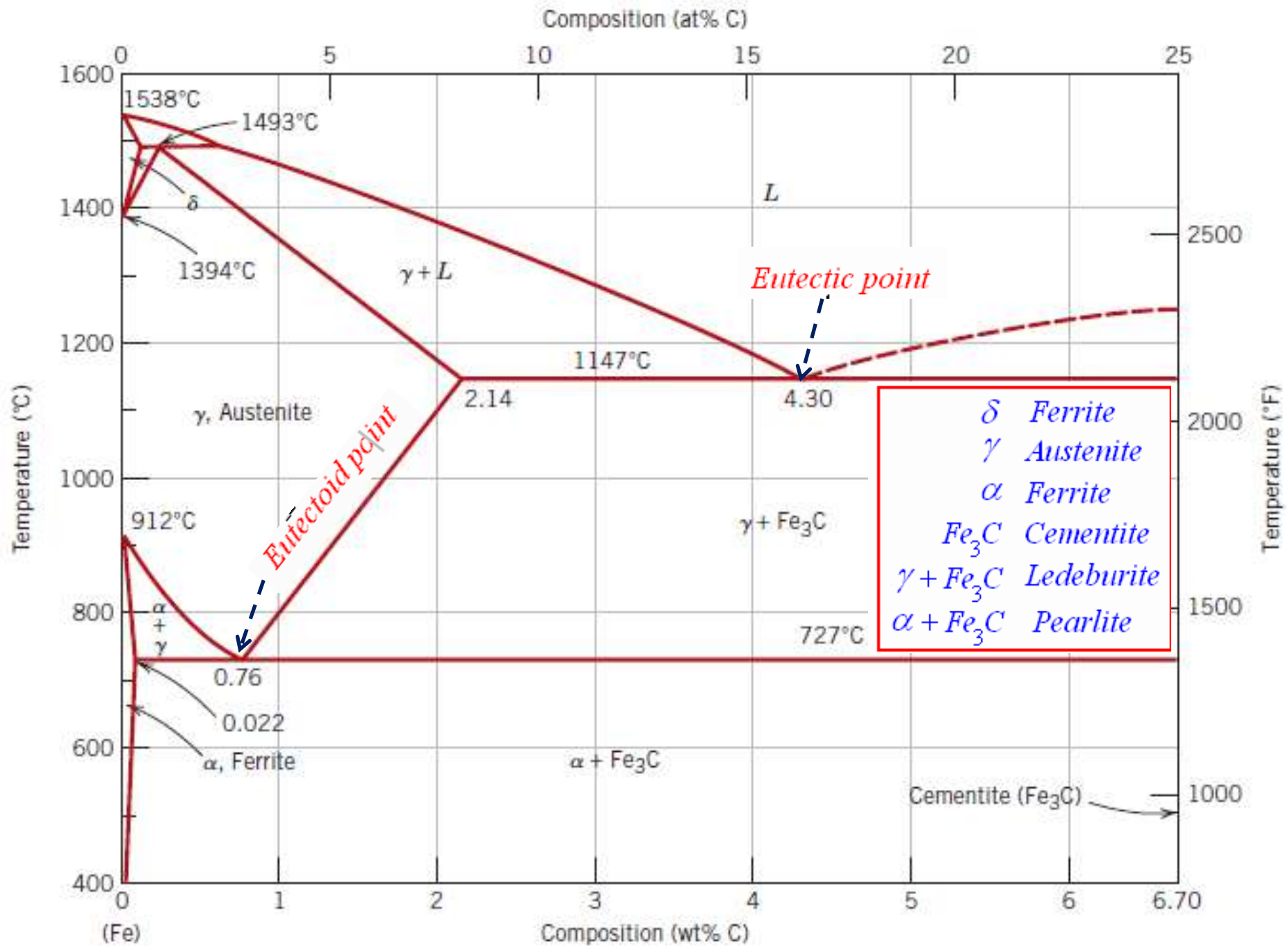


# Allotropic forms of iron

- Pure iron exist in more than one crystal structure in solid state.
- Soft iron is the best known example for allotropy of iron, which can be strengthened/hardened by adding small amount of other metals.
- Addition of carbon to soft iron can increase the hardness of soft iron by 1000 times, the alloy is called as steel.
- There are three allotropic forms of carbon  $\alpha$  (BCC),  $\gamma$  (FCC), and  $\delta$  (BCC)
- When liquid iron is cooled down, it crystallizes at 1538 °C to  $\delta$  (BCC) iron.
- Upon further cooling, the crystal structure gets converted to  $\gamma$  (FCC) at 1394 °C.
- The crystal structure changes into  $\alpha$ -phase (BCC) at 912°C .

# Iron carbon alloys

- Family of iron carbon alloys having carbon content upto 2.14% is called as steel.
- Steels are solid solutions of iron and carbon
- If the carbon content is more than 2.14% then it is called as cast iron.
- In cast irons most of the carbon exists as inter metallic compound, iron carbide.
- In phase diagram, the allotropic forms of iron forms different solid solutions which also can be considered as phases.
- The intermetallic compound, iron carbide, is also a phase present in the system.



# Iron-carbon phase diagram

- The iron–carbon system may be divided into two parts: an iron-rich portion, and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite).
- In practice, all steels and cast irons have carbon contents less than 6.70 wt% C;
- Since, iron-carbon forms the intermetallic compound, iron carbide, this phase diagram is also called as iron–iron carbide phase diagram; and  $\text{Fe}_3\text{C}$  is a components here.
- Even though the phase diagram has carbon percentage up to 6.67%, it is the complete phase diagram of Fe- $\text{Fe}_3\text{C}$ .
- In this phase diagram, there are 11 different phase regions separated by phase boundaries.
- There are 5 phases and 3 invariant reactions along the horizontal lines.

- Pure iron, upon heating, experiences two changes in crystal structure before it melts.
- At room temperature the stable form, called ferrite, or  $\alpha$  iron, has a BCC crystal structure.
- Ferrite experiences a polymorphic transformation to FCC austenite ( $\gamma$ ) iron, at  $912^{\circ}\text{C}$ .
- This austenite phase remains up to  $1394^{\circ}\text{C}$ , at this temperature the FCC austenite reverts back to a BCC phase known as  $\delta$  ferrite, which finally melts at  $1538^{\circ}\text{C}$ .
- All these solutions are interstitial solid solutions.
- $\delta$  ferrite exist only in the temperature range  $1394\text{-}1538^{\circ}\text{C}$ .
- The maximum solubility of carbon in  $\delta$  ferrite is  $0.09\text{ wt}\%$ , does not have much significance as it exist at high temperature.

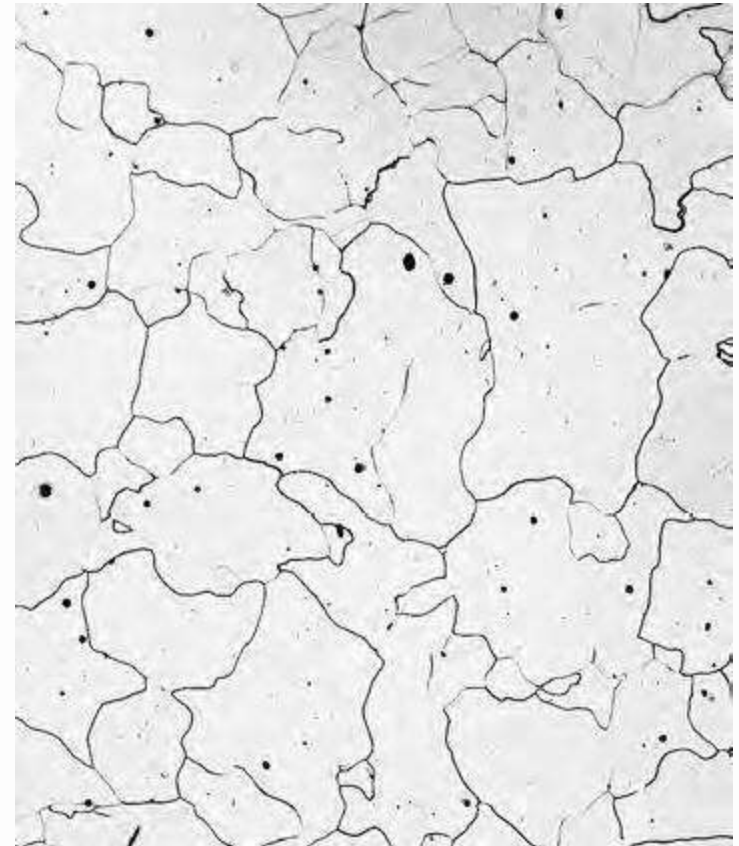


# Five individual phases

- ✓  $\alpha$ -ferrite (BCC) Fe-C solid solution
- ✓  $\gamma$ -austenite (FCC) Fe-C solid solution
- ✓  $\delta$ -ferrite (BCC) Fe-C solid solution
- ✓  $\text{Fe}_3\text{C}$  (Iron Carbide) *or* cementite –
  - ✓ an inter-metallic compound
- ✓ Liquid Fe-C solution

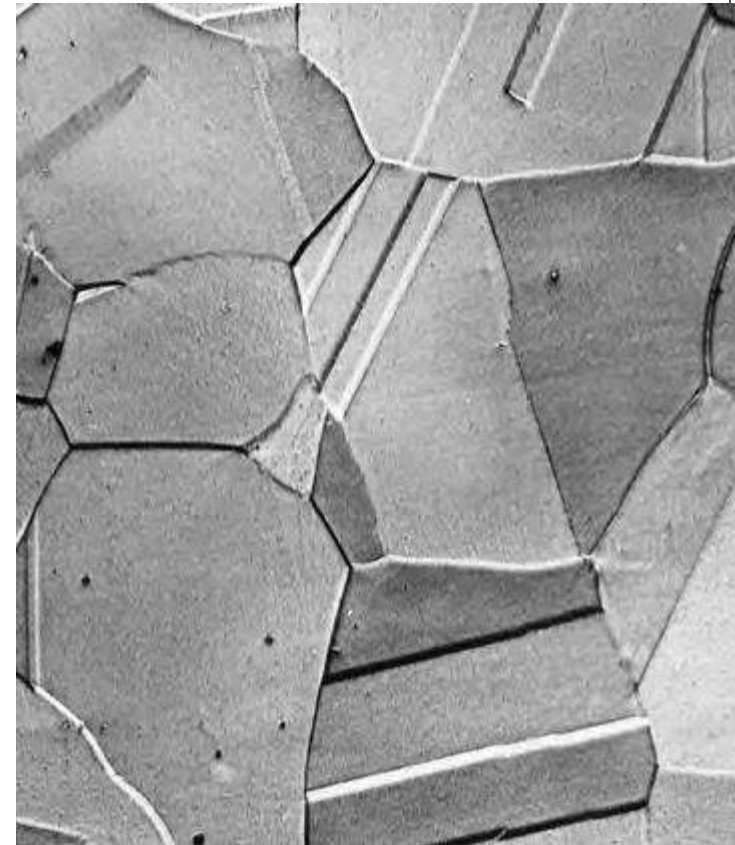
# $\alpha$ ferrite

- BCC  $\alpha$  ferrite is also an interstitial solid solution of carbon in BCC iron.
- In the BCC  $\alpha$  ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727°C and at room temperature it is reduced to 0.008%.
- The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms.
- Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite.
- This particular iron–carbon phase is relatively soft, may be made magnetic at



# Austenite

- The austenite, or  $\gamma$  phase of iron (FCC), when alloyed with carbon alone, is not stable below  $727^{\circ}\text{C}$ .
- The maximum solubility of carbon in austenite, 2.14 wt%, occurs at  $1147^{\circ}\text{C}$ . This solubility is approximately 100 times greater than the maximum for BCC ferrite.
- Stable between  $912$ - $1394^{\circ}\text{C}$
- The FCC interstitial positions are larger, and, therefore, the strains imposed on the surrounding iron atoms are much lower.
- The phase transformations involving austenite are very important in the heat treating of steels.
- Austenite is non-magnetic.
- The  $\alpha$  and  $\delta$  ferrite is virtually the same as ferrite, except for the range of temperatures

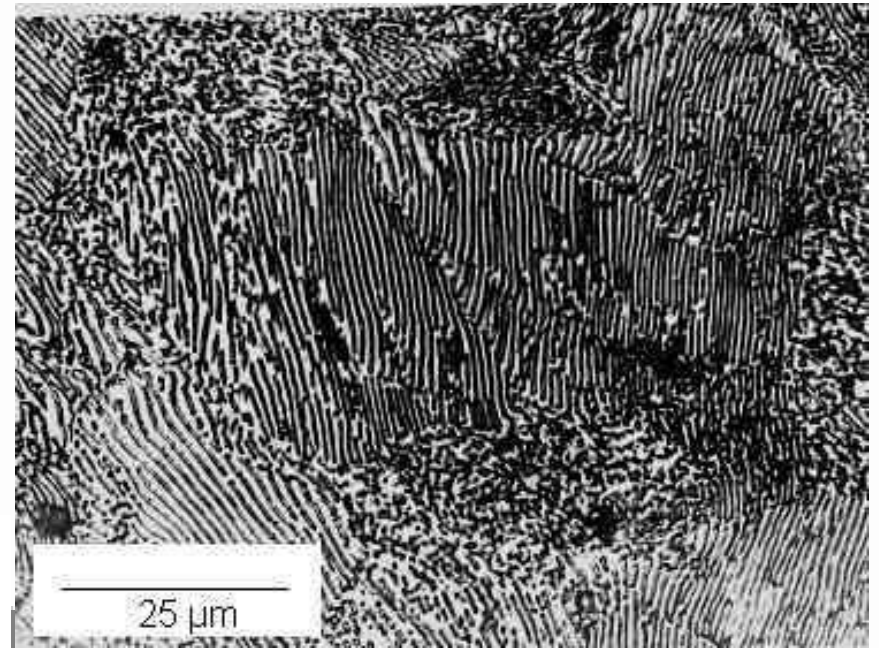


# Cementite or $\text{Fe}_3\text{C}$ or iron carbide

- Cementite ( $\text{Fe}_3\text{C}$ ) forms when the solubility limit of carbon in ferrite is exceeded 0.002% below  $727^\circ\text{C}$  (for compositions within the  $\alpha + \text{Fe}_3\text{C}$  phase region).
- $\text{Fe}_3\text{C}$  will also coexist with the phase between  $727$  and  $1147^\circ\text{C}$ ).
- Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.
- Strictly speaking, cementite is only metastable; that is, it will remain as a compound indefinitely at room temperature.
- However, if heated to between  $650$  and  $700^\circ\text{C}$  for several years, it will gradually change or transform into a iron and carbon, in the form of graphite, which will remain upon subsequent cooling to room temperature.
- It may be noted that one eutectic exists for the iron–iron carbide system, at 4.30 wt% C and  $1147^\circ\text{C}$ ; the eutectic reaction is,

# Pearlite structure

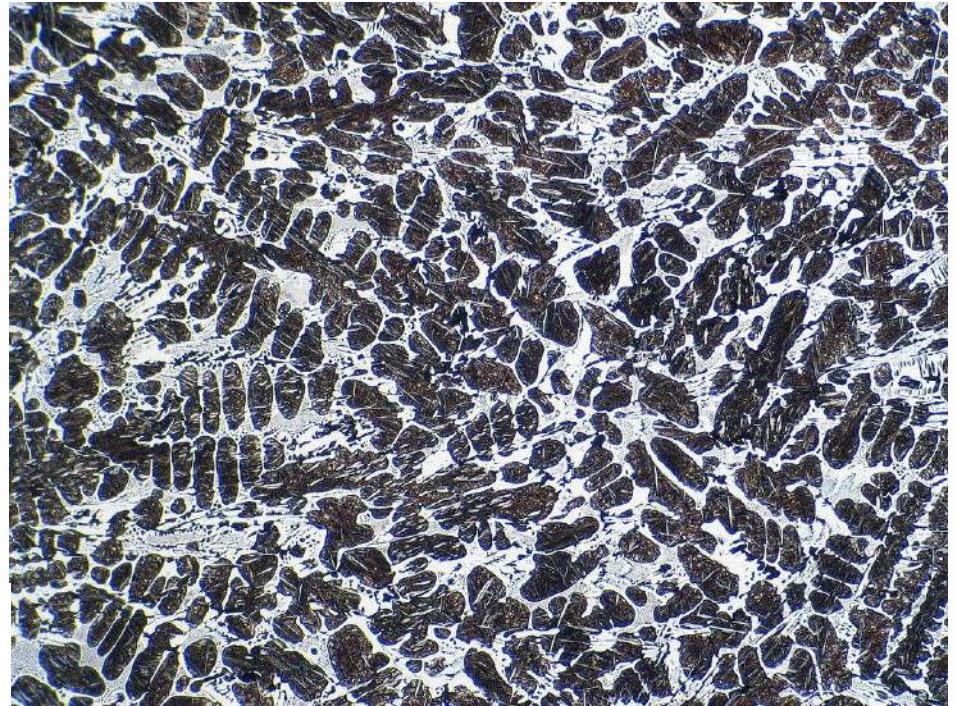
- ✓ A laminated structure formed of alternate layers of ferrite and cementite with average composition 0.83% carbon
- ✓ Pearly lustre in the microscope
  - ✓ Interference of light in its regular layers
- ✓ Most common constituent of steel
- ✓ It combines the hardness and strength of cementite with the ductility of ferrite and is the key to the wide range of the properties of steels.
- ✓ The laminar structure also acts as a barrier to crack movement as in composites. This gives it toughness.





# ledeburite

- **ledeburite** is a mixture of 4.3% carbon in iron and is a eutectic mixture of austenite and cementite.

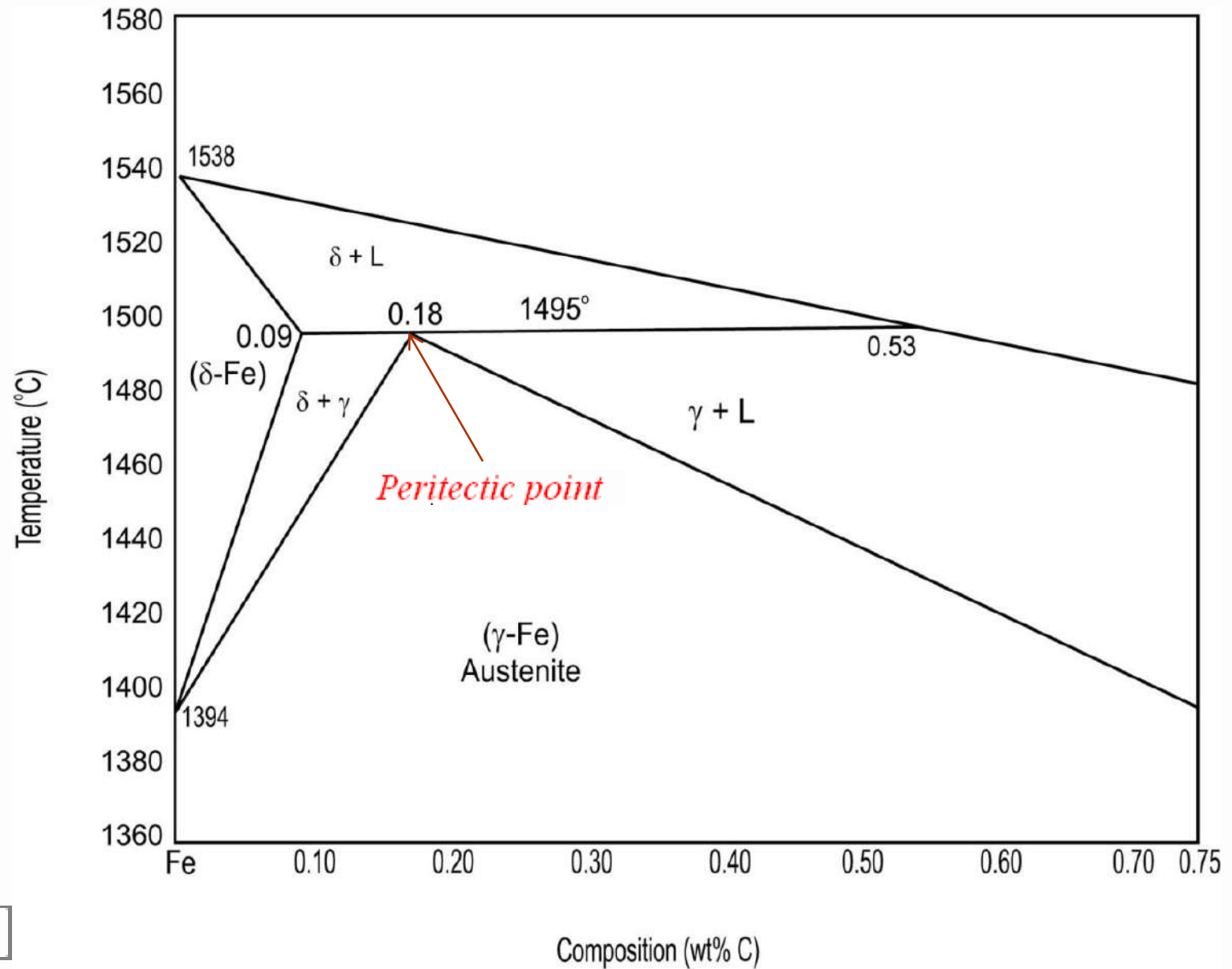


# Invariant reactions

A horizontal line always indicates an invariant reaction in binary phase diagrams

- ❑ Peritectic reaction at  $1495^{\circ}\text{C}$  and  $0.18\%\text{C}$ ,
  - $\delta\text{-ferrite} + L \leftrightarrow \gamma\text{-iron (austenite)}$
- ❑ Eutectic reaction at  $1147^{\circ}\text{C}$  and  $4.3\%\text{C}$ ,
  - $L \leftrightarrow \gamma\text{-iron} + \text{Fe}_3\text{C (cementite) [ledeburite]}$
- ❑ Eutectoid reaction at  $727^{\circ}\text{C}$  and  $0.77\%\text{C}$ ,
  - $\gamma\text{-iron} \leftrightarrow \alpha\text{-ferrite} + \text{Fe}_3\text{C (cementite) [pearlite]}$

# Peritectic Reaction



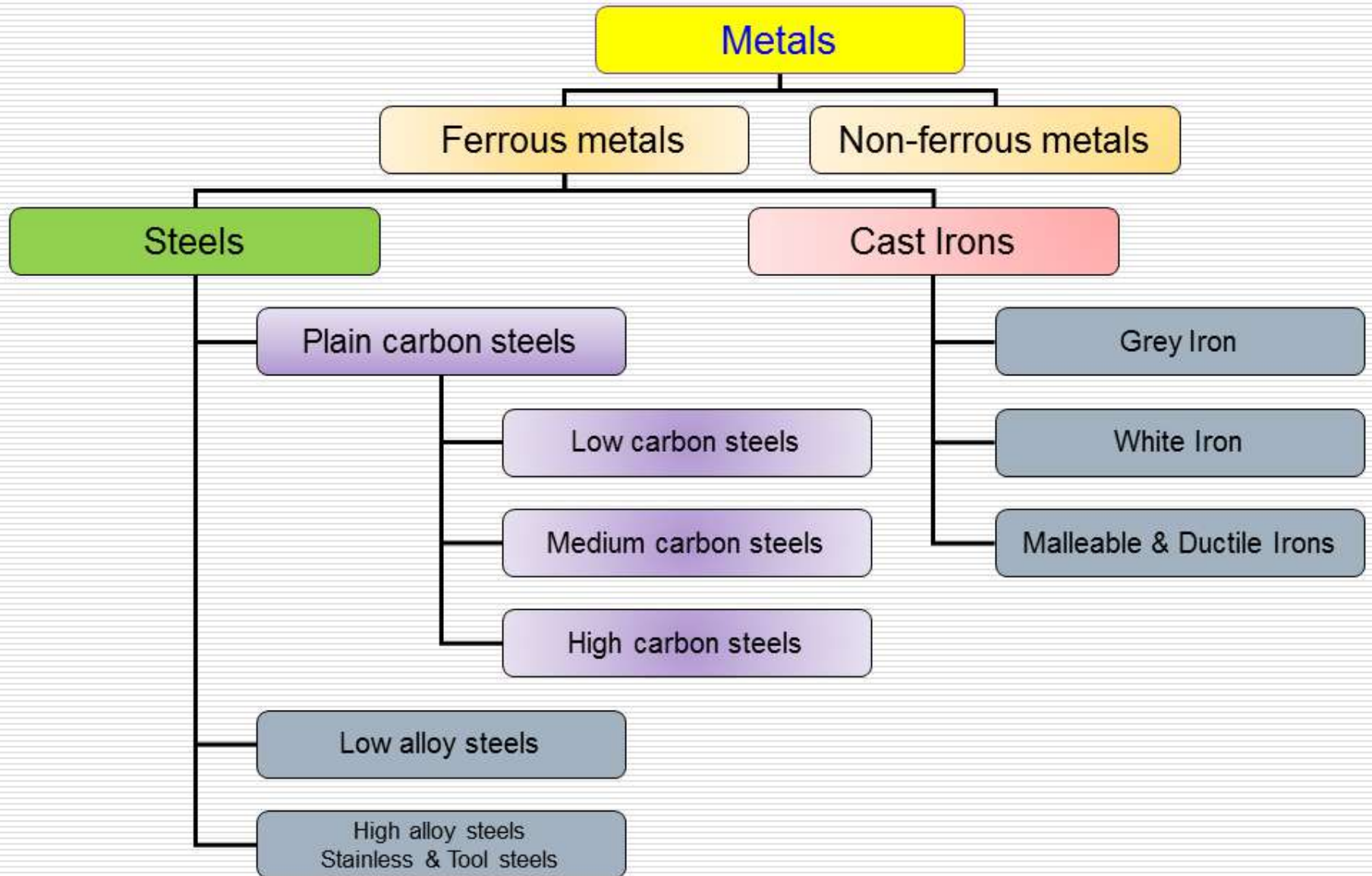


# Classification of Fe-C alloy

Fe-C alloys are classified according to wt.% C present in the alloys

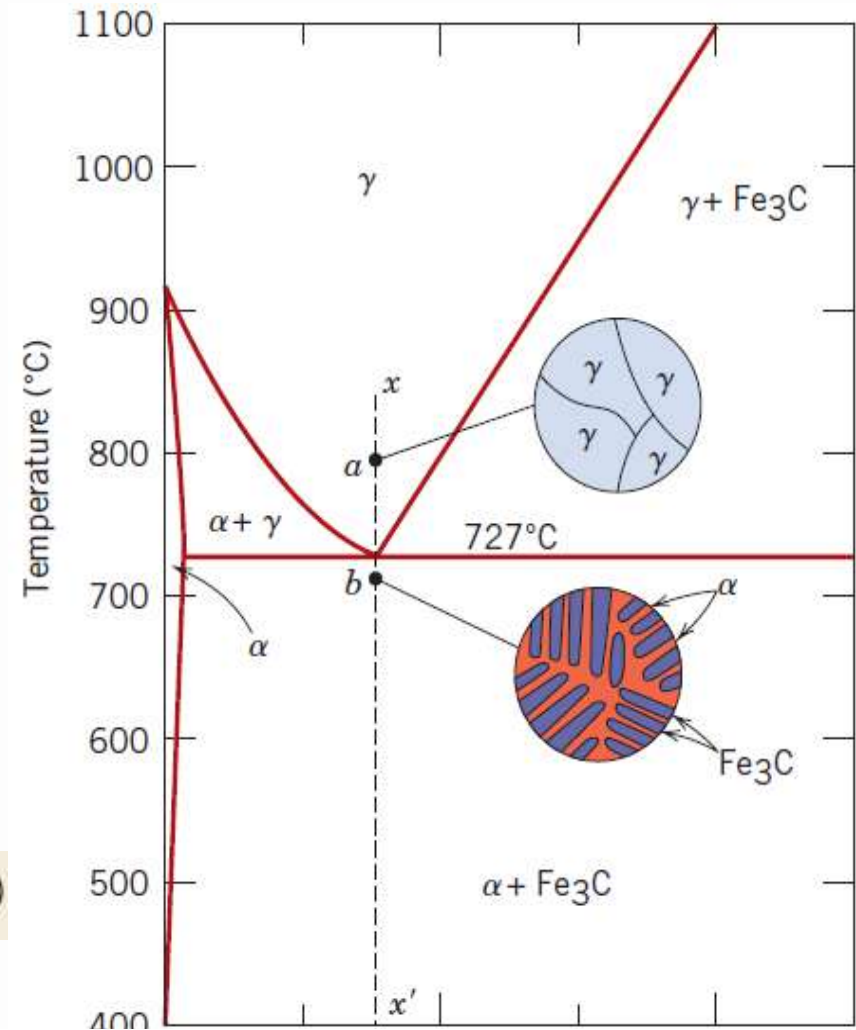
- Commercial pure irons                       $\% \text{C} < 0.008$
  - Low-carbon steels                       $0.008 - \% \text{C} - 0.3$
  - Medium carbon steels                       $0.3 - \% \text{C} - 0.8$
  - High-carbon steels                       $0.8 - \% \text{C} - 2.14$
  - Cast irons                       $2.14 < \% \text{C}$
- The region in phase diagram around the eutectoid point is related to steel (0.76% of C).

# Fe-C alloy classification



# Eutectoid steel

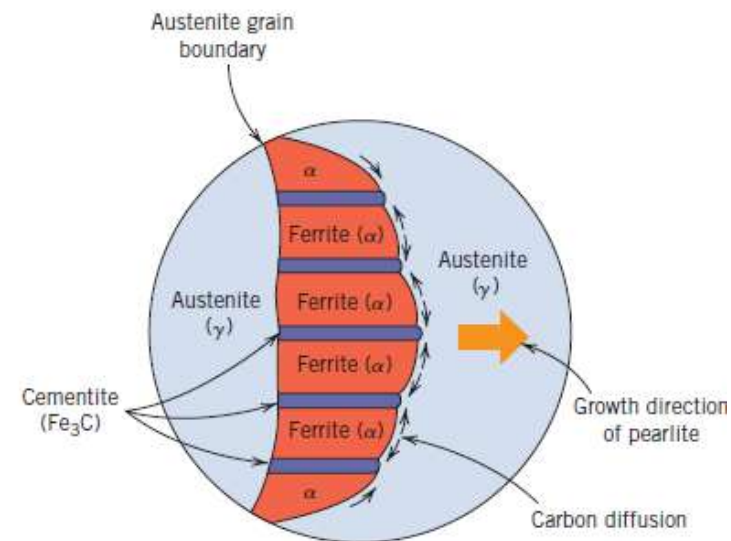
- Consider, an alloy of eutectoid composition (0.76 wt% C) is cooled from a temperature within the  $\gamma$  phase region, say, 800°C—that is, beginning at point  $a$  and moving down the vertical line  $xx'$ .
- Initially, the alloy is composed entirely of the austenite phase having a composition of 0.76 wt% C.
- As the alloy is cooled, there will be no changes until the eutectoid temperature (727°C) is reached.
- Upon crossing this temperature to point  $b$ , the austenite transforms according to the following Equation.



- The microstructure for eutectoid steel that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases ( $\alpha$  and  $\text{Fe}_3\text{C}$ ) that form simultaneously during the transformation.
- This microstructure, point b, is called pearlite because it has the appearance of mother of pearl when viewed under the microscope at low magnifications.
- The pearlite exists as grains, often termed “colonies”; within each colony the layers are oriented in essentially the same direction, which varies from one colony to another.
- The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae most of which appear dark.
- Mechanically, pearlite has properties intermediate between the soft, ductile ferrite and the hard, brittle cementite

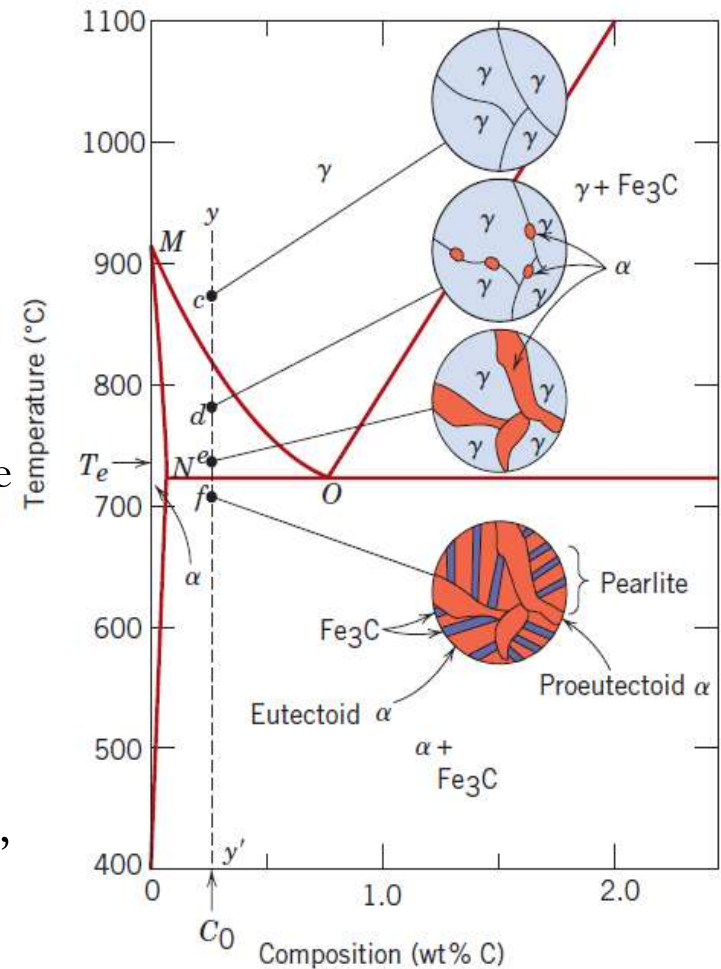


- The alternating  $\alpha$  and  $\text{Fe}_3\text{C}$  layers in pearlite form as such for the same reason that the eutectic structure forms, because the composition of the parent phase [in this case austenite (0.76 wt% C)] is different from either of the product phases [ferrite (0.022 wt% C) and cementite (6.7 wt% C)], and the phase transformation requires that there be a redistribution of the carbon by diffusion.
- The directions of carbon diffusion are indicated by arrows. Carbon atoms diffuse away from the 0.022 wt% ferrite regions and to the 6.7 wt% cementite layers, as the pearlite extends from the grain boundary into the unreacted austenite grain. The layered pearlite forms because carbon atoms need diffuse only minimal distances with the formation of this structure.



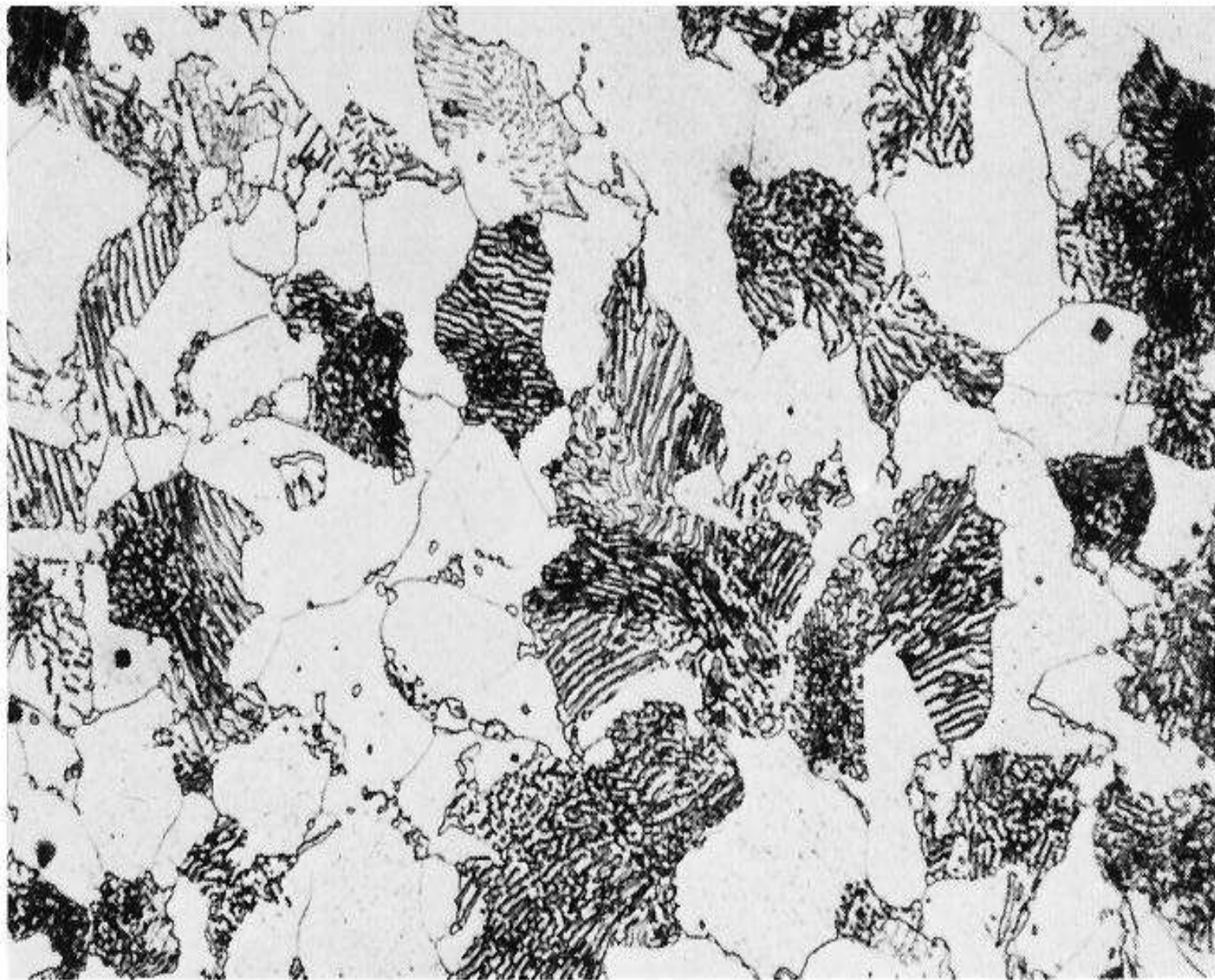
# Hypoeutectoid steel

- Consider a composition  $C_0$  to the left of the eutectoid, between 0.022 and 0.76 wt% C; this is termed a **hypoeutectoid** (less than eutectoid) alloy.
- Cooling an alloy of this composition is represented by moving down the vertical line  $yy'$
- At about 875°C, point c, the microstructure will consist entirely of grains of the  $\gamma$  phase, as
- In cooling to point d, about 775°C, which is within the  $\alpha + \gamma$  phase region, both these phases will coexist as in the schematic microstructure.
- Most of the small  $\alpha$  particles will form along the original  $\gamma$  grain boundaries.
- While cooling an alloy through the  $\alpha + \gamma$  phase region, the composition of the ferrite phase changes with temperature along the  $\alpha - (\alpha + \gamma)$  phase boundary, line MN, becoming slightly richer in carbon.



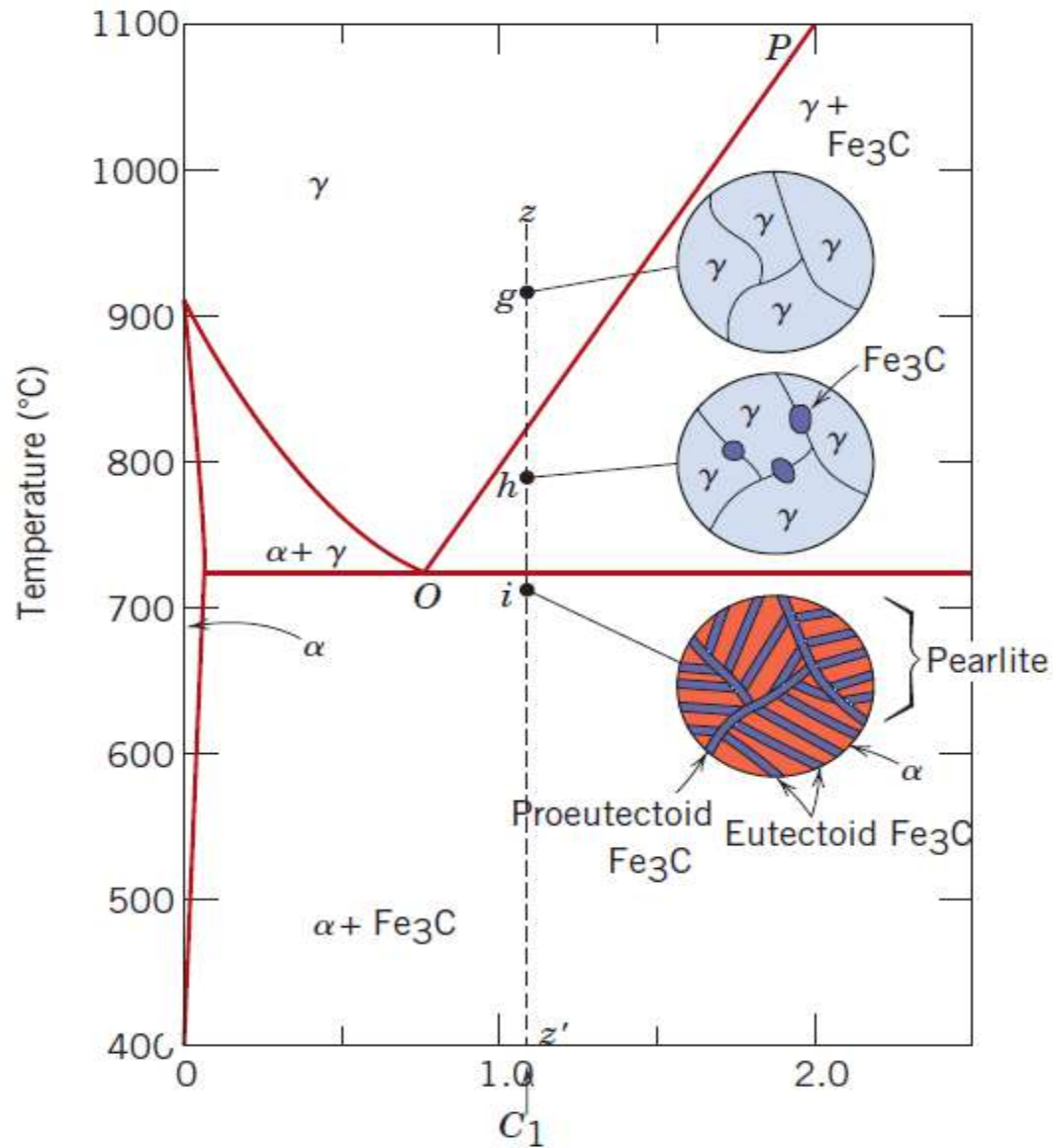


- On the other hand, the change in composition of the austenite is more dramatic, proceeding along the  $(\alpha+\gamma) - \gamma$  boundary, line MO, as the temperature is reduced.
- Cooling from point d to e, just above the eutectoid but still in the  $\alpha+\gamma$  region, will produce an increased fraction of the  $\alpha$  phase and a microstructure similar to that also shown: the  $\alpha$  particles will have grown larger. The  $\alpha$  phase will contain 0.022 wt% C, while the  $\gamma$  phase will be of the eutectoid composition, 0.76 wt% C.
- As the temperature is lowered just below the eutectoid, to point f, all the  $\gamma$  phase that was present at temperature  $T_e$  (and having the eutectoid composition) will transform to pearlite.
- There will be virtually no change in the  $\alpha$  phase that existed at point e in crossing the eutectoid temperature—it will normally be present as a continuous matrix phase surrounding the isolated pearlite colonies. Thus the ferrite ( $\alpha$ ) phase will be present both in the pearlite and also as the phase that formed while cooling through the  $\alpha+\gamma$  phase region.
- The ferrite that is present in the pearlite is called *eutectoid ferrite*, whereas the other, that formed above  $T_e$ , is termed *proeutectoid* (meaning pre- or before eutectoid) ferrite.





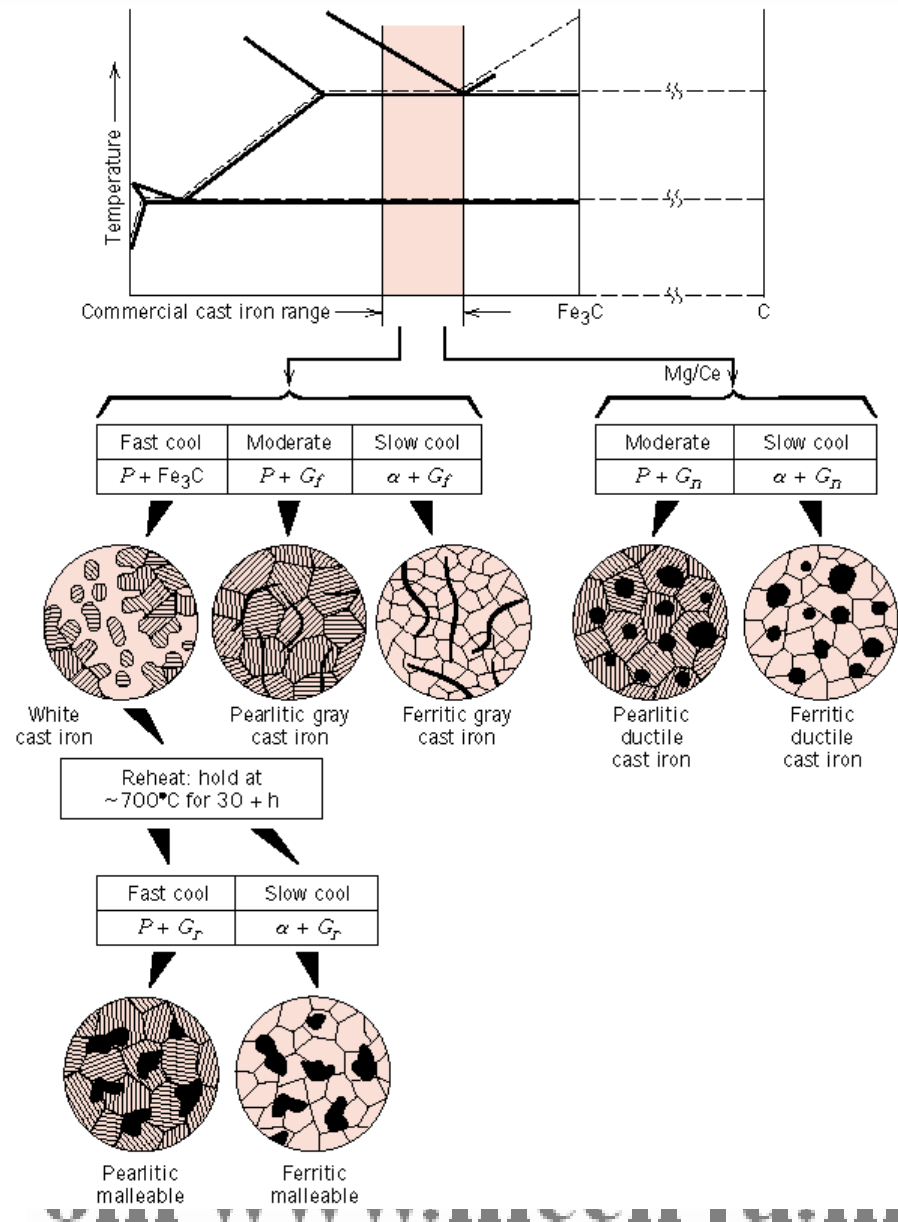
# Hypereutectoid steel



# Hypereutectoid steel

- Similar transformations and microstructures result for *hypereutectoid alloys*, when the carbon composition is in between 0.76 and 2.14 wt%,
- When a *hypereutectoid* solution is cooled from temperatures within the  $\gamma$  phase field, down the line  $zz^1$ . At point  $g$  only the  $\gamma$  phase will be present with a composition of  $C_1$ ; the microstructure will appear as shown, having only  $\gamma$  grains.
- Upon cooling into the  $\gamma + \text{Fe}_3\text{C}$  phase field -say, to point  $h$ - the cementite phase will begin to form along the initial  $g$  grain boundaries, similar to the  $\alpha$  phase hypoeutectic.
- This cementite is called *proeutectoid cementite*- which forms before the eutectoid reaction.
- The cementite composition remains constant (6.70 wt% C) as the temperature changes.
- The composition of the austenite phase will move along line  $PO$  toward the eutectoid. As the temperature is lowered through the eutectoid to point  $i$ , all remaining austenite of eutectoid composition is converted into pearlite; thus, the resulting microstructure consists of pearlite and proeutectoid cementite as microconstituents.

# Microstructure in cast iron



# Limitations of phase diagram

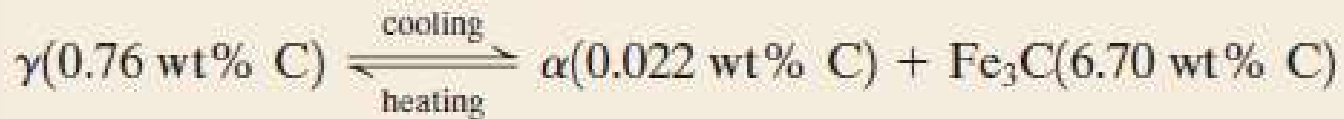
- There are several restrictions for the phase diagram, even though they are useful in the interpretations of metallic and ceramic materials.
- It presents only compositional data, no information on the structural form.
- Phase diagram gives only equilibrium states.
- Alloys are rarely cooled at very slow rates or at equilibrium cooling.
- To overcome these difficulties isothermal transformation diagrams are used.

# Phase transformation diagrams

- In phase transformations, normally at least one new phase is formed that has different physical/chemical characteristics and/or a different structure than the parent phase, and usually they involve some alteration of the microstructure.
- The phase transformations are divided into three classifications,
  - In one group are simple diffusion-dependent transformations in which there is no change in either the number or composition of the phases present. These include solidification of a pure metal, allotropic transformations, and, recrystallization and grain growth.
  - In another type of diffusion-dependent transformation, there is some alteration in phase compositions and often in the number of phases present; the final microstructure ordinarily consists of two phases. The eutectoid reaction is of this type.
  - The third kind of transformation is diffusionless, wherein a metastable phase is produced, a martensitic transformation, which may be induced in some steel alloys, falls into this category.
- Furthermore, most phase transformations do not occur instantaneously.
- The progress of a phase transformation can be divided into two stages: **nucleation** and **growth**.
- Nucleation involves the appearance of very small particles, or nuclei of the new phase (often consisting of only a few hundred atoms), which are capable of growing.

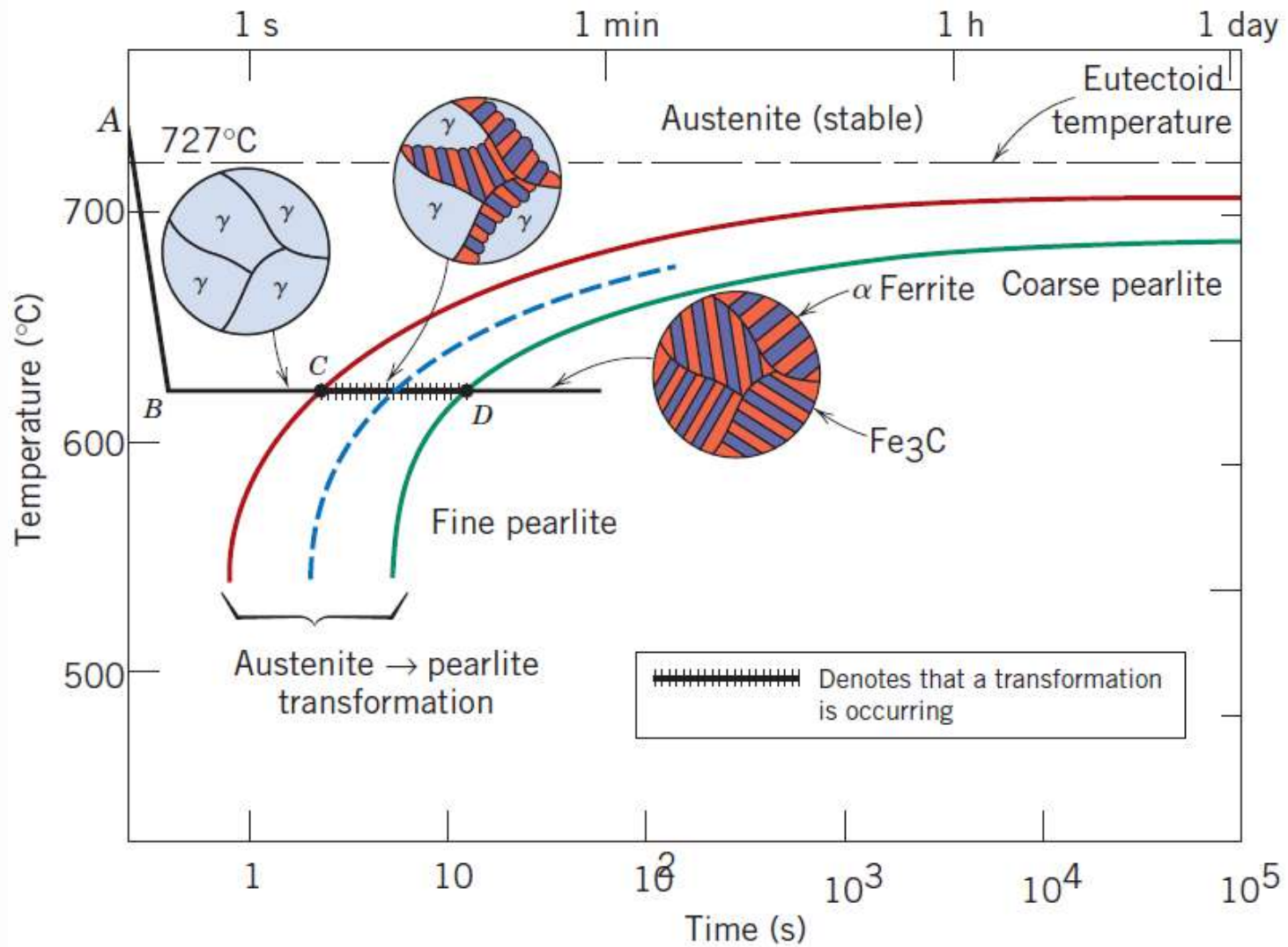
# ISOTHERMAL TRANSFORMATION DIAGRAMS (TTT DIAGRAMS)

- Temperature and cooling rate play a very important role in austenite to pearlite transformation in steel.



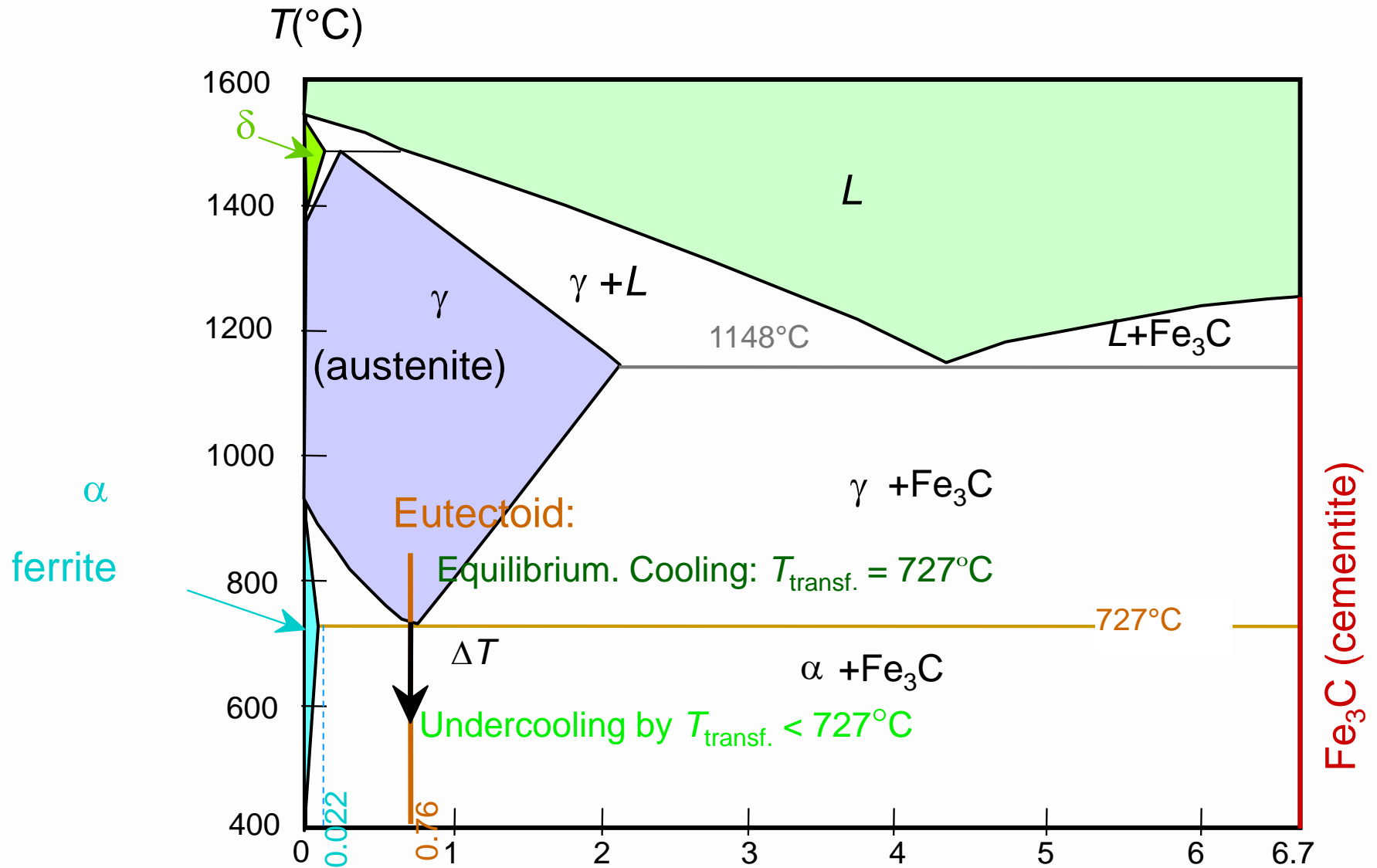
- The fundamental equation to the development of microstructure in steel alloys.
- Upon cooling, austenite, having an intermediate carbon concentration, transforms to *a ferrite phase, having a much lower carbon content*, and also *cementite, with a much higher carbon concentration*. Pearlite is one microstructural product of this transformation

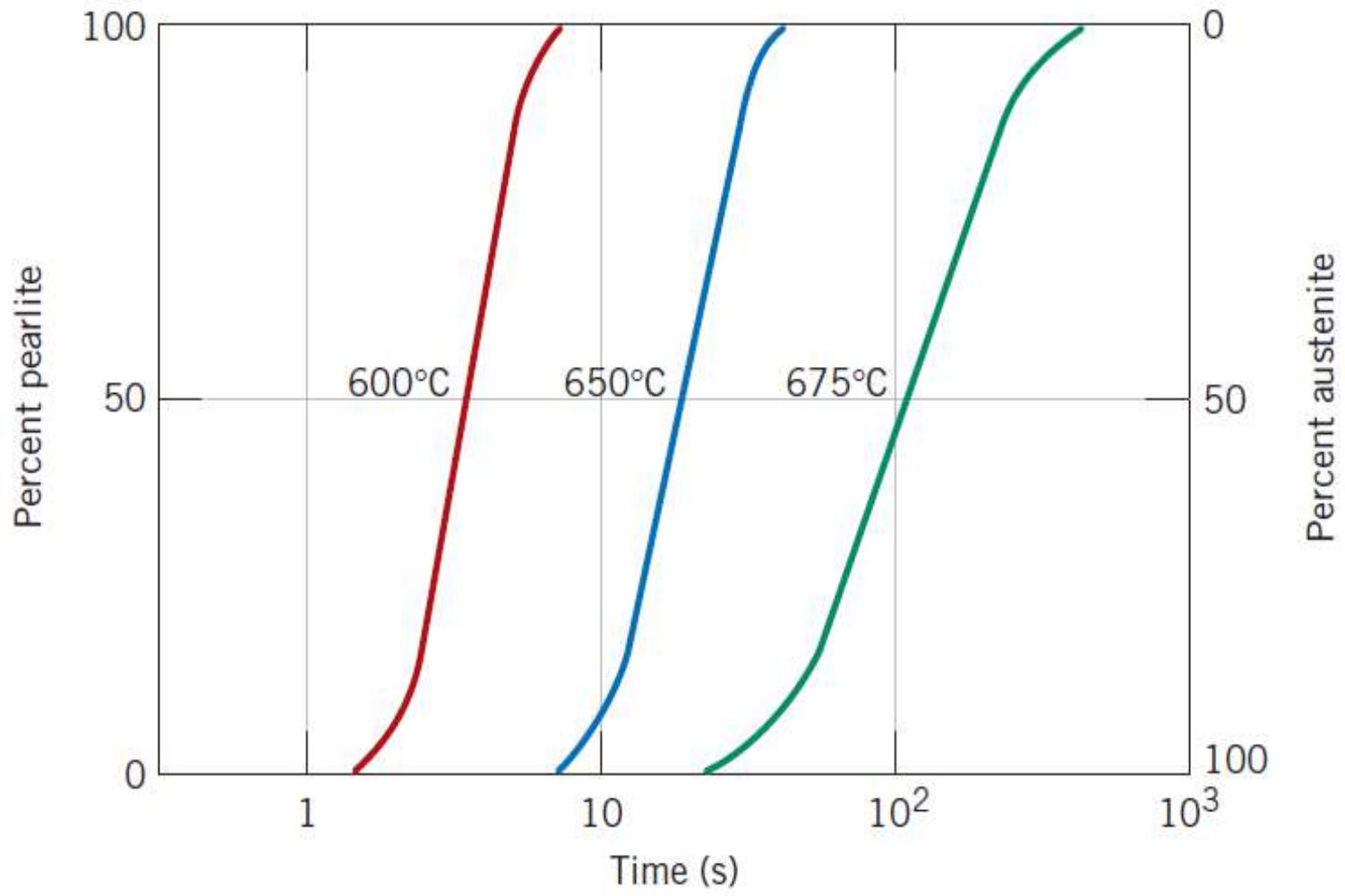


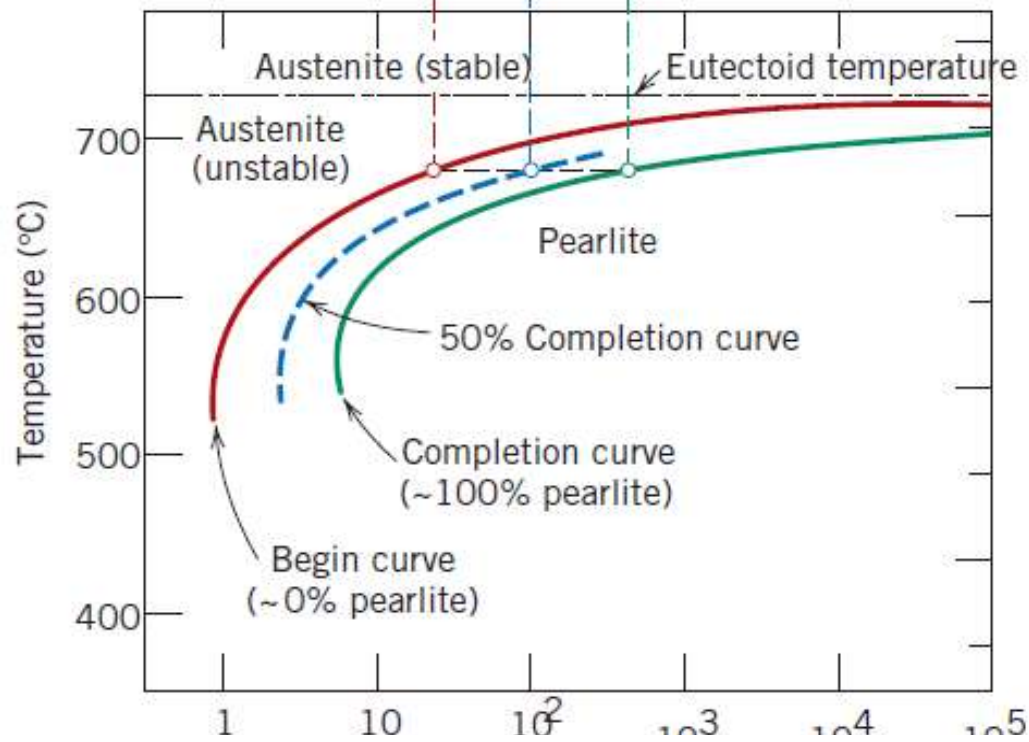
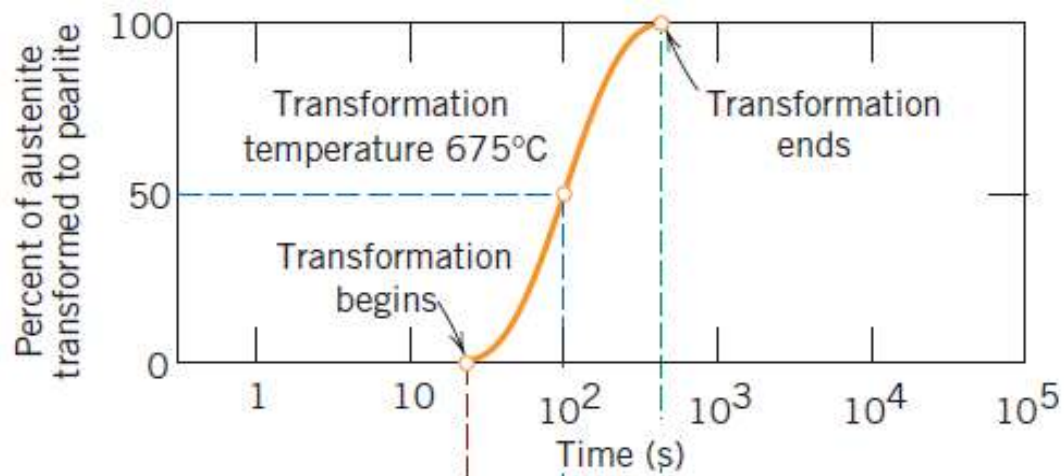


- Temperature plays an important role in the rate of the austenite-to-pearlite transformation.
- The temperature dependence for an iron–carbon alloy of eutectoid composition is indicated in **Figure**, which plots S-shaped curves of the percentage transformation versus the logarithm of time at three different temperatures.
- For each curve, data were collected after rapidly cooling a specimen composed of 100% austenite (heated  $>727^{\circ}\text{C}$ , depending on the composition of Carbon) to the indicated temperature; maintained at this constant temperature during the course of the reaction.
- The time required for austenite to pearlite transformation is noted. As the temperature to which the samples are cooled increases, the time required for transformation ( $t$ ) increases (i.e.,  $t_{600} < t_{650} < t_{675}$ )
- A more convenient way of representing both the time and temperature dependence of this transformation can be represented in TTT diagram.
- Two solid curves are plotted; one represents the time required at each temperature for the initiation or start of the transformation; the other is for the finish of transformation.



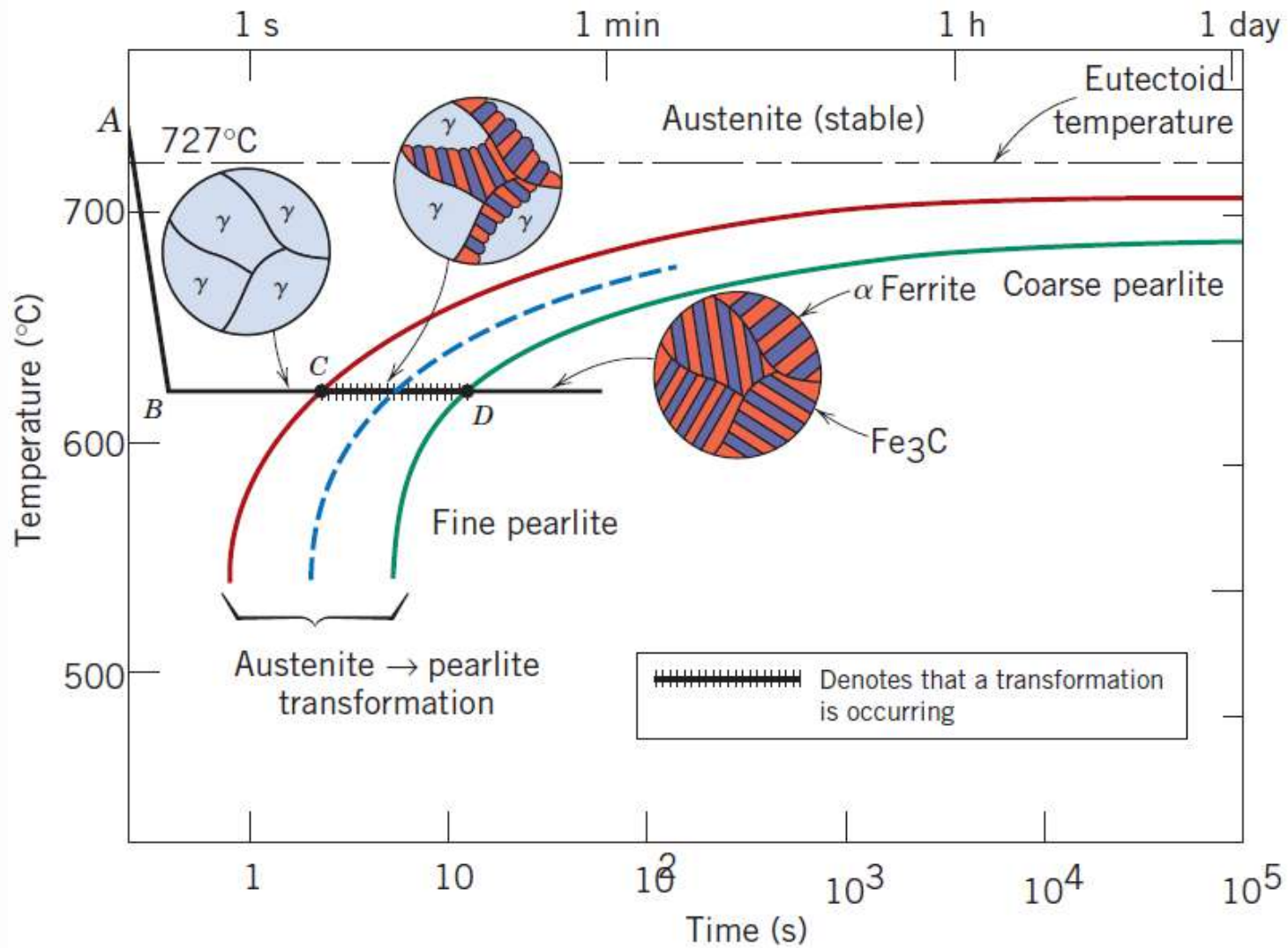






- In interpreting this diagram, note first that the eutectoid temperature [ $727^{\circ}\text{C}$ ] is indicated by a horizontal line; at temperatures above the eutectoid and for all times, only austenite will exist.
- The austenite-to-pearlite transformation will occur only if an alloy is super cooled to below the eutectoid, the time necessary for the transformation to begin and then end depends on temperature.
- The start and finish curves are nearly parallel, and they approach the eutectoid line asymptotically. To the left of the transformation start curve, only austenite (which is unstable) will be present, whereas to the right of the finish curve, only pearlite will exist.
- In between, the austenite is in the process of transforming to pearlite, and thus both microconstituents will be present.
- The transformation rate at some particular temperature is inversely proportional to the time required for the reaction to proceed to 50% completion (to the dashed line in **Figure**).
- That is, the shorter the time, the higher is the rate. Thus, at temperatures just below the eutectoid (corresponding to just a slight degree of undercooling) very long times (on the order of  $10^5$  s) are required for the 50% transformation, and therefore the reaction rate is very slow.
- The transformation rate increases with decreasing temperature such that at  $540^{\circ}\text{C}$

- At temperatures just below the eutectoid, relatively thick layers of both the  $\alpha$ -ferrite and  $\text{Fe}_3\text{C}$  phases are produced; this microstructure is called **coarse pearlite**,
- At these temperatures, diffusion rates are relatively high, such that during the transformation carbon atoms can diffuse relatively long distances, which results in the formation of thick lamellae.
- With decreasing temperature, the carbon diffusion rate decreases, and the layers become progressively thinner.
- The thin-layered structure produced is termed **fine pearlite**.
- Fine pearlite leads to better hardness and strength due to the greater reinforcement and restriction to motion dislocation.
- Coarse pearlite is more ductile than fine pearlite at the cost of

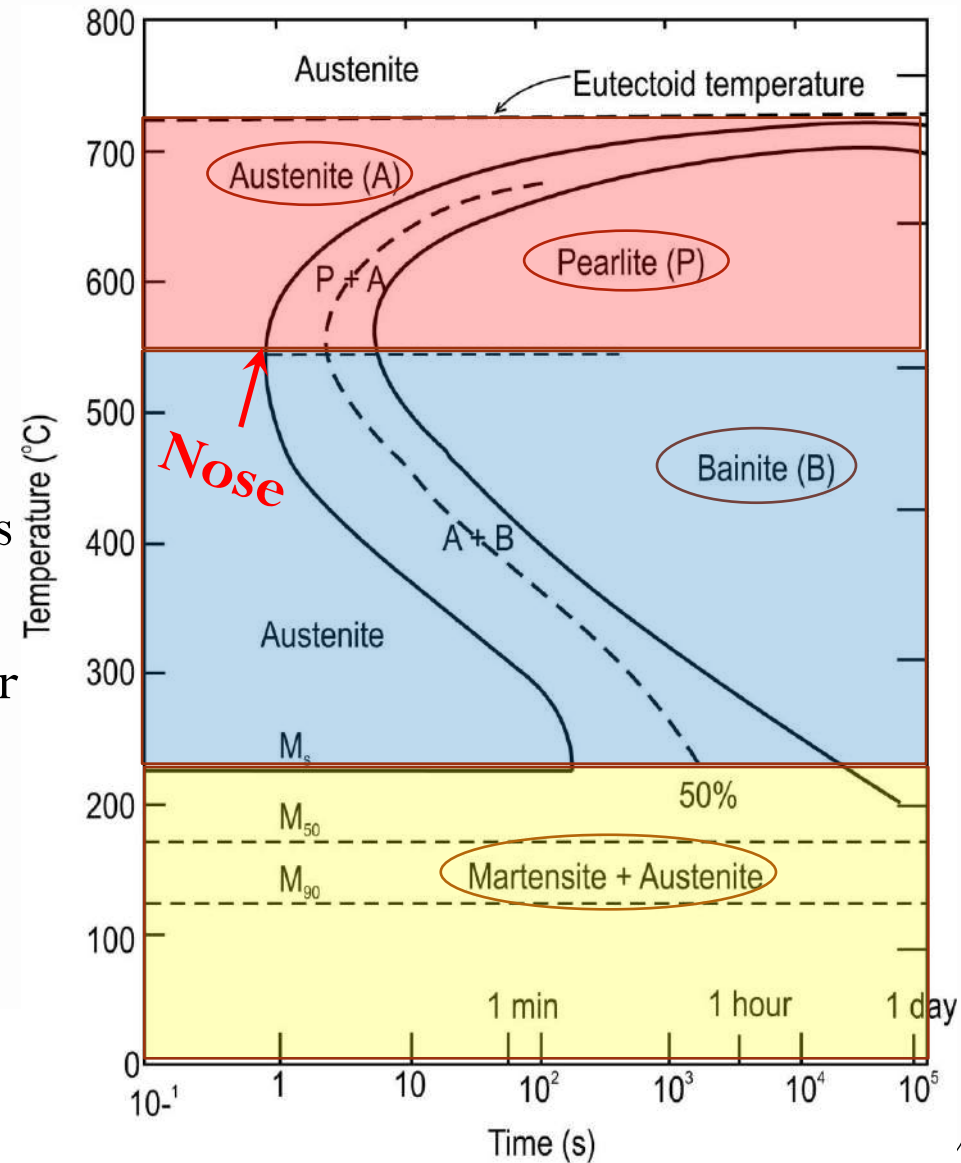


- An actual isothermal heat treatment curve (ABCD) is superimposed on the isothermal transformation diagram for a eutectoid iron–carbon alloy in **Figure**.
- Very rapid cooling of austenite to a temperature is indicated by the near-vertical line AB, and the isothermal treatment at this temperature is represented by the horizontal segment BCD.
- The transformation of austenite to pearlite begins at the intersection, point C (after approximately 3.5 s), and has reached completion by about 15 s, corresponding to point D.

# TTT Diagram Complete

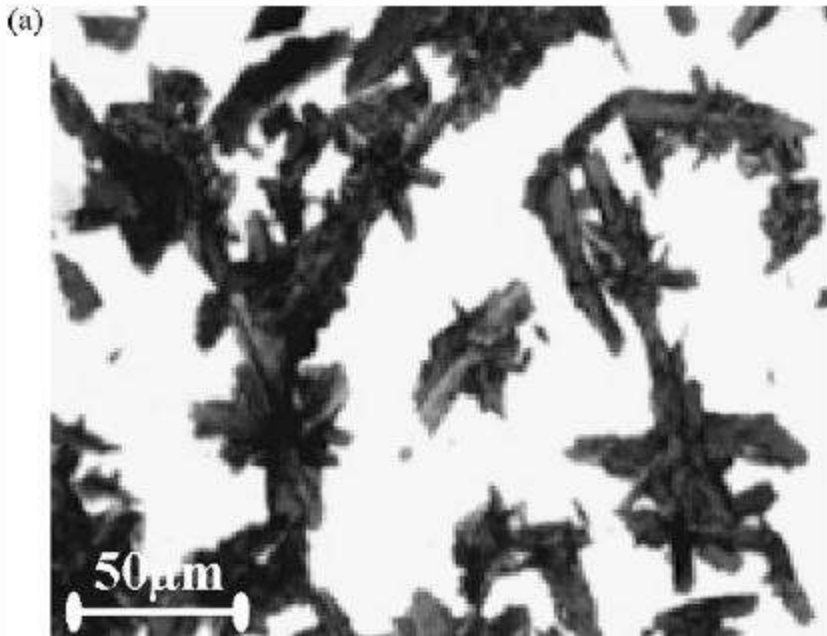
## Bainite

- In addition to pearlite, other microconstituents that are products of the austenitic transformation exist; one of these is called **bainite**.
- The microstructure of **bainite** consists of ferrite and cementite phases, and thus diffusional processes are involved in its formation.
- Bainite forms as feather or needles or plate like cementite, depending on the temperature of the transformation; the microstructural details of **bainite** are so fine that

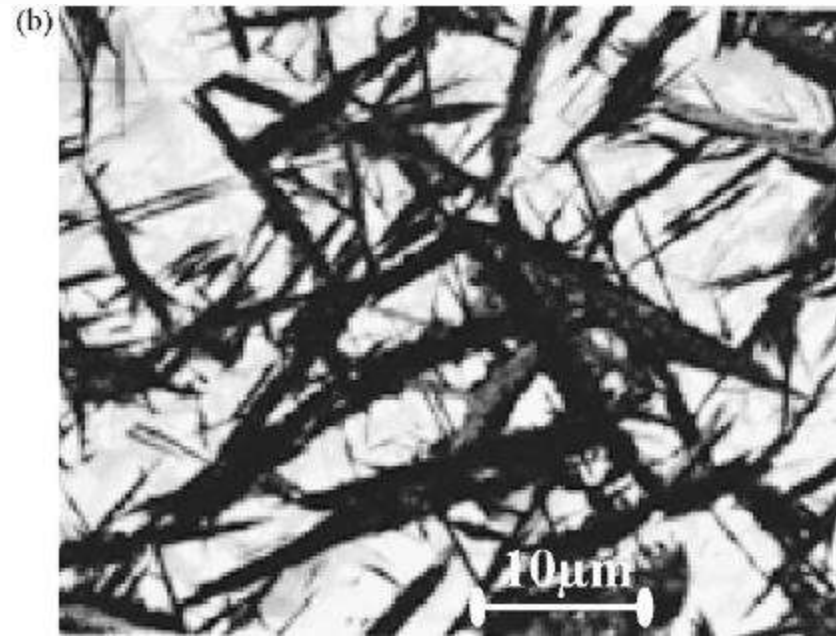




- The time–temperature dependence of the bainite transformation can be represented on the isothermal transformation diagram.
- It occurs at temperatures below those at which pearlite forms; begin-, end-, and half-reaction curves are just extensions of those for the pearlitic transformation.
- The isothermal transformation diagram for an iron–carbon alloy of eutectoid composition that has been extended to lower temperatures.
- All three curves are C-shaped and have a “nose” at point *N*, where the rate of transformation is a maximum.
- Pearlite forms above the nose [i.e., over the temperature range of about 540 to 727 °C, at temperatures between about 215 and 540 °C, bainite is the transformation product.
- Temperatures just below the nose TTT curve is called *upper bainite* with feathery cementite appearance.
- At lower temperatures, the cementite grains become too fine and an acicular needle like pattern is observed. This is lower bainite which is also



*Upper bainite*

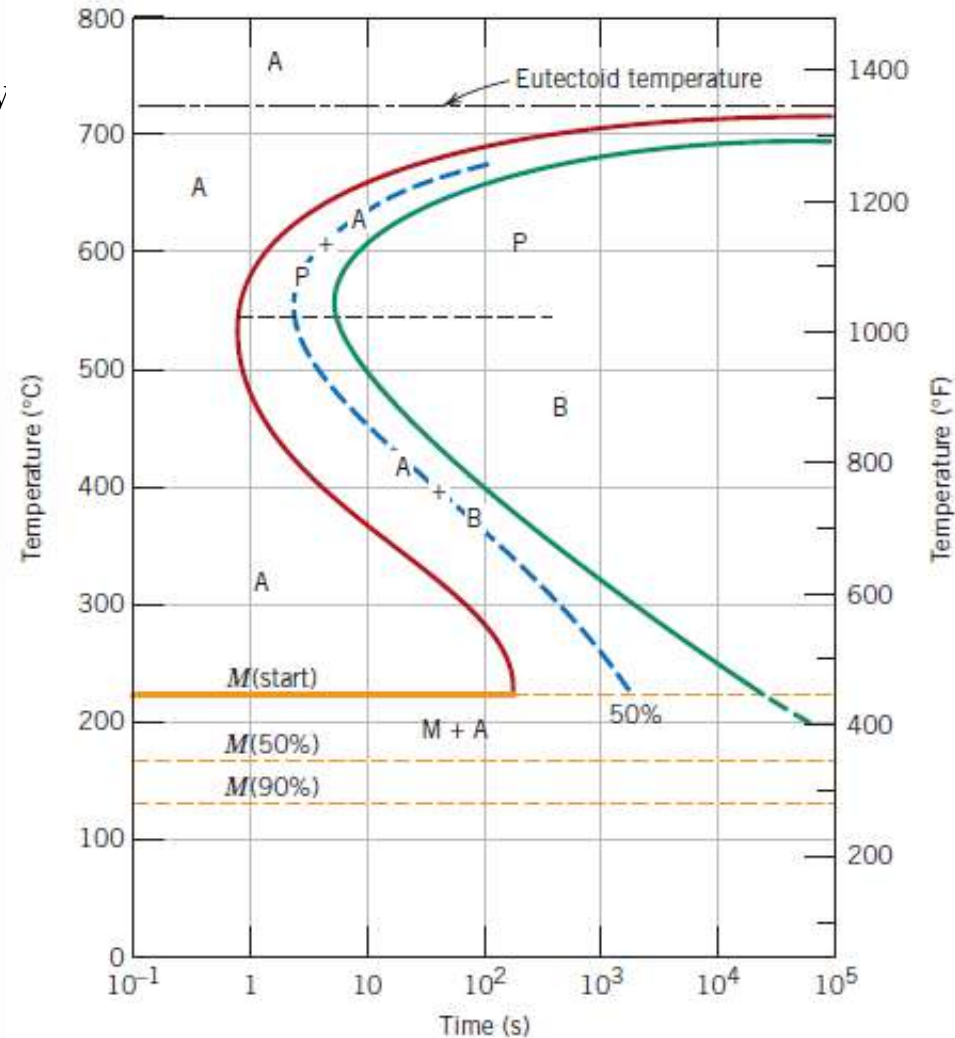


*Acicular bainite*

- Bainite leads to more strength and hardness compared to pearlite.
- This is due to smaller ferrite particles.
- There will be an increase in strength associated decrease in

# TTT diagram

- On rapid cooling (quenching) to low temperatures ( $< 215\text{ }^{\circ}\text{C}$ ), the austenite transforms to another microstructure called Martensite.
- Martensite forms when the rate of cooling is rapid enough to prevent diffusion.
- The formation of martensite grains nucleate and grow at a very rapid rate.



- Being a nonequilibrium phase, martensite does not appear on the iron–iron carbide phase diagram.
- The austenite-to-martensite transformation is, however, represented on the isothermal transformation diagram.
- The martensitic transformation is diffusionless and instantaneous, it is not depicted in this diagram as the pearlitic and bainitic reactions.
- The beginning of this transformation is represented by a horizontal line designated  $M(\text{start})$ . Two other horizontal and dashed lines, labeled  $M(50\%)$  and  $M(90\%)$ , indicate percentages of the austenite-to-martensite transformation.
- The temperatures at which these lines are located vary with alloy composition but, nevertheless, must be relatively low because carbon diffusion must be low.
- The horizontal and linear character of these lines indicates that the martensitic transformation is independent of time; it is a function only of the temperature to which the alloy is quenched or rapidly cooled.
- A transformation of this type is termed an **athermal transformation**.

- In martensite transformation, a sudden orientation of carbon and iron atoms from FCC solid solution (Austenite) into a body centered tetragonal (BCT) solid solution happens here.
- Compared to other microstructures observed in steel, martensite is the strongest and hardest.
- These properties are due to the presence of Interstitial carbon atoms.
- The interstitial impurities acts as barriers to dislocation motion.



# Use of TTT diagram

- This diagram indicates the phases existing in steel of a specific composition at various temperatures and times.
- It is helpful to obtain desired microstructure and hence to design properties of the alloy.

# Use of TTT diagram

- ❑ Iron-carbon alloy with eutectoid composition.
- ❑ Specify the nature of the final microstructure (% bainite, martensite, pearlite etc) for the alloy that is subjected to the following time-temperature treatments:
- ❑ Alloy begins at  $760^{\circ}\text{C}$  and has been held long enough to achieve a complete and homogeneous austenitic structure.

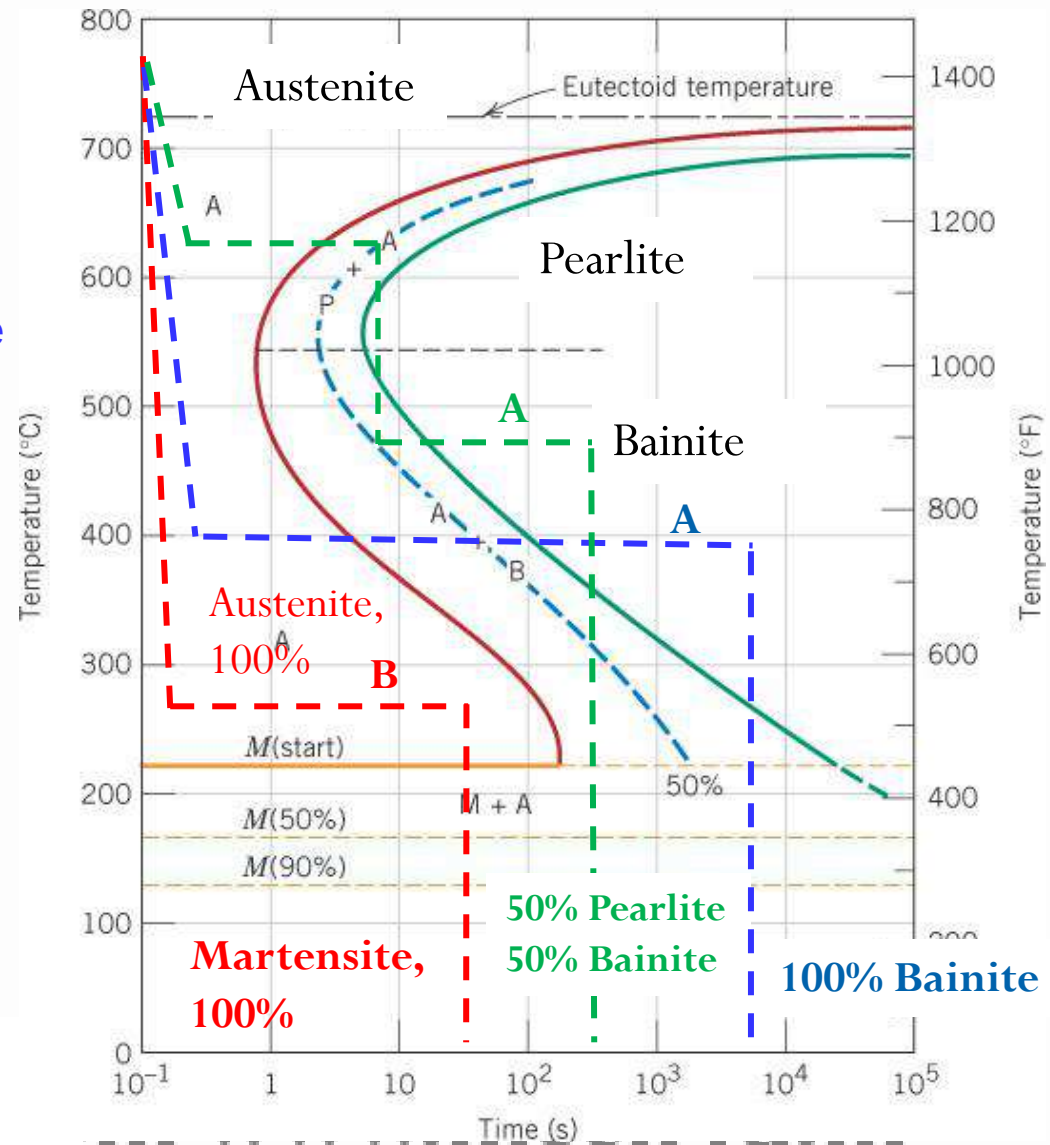
## Treatment (A)

- ❑ Rapidly cool to  $650^{\circ}\text{C}$
- ❑ Hold for 20 seconds
- ❑ Rapidly cool to  $400^{\circ}\text{C}$
- ❑ Hold for  $10^3$  seconds
- ❑ Quench to room temperature

## Treatment (b)

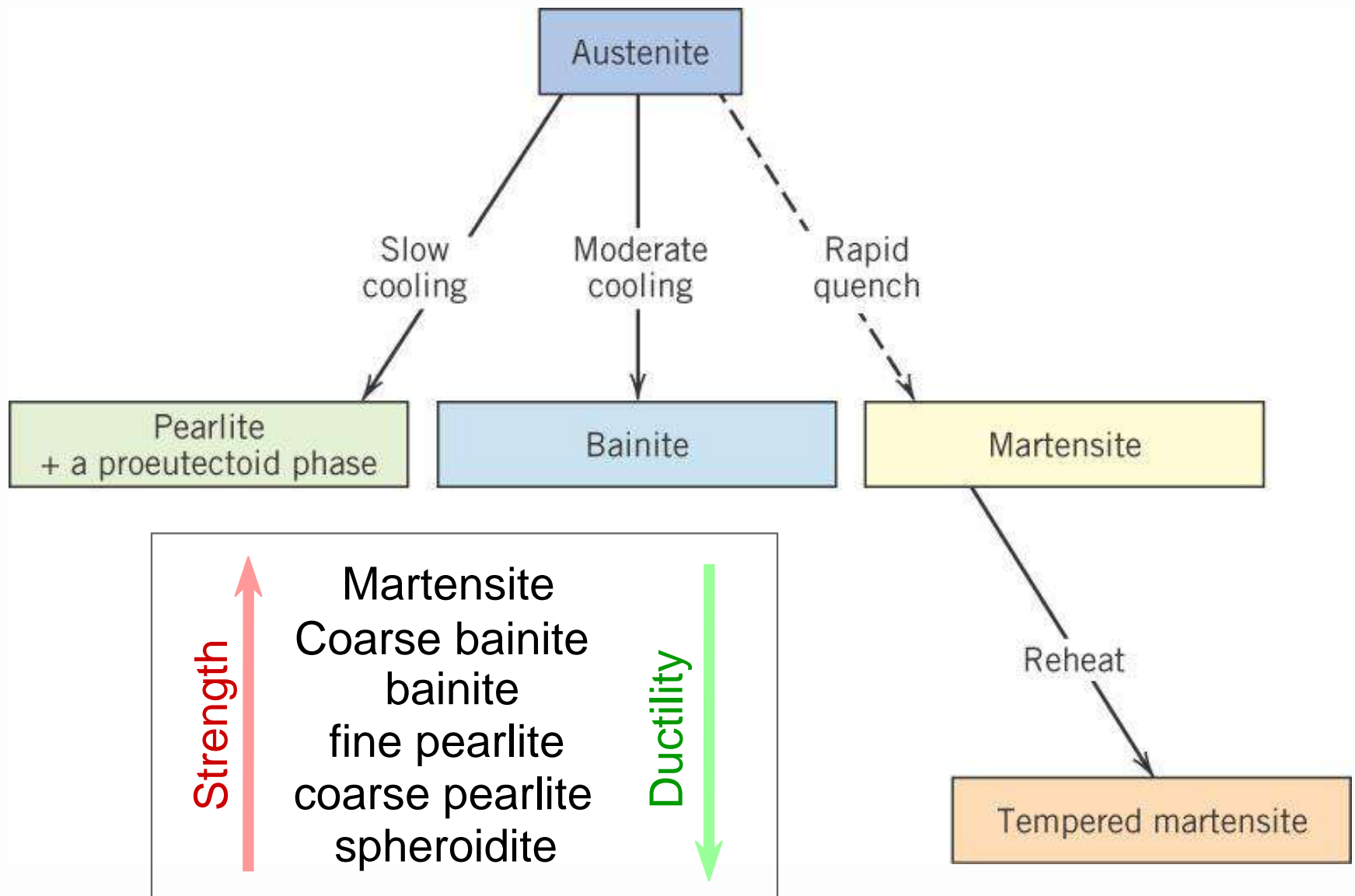
- ❑ Rapidly cool to  $250^{\circ}\text{C}$
- ❑ Hold for 100 seconds
- ❑ Quench to room temperature

## Treatment (a)





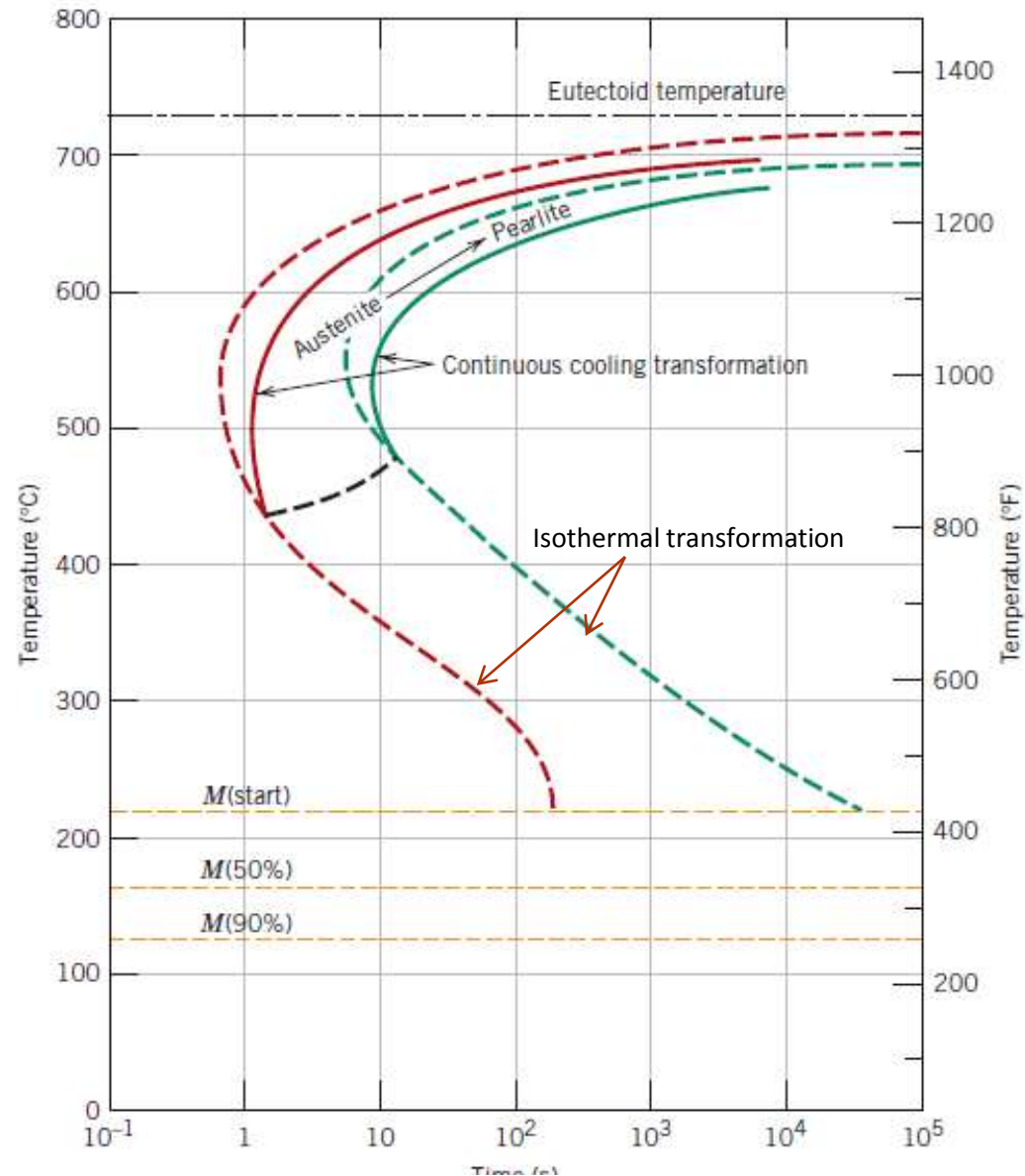
# Possible Transformations



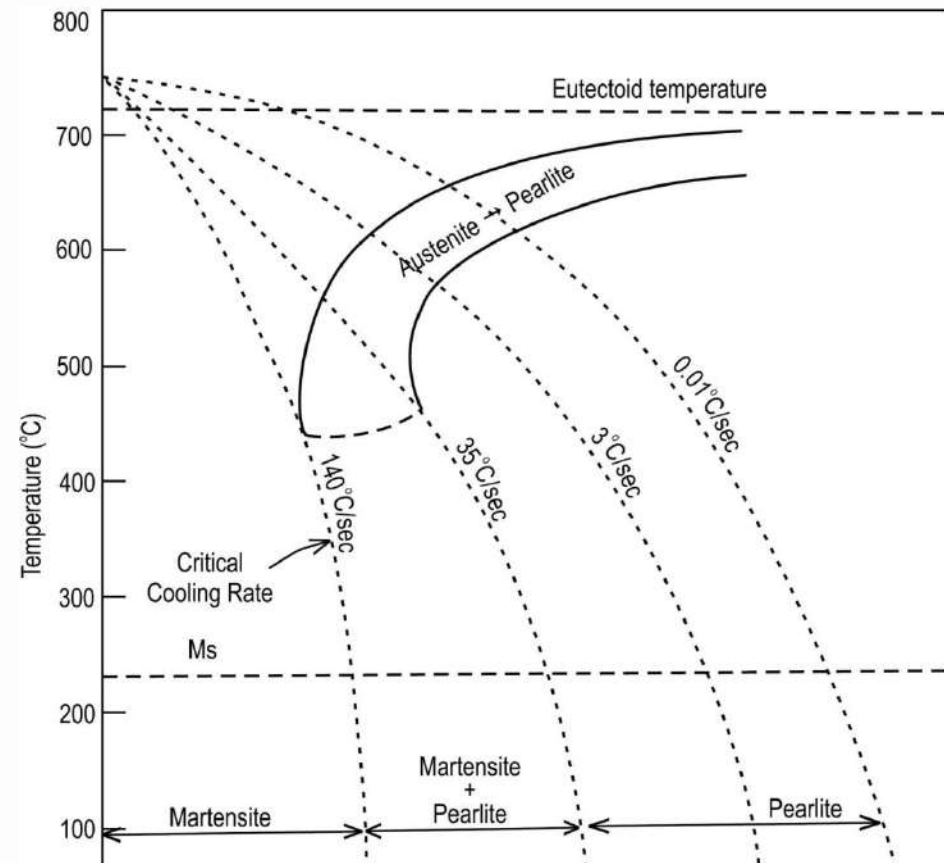


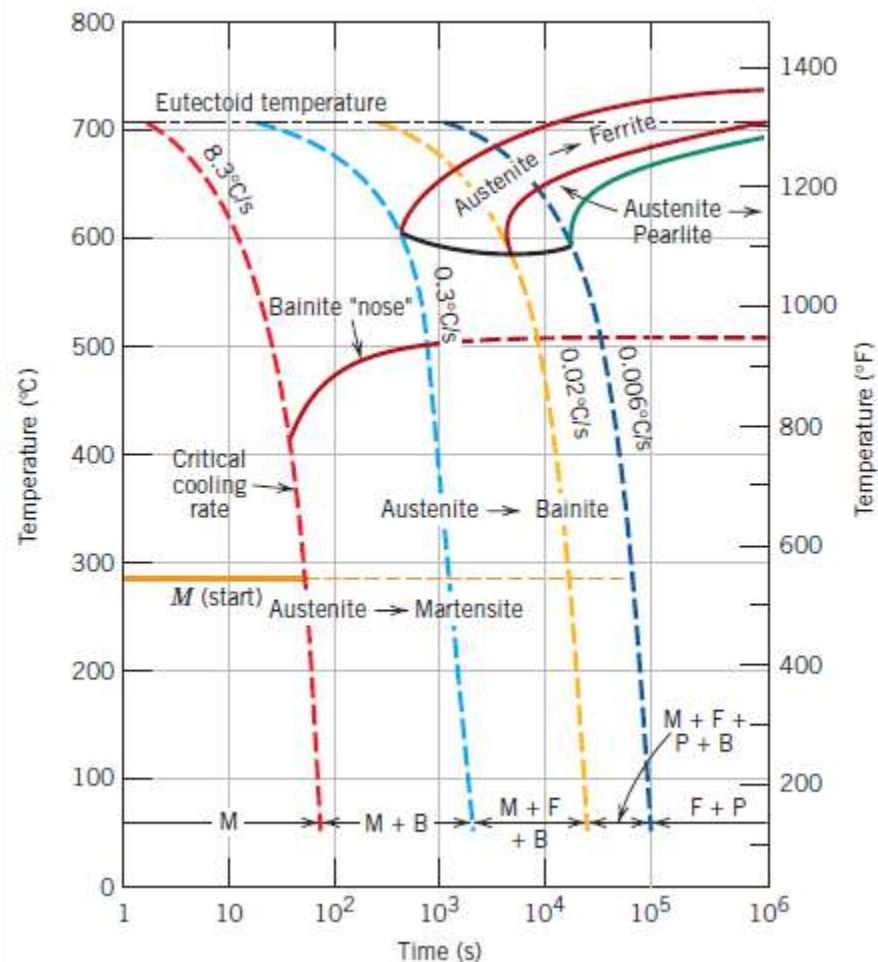
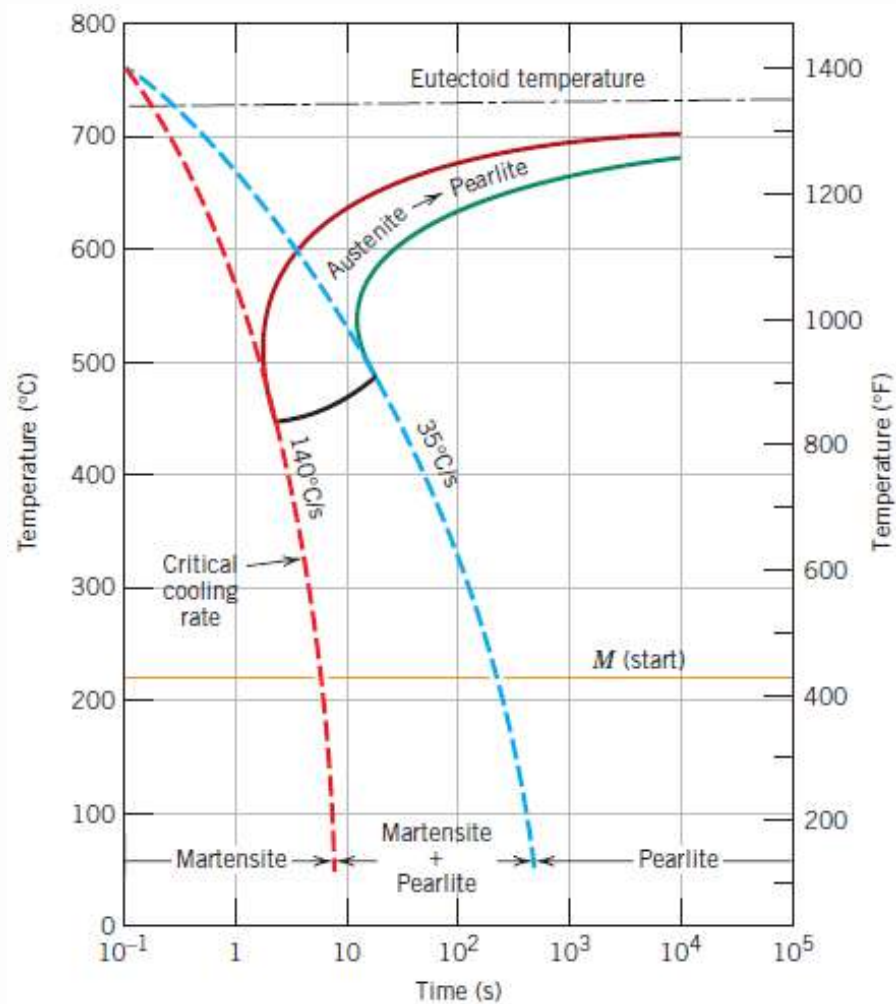
# CCT Diagram

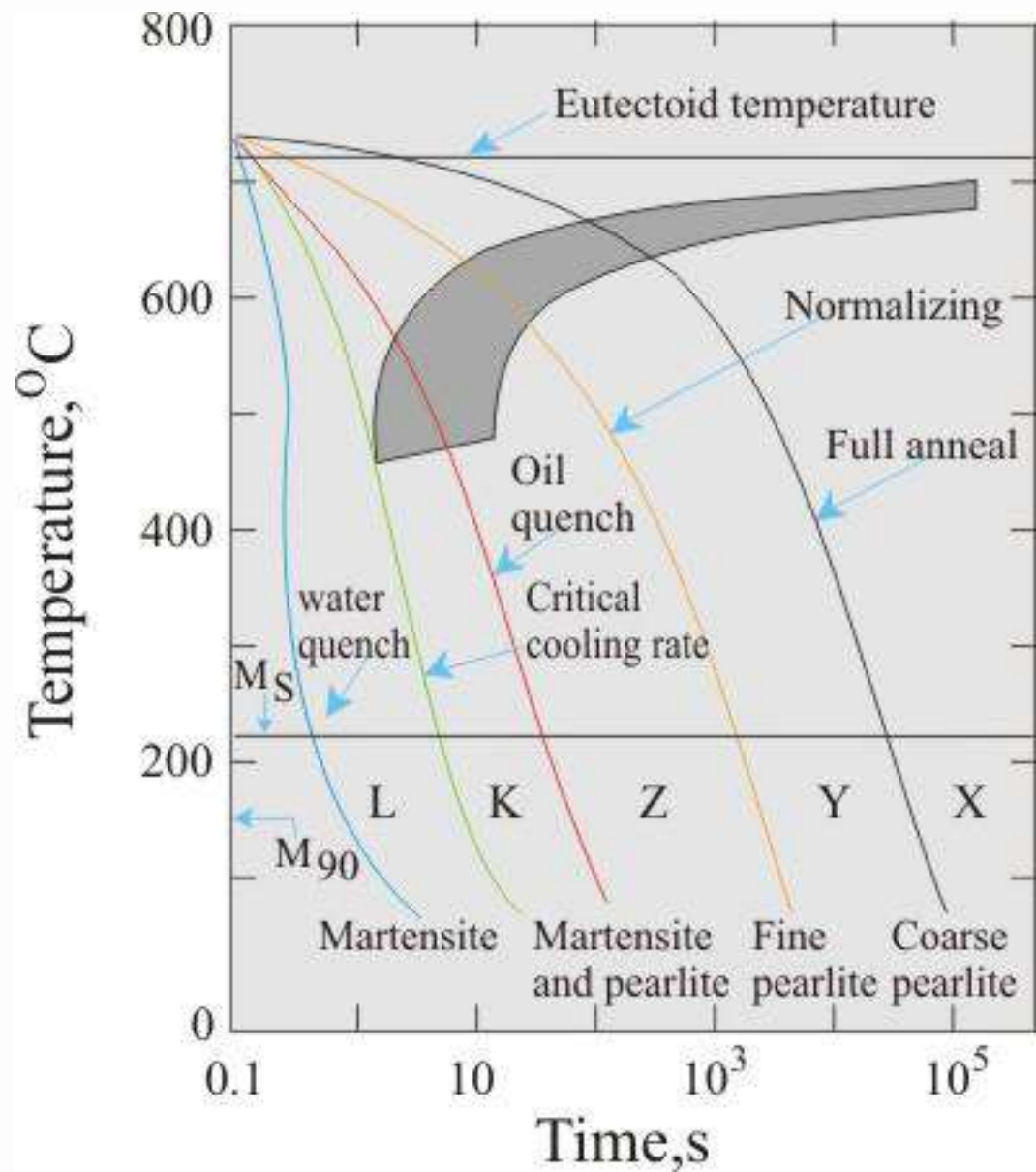
- Isothermal heat treatments are not the most practical to conduct because an alloy must be rapidly cooled to and maintained at an elevated temperature from a higher temperature above the eutectoid.
- Most heat treatments for steels involve the continuous cooling of a specimen to room temperature.
- An isothermal transformation diagram is valid only for conditions of constant temperature; this diagram must be modified for transformations that occur as the temperature is constantly changing.



- A **continuous cooling transformation (CCT) diagram** shows the relationship between transformation temperature and time during continuous cooling.
- In CCT diagram, it can be seen that the transformation starts at lower temperatures and after longer duration as compared to isothermal transformation.
- Here, in CCT diagram, the obtention of structure is totally depend on the cooling rate.
- At low cooling rates, the curve passes through the pearlite start and pearlite end curve.
- Whereas, as the cooling rate increases ( $35^{\circ}\text{C}$ ), the cooling curves touches the pearlite start but does not touch the 100% pearlite curve; indicating the partial conversion of austenite to Martensite+pearlite.
- As the cooling rate is increased further ( $140^{\circ}\text{C}$ ), direct transformation of austenite to martensite transformation take place.
- CCT diagrams are thus helpful in predicting the microstructure after some







# Heat treatments

- Heat treatment can be defined as a combination of heating and cooling operations timed and applied to a metal or alloy in a solid state to produce desired properties.
- Heat treatment process are designed based on the information available from the phase diagram.
- The first step in most heat treatment process is to heat the material to a higher temperature to transform the microstructure to austenite.
- Upon cooling, the austenite decomposes or transforms into various forms depending on the cooling path and composition of alloy.

# Objective of heat treatment

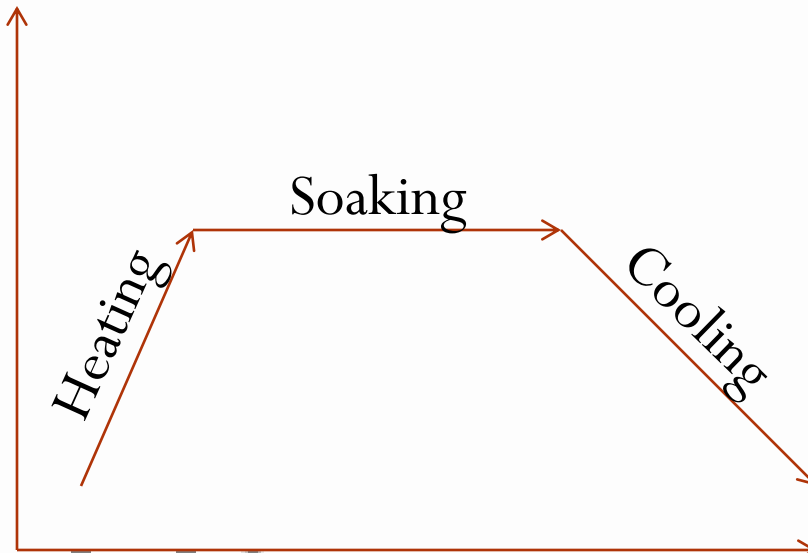
- To improve the **mechanical properties** like tensile strength, ductility and impact resistance.
- To improve **surface hardness**
- To increase the **resistance to wear, heat and corrosion.**
- To improve machinability.
- To **relieve internal stresses** set up in the material during cold working.
- To **refine grain structure** after hot working.
- To improve **magnetic and electrical** properties.

# Classification of heat treatment

- Simple heat treatments
  - Process annealing
  - Full annealing
  - Spherodising
  - Normalizing
- Quench and Temper heat treatments
  - Hardening
  - Tempering
- Isothermal Heat treatments
  - Austempering
  - Martempering
  - Marquenching
- Precipitation Hardening
- Diffusion methods (case hardening)
  - Carburising
  - Cyaniding
  - Nitriding
  - Carbonitriding
- Selective hardening methods
  - Flame hardening
  - Induction hardening

# Steps in heat treatment

1. **Heating** the material to a specified temperature
2. **Holding or soaking** the material at this temperature for a specified period of time
3. **Cooling** the material according to the specified rate of cooling.





A heat treatment process does not involve any chemical change in the material.

- **Heating**

- The temperature to which a steel is heated depends on the carbon content and also on the process involved.

- **Soaking**

- Ensures the uniformity of temperature through out the mass of the material.
- Internal structural changes take place.
- Soaking period depends on the chemical analysis of the metal and the mass of the part.

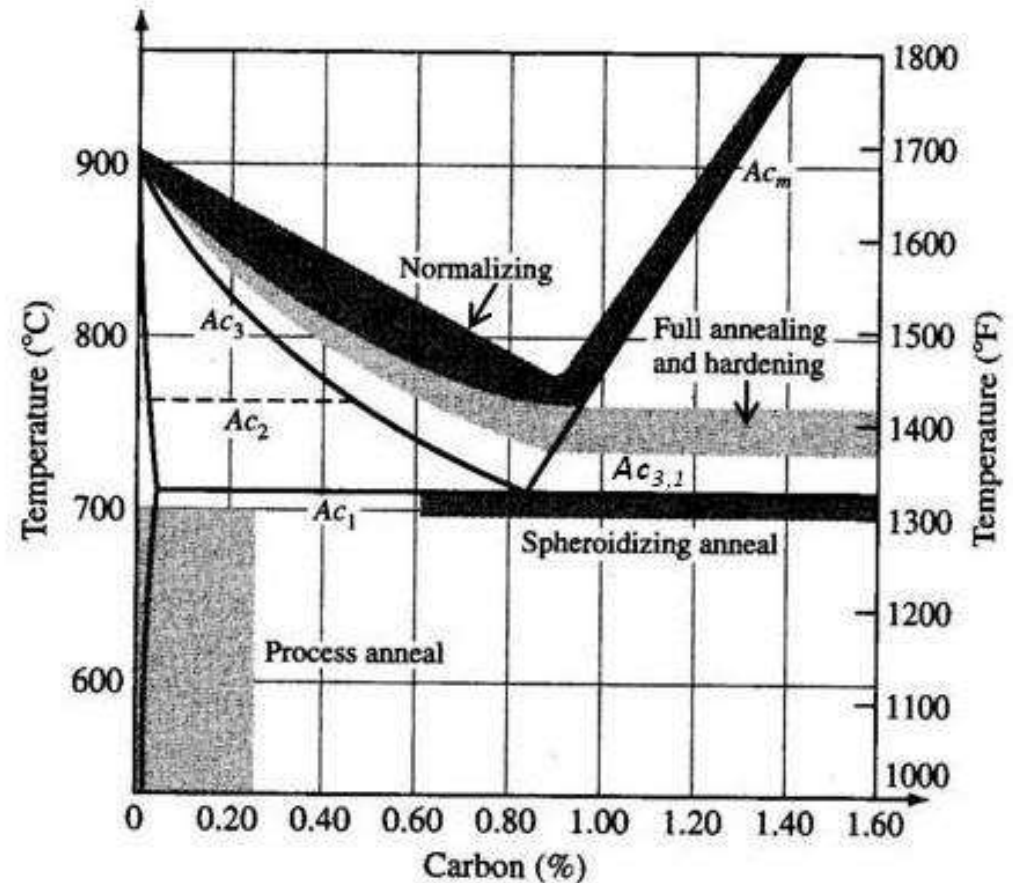
- **Cooling Stage**

- The transformation take place during the cooling process.
- The cooling rate decides the final microstructure of the material.
- To cool the metal, you can place it in direct contact with a COOLING

# Applications -Annealing,

Ordinarily, annealing is carried out to

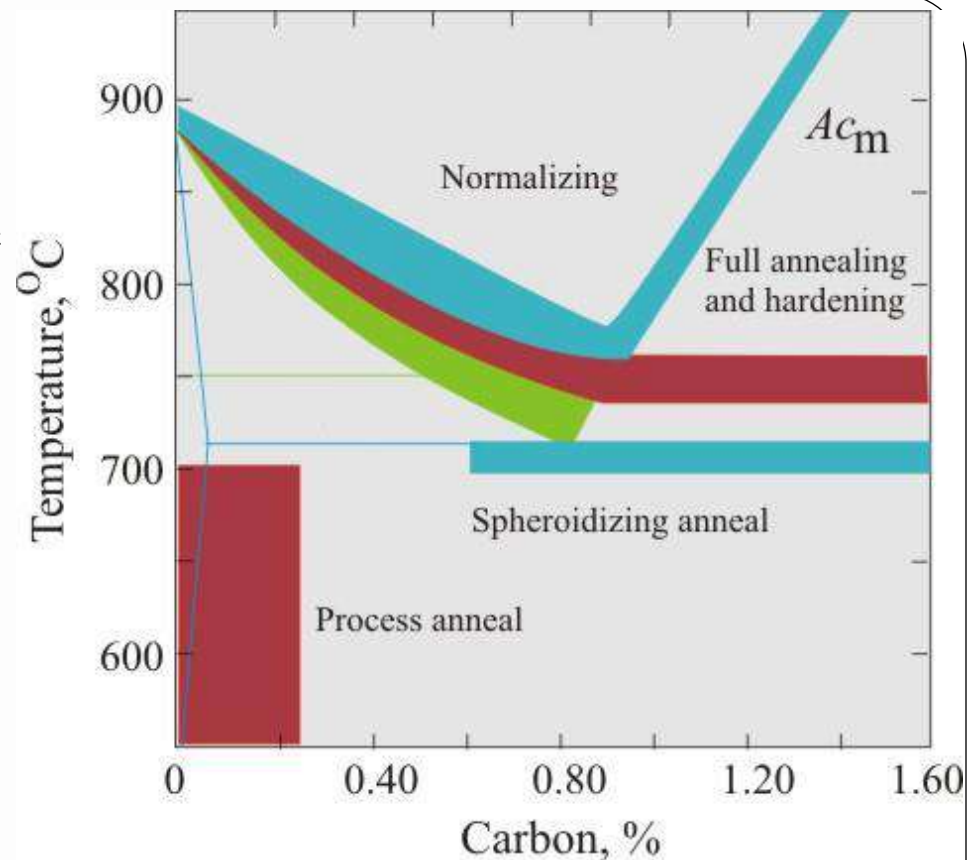
1. Relieve stresses (Cold wok).
2. Increase softness, ductility, and toughness;
3. Produce a specific microstructure.

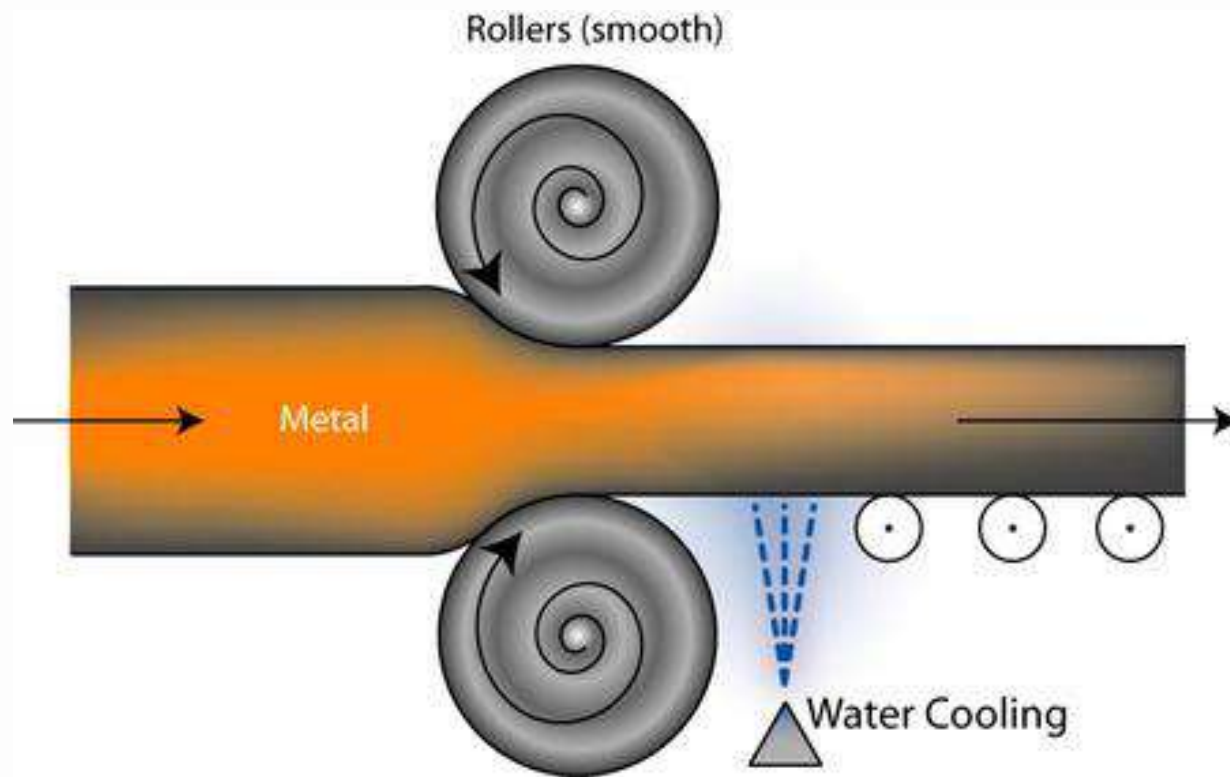


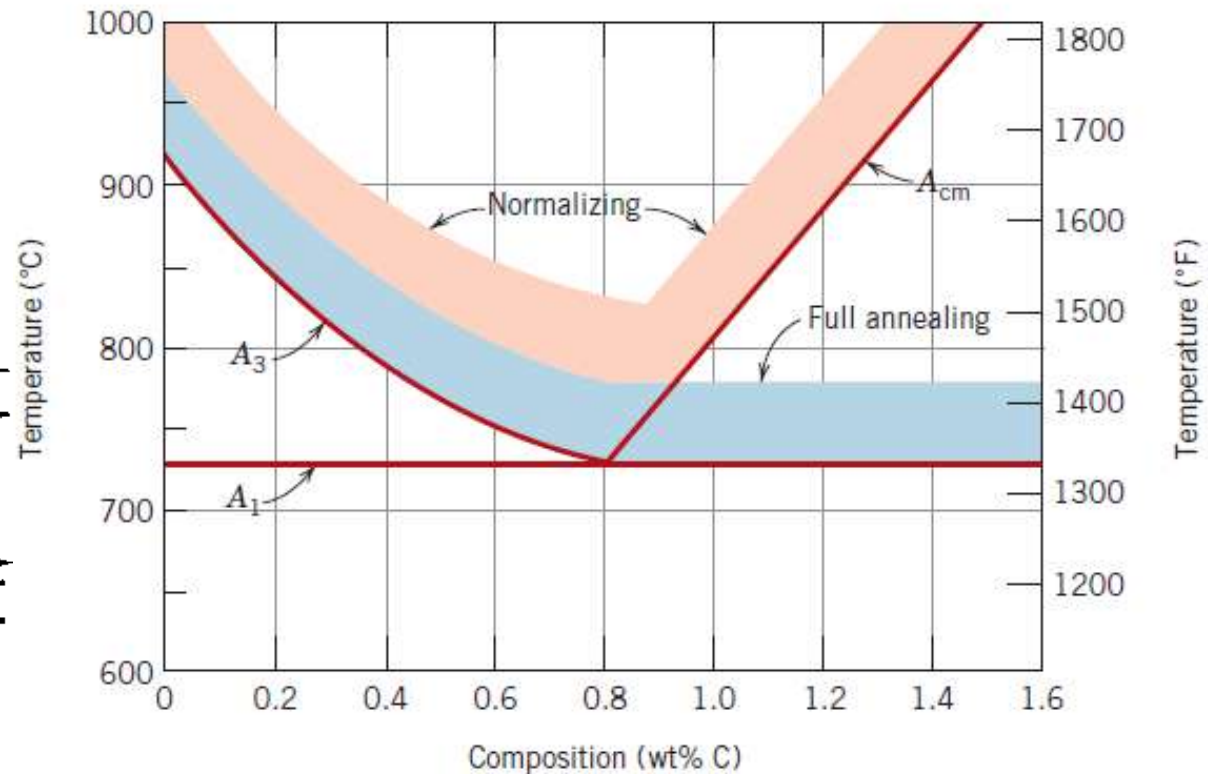
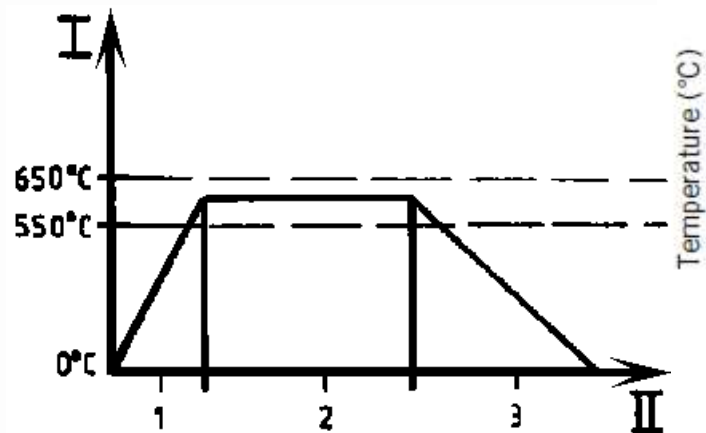
Temperature Range for Heat Treatment of Carbon Steels

# Process Annealing

- **Process annealing** is a heat treatment that is used to remove the effects of cold work—that is, to soften and increase the ductility of a previously strain-hardened Material for further deformation.
- It is usually done between different stages of cold working.
- When steel is cold-worked, strain hardening occurs and thereby difficult to machine, during process annealing, the material will be softened and improved machinability.
- During process annealing, the material is heated to a range of 550-650 °C, Just below lower critical temperature.



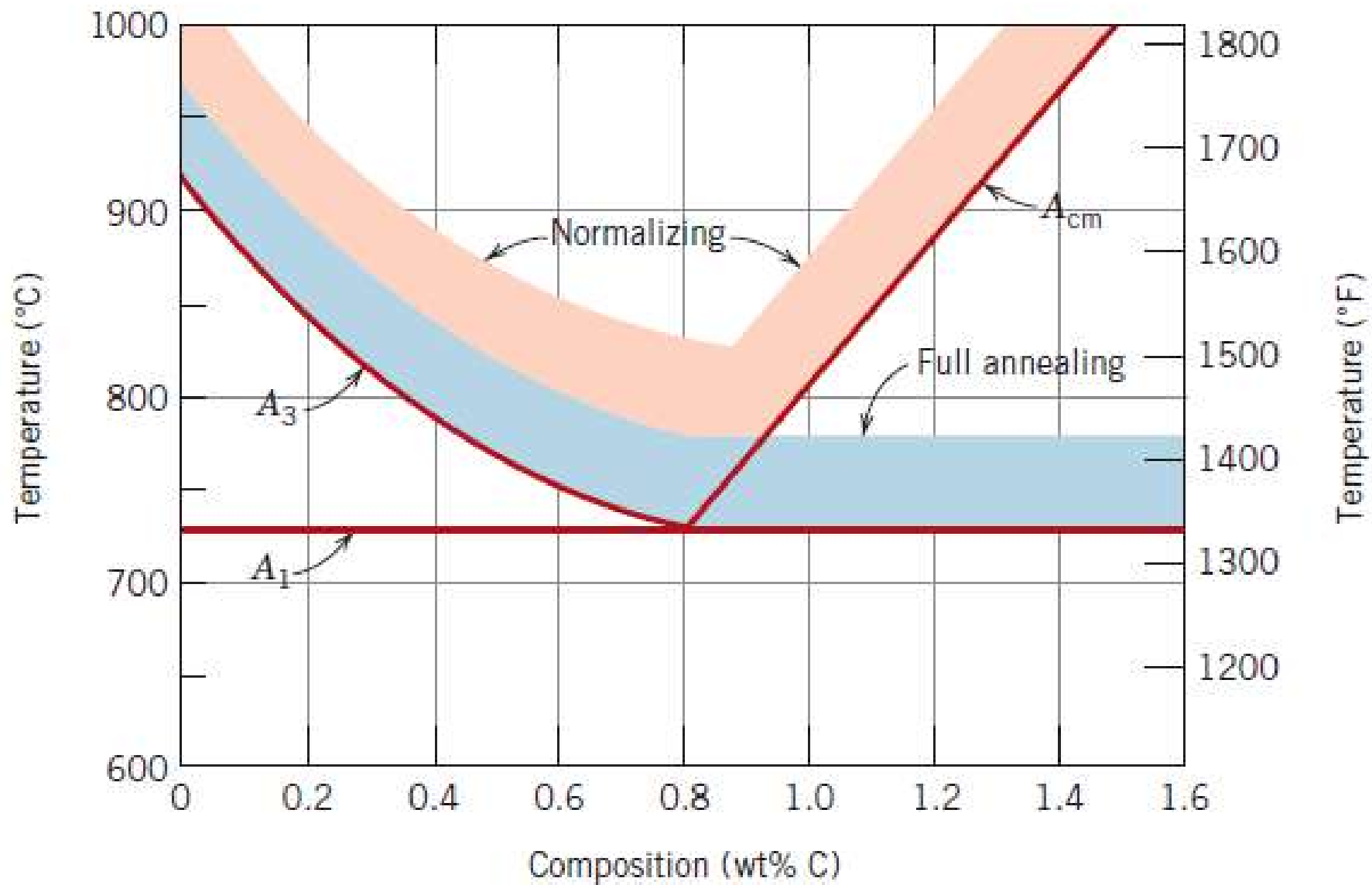




- $A_3$  and  $A_{cm}$  represent the **upper critical temperature** lines, for hypoeutectoid and hypereutectoid steels.
- The horizontal line  $A_1$ , at the eutectoid temperature is termed the **lower critical temperature**

# Full Annealing

- **Full annealing** is often utilized in low- and medium carbon steels, which involves **heating steel to austenite state** followed by **slow cooling**.
- To remove structural imperfections by complete re-crystallization, for materials undergone extensive plastic deformation during a forming operation.
- During full annealing, for compositions less than the eutectoid, the alloy is treated by heating to a temperature of about  $50\text{ }^{\circ}\text{C}$  above the line  $A_3$  to form austenite, process is called as *austenitizing*.
- Upon slow cooling austenite transforms to ferrite and cementite, structure is completely refined and thus result in a softened material.
- For compositions in excess of the eutectoid, the alloy is heated  $50\text{ }^{\circ}\text{C}$  above the  $A_1$  line to form austenite and  $\text{Fe}_3\text{C}$  phases.
- The pearlite transform to austenite and cementite, during slow cooling, austenite transforms back to coarse pearlite and cementite remains the same.
- Coarse pearlite is soft and thus the mechanical properties will be improved, but due to the brittle cementite phase around the pearlite network reduces the machinability of the alloy.

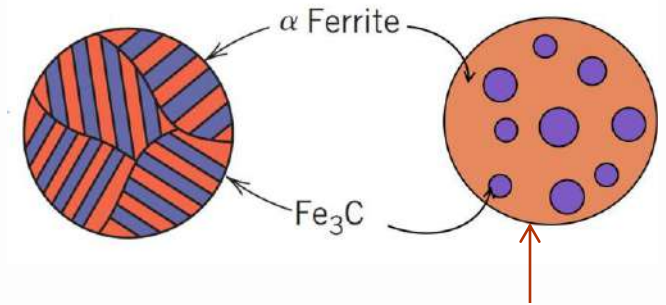
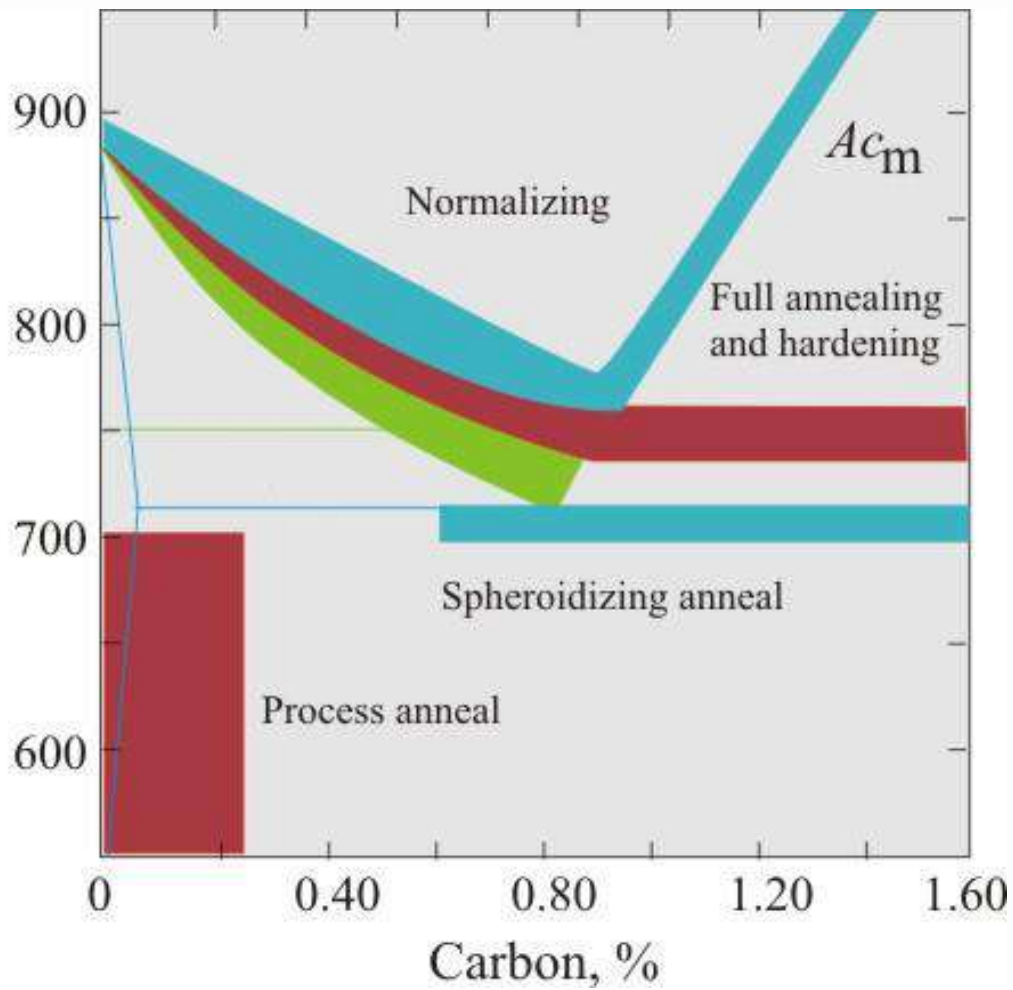


# Spheroidising

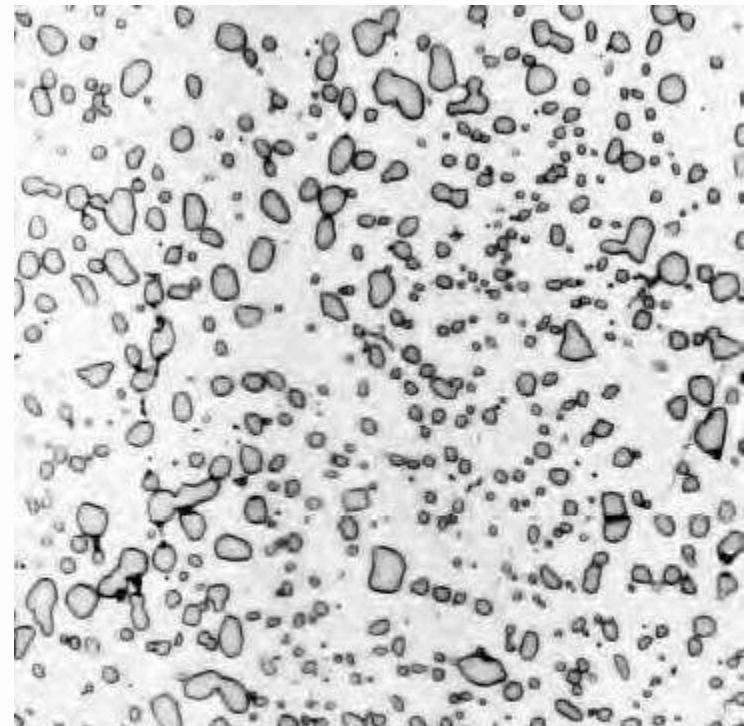
- Medium- and high-carbon steels having a microstructure containing even coarse pearlite may still be too hard to conveniently machine or plastically deform.
- These steels, or any steel, are heat treated or annealed to develop structure with globules or spheroids of cementite in a matrix of ferrite.
- The purpose of spheroidising is to improve machinability for further cold working and to reduce hardness and improve ductility.
- Processes involve heating the alloy at a temperature just below the eutectoid [line  $A_1$ ] in the region of the phase diagram, holding at that temperature for several hours and cooling slowly to room temperature in the furnace itself.
- It is used for high carbon steels ( $>0.6\% \text{ C}$ ), which has the cementite phases, which will be converted to spheroidal structure there by reducing the surface area of the lamellar cementite.
- Generally for the machining of tool steels, spheroidising is done



Temperature, °C

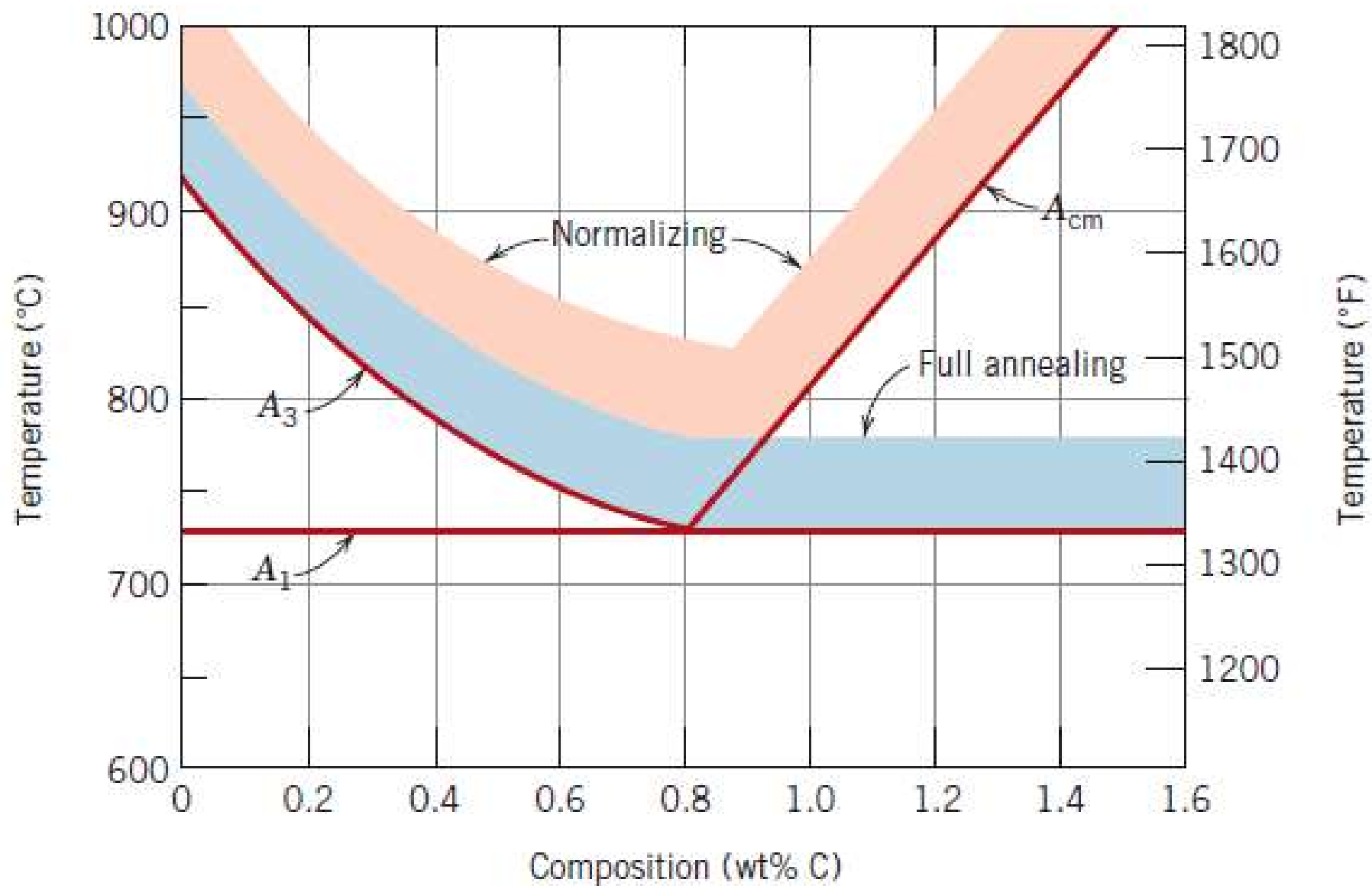


Spheroidite



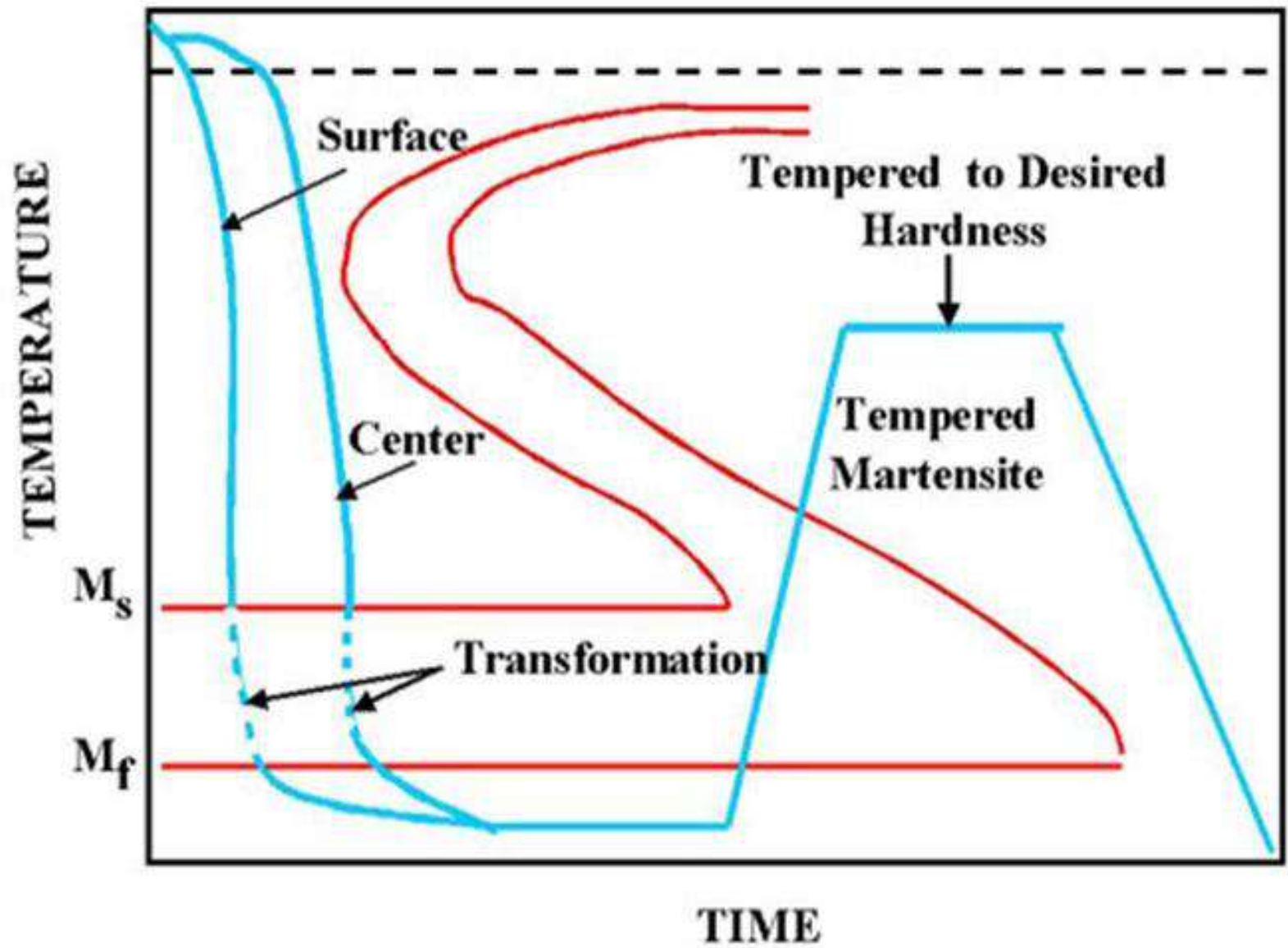
# Normalizing

- Controlling the fineness of pearlite, effect of dispersion strengthening in steel can be managed.
- Normalising uses a faster cooling rate than used in annealing, thereby producing fine pearlite.
- Steels that have been plastically deformed by, for example, a rolling operation, consist of grains of pearlite (and most likely a proeutectoid phase), which are irregularly shaped and relatively large, but vary substantially in size.
- An annealing heat treatment called **normalizing** is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse-grained ones.
- Normalizing is accomplished by heating at least 50 °C above the upper critical temperature—that is, above  $A_3$  line for compositions less than the eutectoid (0.76 wt% C), and above  $A_{cm}$  line for compositions greater than the eutectoid point.
- After sufficient time has been allowed for the alloy to completely transform to austenite—a procedure termed **austenitizing**—the treatment is terminated by cooling in air.



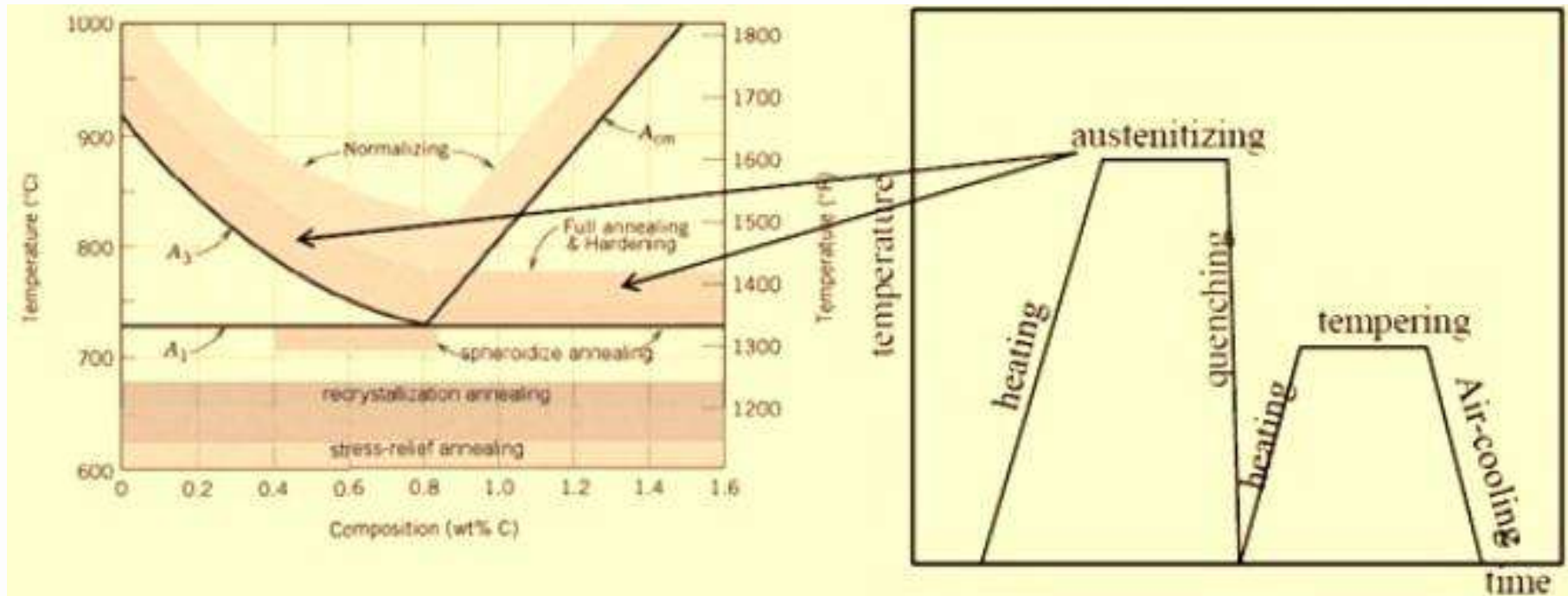
# Hardening

- Heat treatment process to increase the hardness of steel.
- Hardness is attained by the formation of martensite, the hardest microconstituent found in iron carbon system.
- It also improves the wear resistance, and hence to obtain suitable microstructure which will have the desired mechanical properties after tempering.
- This process is suitable for engineering applications which need high strength and hardness; e.g.; cutting tools, knives etc.,
- The first step in hardening process is austenitising; for hypoeutectoid, austenitising temperature is above upper critical temperature and for hyper eutectoid steels it is below lower critical temperature.
- The red hot material is then **cooled rapidly or quenched in water**.
- The quenching results in the formation of martensitic structure.



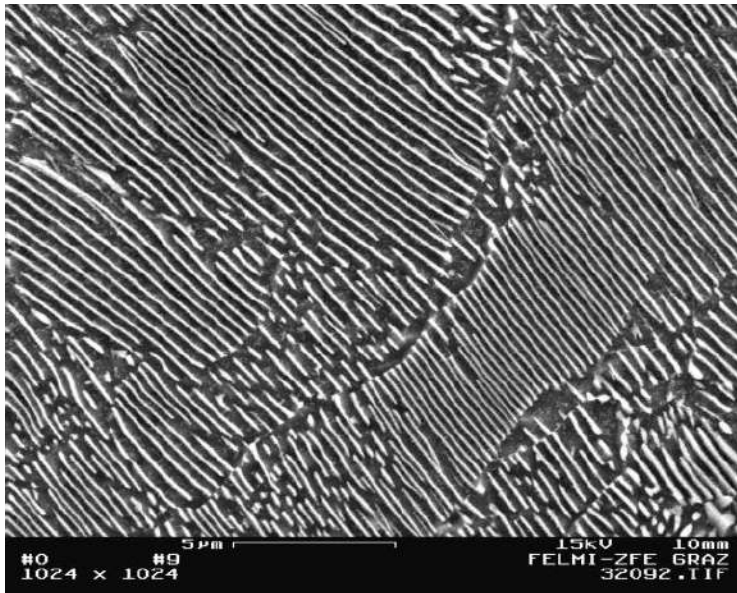
# Tempering

- Heat treatment process immediately follows hardening;
- Steels subjected to hardening are normally very brittle so that even slight impacts can result in fracture of the component.
- Tempering is done to reduce brittleness and to relieve the internal stresses developed during hardening.



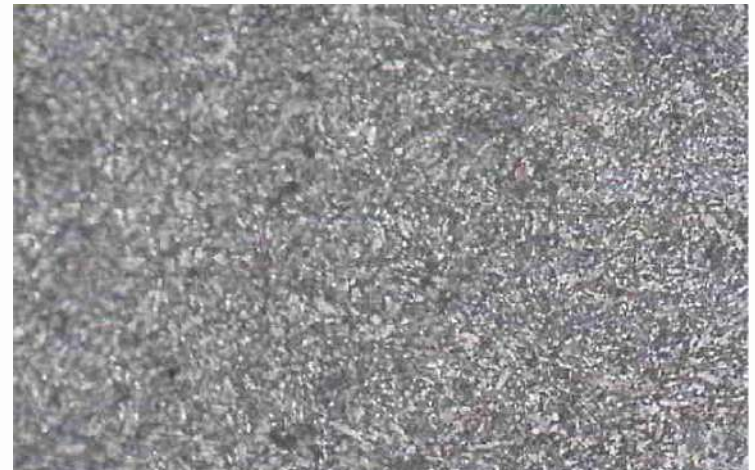
- The temperature varies from 150-680 °C, depending on the purpose for which the hardened component is to be used.
- When low tempering temperatures (150-250 °C) are used; internal stresses will be removed, at the same time toughness and ductility are improved without significant loss in hardness.
- When tempering is done between 300-450 °C; the resulting microstructure consists of martensite, together with a fine pearlite structure called *troostite*.
- This leads to decrease in hardness and strength with an increase in ductility.
- Used for components like; springs, chisels, hammers etc.
- High temperature annealing is done above 450 °C, at this temperature martensite transforms to another structure called *sorbite*.
- *Sorbite* has high ductility with adequate hardness and strength.





Troostite

Sorbite



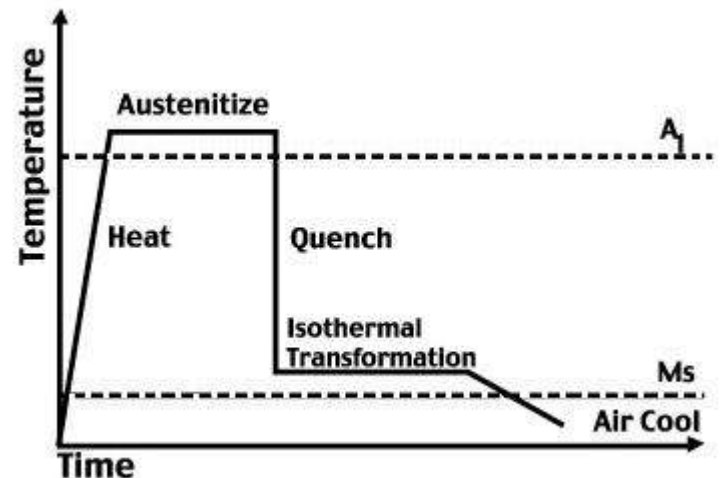
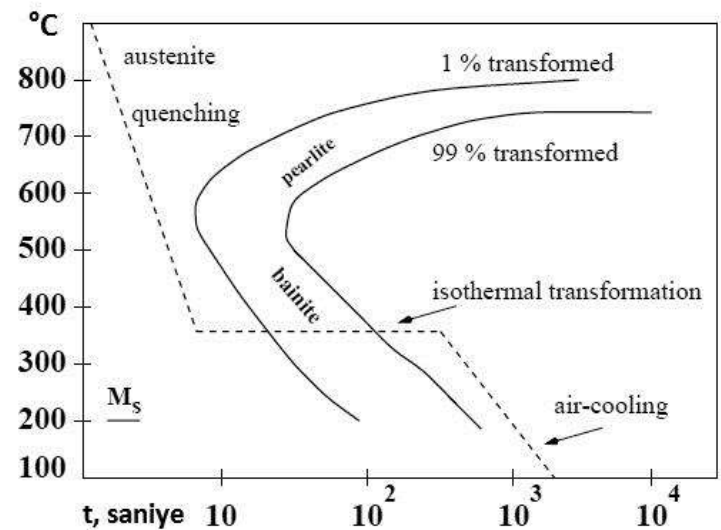


# Isothermal heat treatments

- As the martensitic structures are formed during quenching; the material gets hardened, at the same time, several internal stresses are developed in the material.
- There can be quench cracks and warping of the components.
- To overcome this, two special purpose process, austempering and martempering are used; which are also called as interrupted quenching process.

# Austempering

- A special heat treatment where austenite is completely transformed to bainite.
- The transformation occurs at a constant temperature therefore the process is also called as *isothermal quenching* or *isothermal hardening*.
- To harden and temper springs and other thin sections and to obtain uniform and consistent hardness along with better ductility, toughness and impact strength.

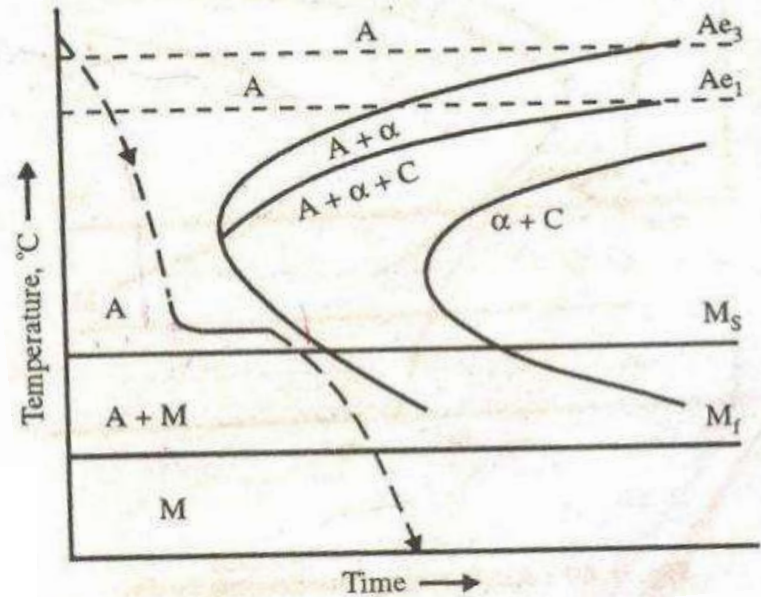


# Austempering

- Austempering begins by heating the steel above the austenitising temperature.
- It is then quenched in molten salt bath maintained at a constant temperature (200-400 °C).
- After holding the steel at this temperature for sufficiently long time, it is then cooled in air.
- On quenching from austenite to bainite range and holding at that point for sufficient time, the complete transformation to bainite structure take place.
- The austempered steel are uniform through out the section, but it is limited to fairly thin sections.

# Martempering

- Similar process to that of austempering, except that the component is slowly cooled through the martensite transformation range.
- The process is used to harden steel minimizing distortion, cracking and residual stresses.
- In the process, steel austenitized is rapidly cooled to 180-250 °C using a salt bath maintained at this temperature.
- After holding the component in the bath for sufficient time, the component will be air cooled to room temperature.

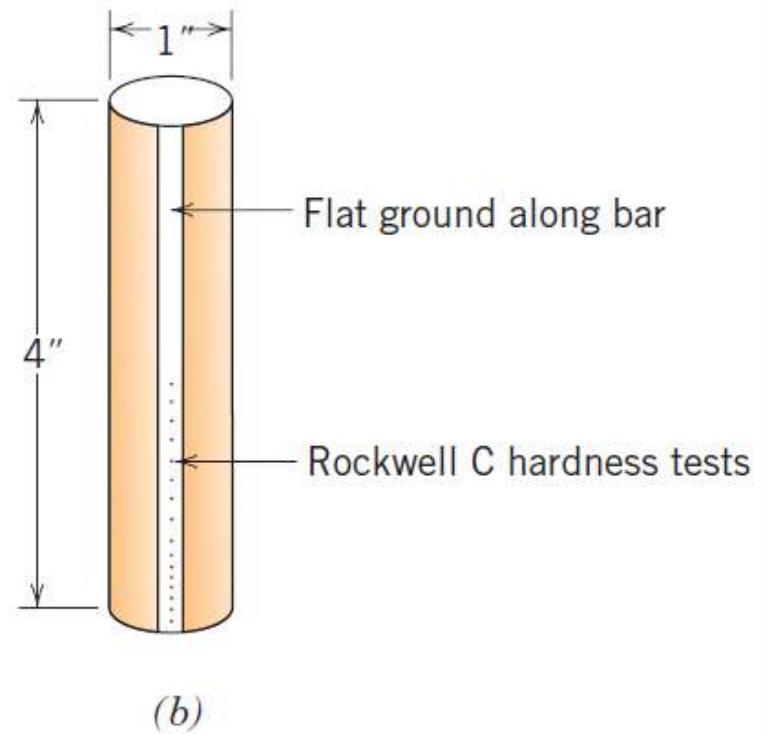
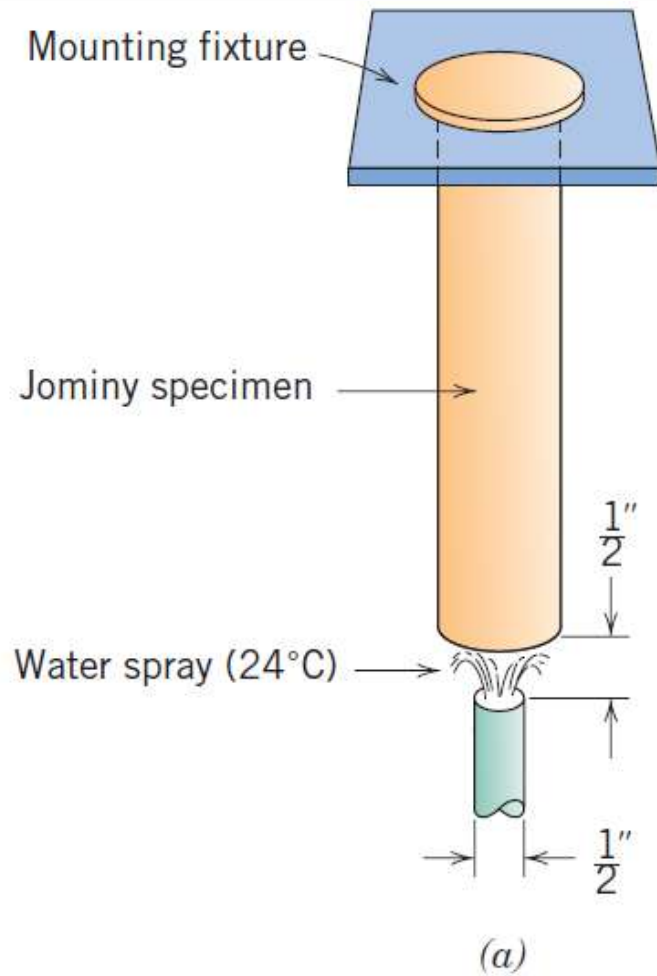


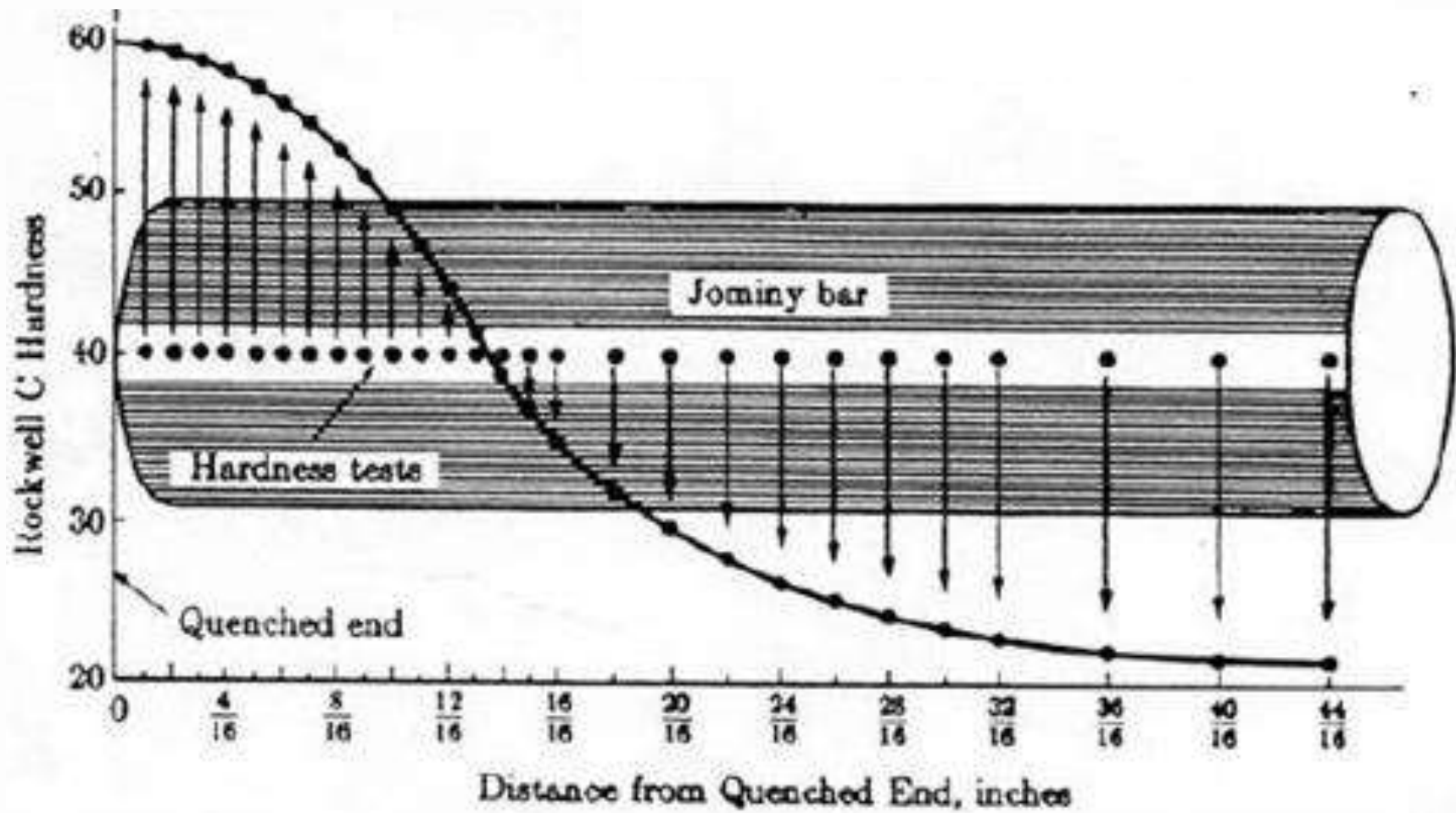
# Hardenability

- “Hardenability” is a term that is used to describe the ability of an alloy to be hardened by the formation of martensite as a result of a given heat treatment.
- The influence of alloy composition on the ability of a steel alloy to transform to martensite for a particular quenching treatment is related to a parameter called hardenability.
- For every different steel alloy there is a specific relationship between the mechanical properties and the cooling rate.
- **Hardenability is not “hardness,”** hardness is the resistance to indentation; whereas, *hardenability is a qualitative measure of the rate at which hardness drops off with distance into the interior of a specimen as a result of reduced martensite content.*
- A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but to a large degree

# Hardenability- Jominy end quench test.

- One standard procedure that is widely utilized to determine hardenability is the *Jominy end-quench test*.
- In this test, except for alloy composition, all factors that may influence the depth to which a piece hardens (i.e., specimen size and shape, and quenching treatment) are maintained constant.
- A cylindrical specimen of standard size, 25.4 mm (1.0 in.) in diameter and 100 mm (4 in.) long is austenitized at a prescribed temperature for a prescribed time.
- After removal from the furnace, it is quickly mounted in a fixture as shown in **Figure**.
- The lower end is quenched by a jet of water of particular flow rate and temperature.
- Thus, the cooling rate is a maximum at the quenched end and diminishes with position from this point along the length of the specimen.
- After the piece has cooled to room temperature, flat levels of 0.4 mm deep are ground (grinding) along the specimen length and Rock-well hardness measurements are made for the first 50 mm along each flat; for the first 12.8 mm, hardness readings are taken at 1.6 mm intervals, and for the remaining 38.4 mm, every 3.2 mm.

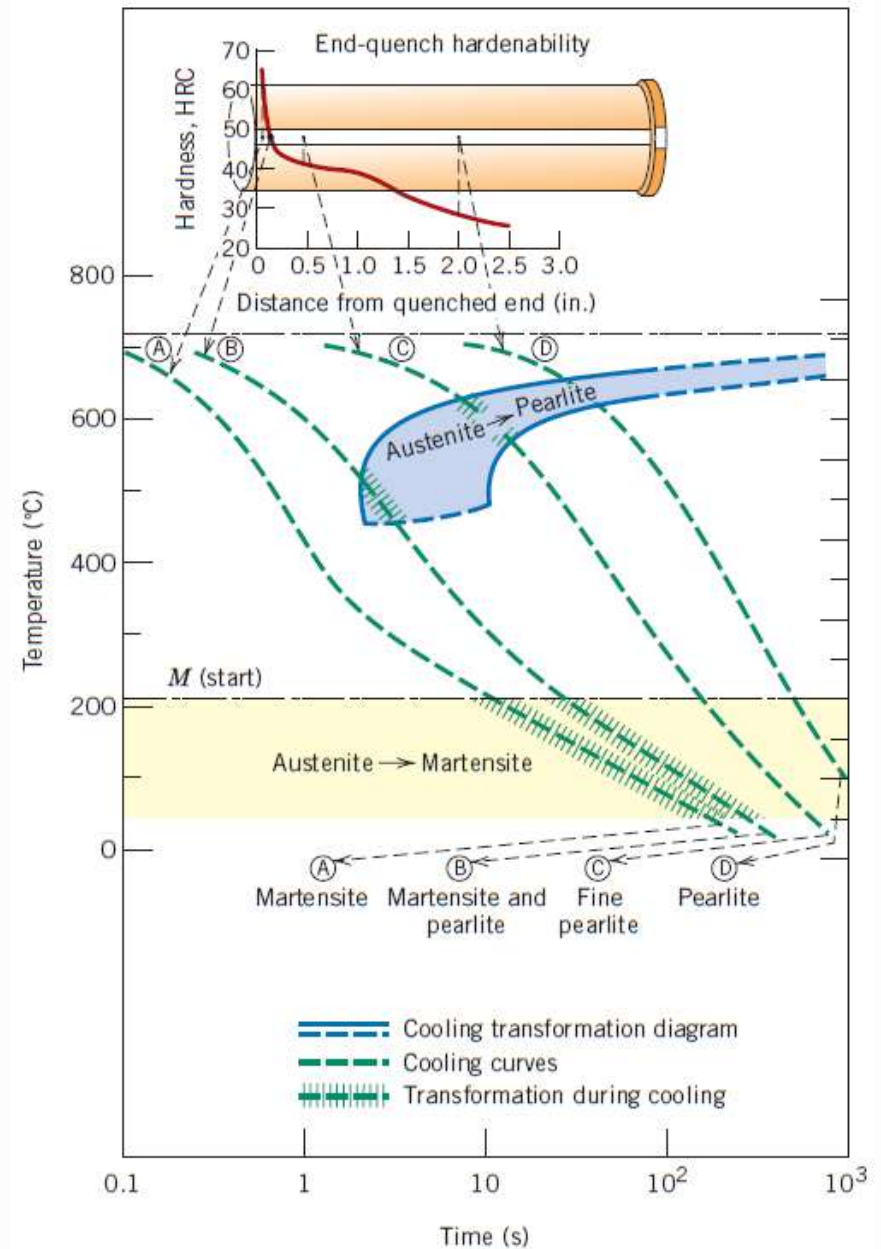
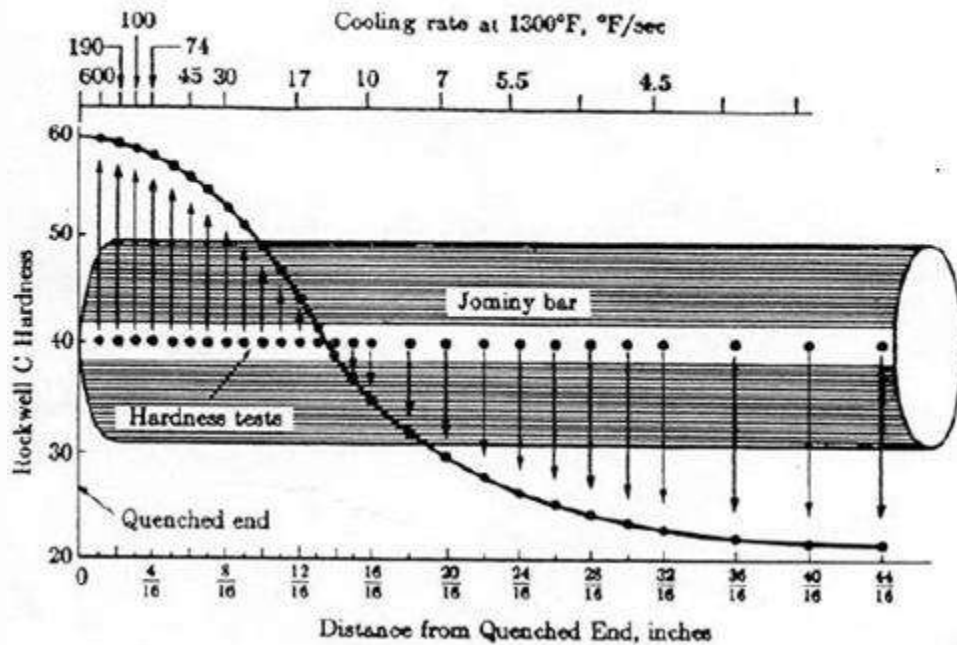






- In a typical hardenability curve the quenched end is cooled most rapidly and exhibits the maximum hardness; 100% martensite is the product at this position for most steels.
- Cooling rate decreases with distance from the quenched end, and the hardness also decreases, as indicated in the figure.
- With a reduction in cooling rate, more time is allowed for carbon diffusion and the formation of a greater proportion of the softer pearlite, which may be mixed with martensite and bainite.
- Thus, a steel that is highly hardenable will retain large hardness values for relatively long distances; a low hardenable one will not. Also, each steel alloy has its own unique hardenability curve.

# Jominy Quench



- Sometimes, it is convenient to relate hardness to a cooling rate rather than to the location from the quenched end of a standard Jominy specimen.
- Cooling rate [taken at 700 °C] is ordinarily shown on the upper horizontal axis of a hardenability diagram; this scale is included with the hardenability plots presented here.
- This correlation between position and cooling rate is the same for plain carbon and many alloy steels because the rate of heat transfer is nearly independent of composition.
- On occasion, cooling rate or position from the quenched end is specified in terms of Jominy distance, one Jominy distance unit being 1.6 mm.

- A correlation may be drawn between position along the Jominy specimen and continuous cooling transformations.
- A continuous cooling transformation diagram for a eutectoid iron–carbon alloy onto which are superimposed the cooling curves at different Jominy positions, and corresponding microstructures that result for each.

# Surface Treatments (Surface hardening)

- ✓ Diffusion methods (case hardening)
- ✓ Selective hardening methods
- ✓ Layer additions
- ✓ Metal Coating

# Surface Treatments

## ☐ Diffusion methods

(case hardening)

- ✓ Carburising
- ✓ Cyaniding
- ✓ Nitriding
- ✓ Carbonitriding

## ☐ Selective hardening methods

- ✓ Flame hardening
- ✓ Induction hardening
- ✓ Laser hardening
- ✓ Electron Beam Hardening

## ☐ Layer additions

- ✓ Physical vapour deposition
- ✓ Chemical vapour deposition
- ✓ Thermal spraying

## ☐ Metal Coating

- ✓ Galvanising
- ✓ Electroplating
- ✓ Metal cladding

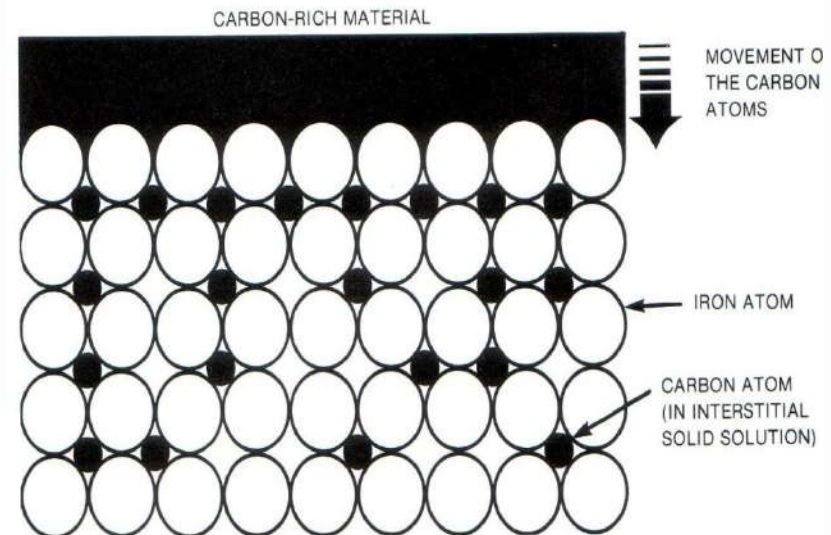
# Surface Hardening with change in chemical composition

## Case Hardening

- The primary purpose of case hardening is to produce a surface which is resistant to wear while maintaining the overall toughness and strength of the steel core.
- Normally used on steel with a low carbon content and introduces **carbon by diffusion** (carburising) into the local surfaces requiring treatment.
- Heating steel in the presence of a solid, liquid or gas rich in carbon.

# Carburising

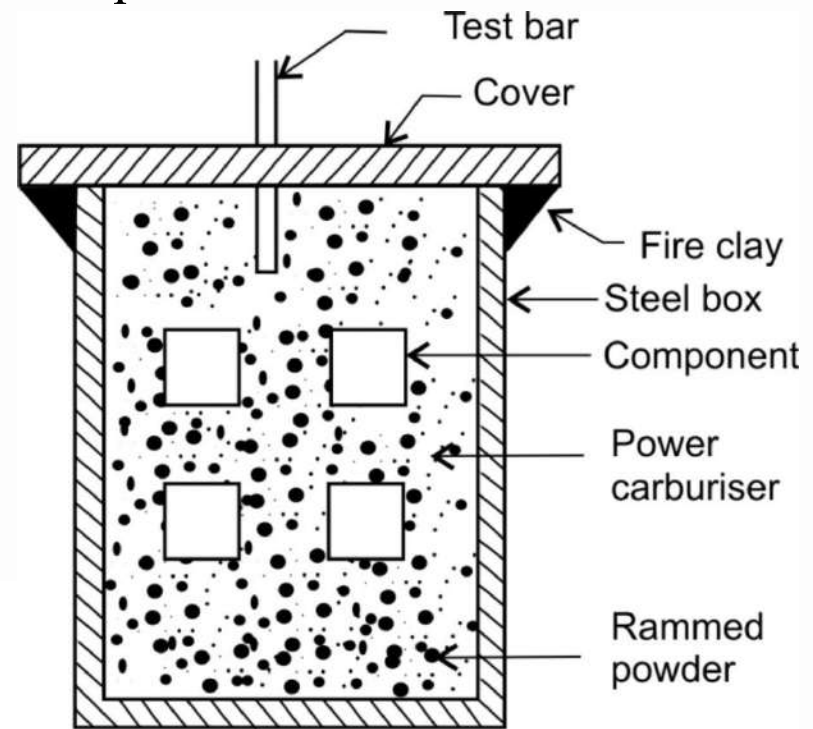
- ✓ The carbon content will be 1.2% after treatment and before 0.25 W%.
- ✓ This method is used for producing steel having tough inner core and hard outer surfaces.
- ✓ Case hardened materials are capable of absorbing shock waves and resist wear.
- ✓ The process involves heating of steel in contact with a carbon-rich substance above critical temperature for a prolonged duration
  - Solid or pack carburising
  - Gas carburising
  - Liquid carburising





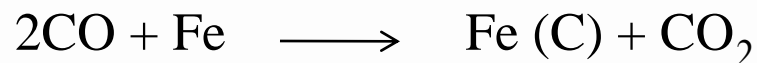
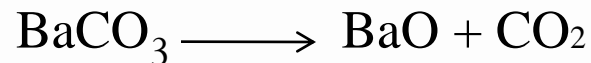
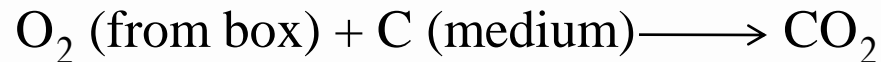
# Pack Carburising

- In this process, solid substances which are rich in carbon; *coke, coal, charcoal, carbon black, carbonates of Barium, sodium or calcium* are used.
- The steel object to be hardened is cleaned and placed in the middle of the carbon rich substances in a steel chamber.
- The chamber will be heated to the desired temperature.
- The soaking time is depend on the depth of penetration required.
- Heating is done in heat treatment furnaces at a temperature Above upper critical temperature; for 5-10 hours for a satisfactory penetration.
- The steel will be austenitised at this temperature and can absorb carbon up to 1.2%.
- The carbonatious materials releases carbon



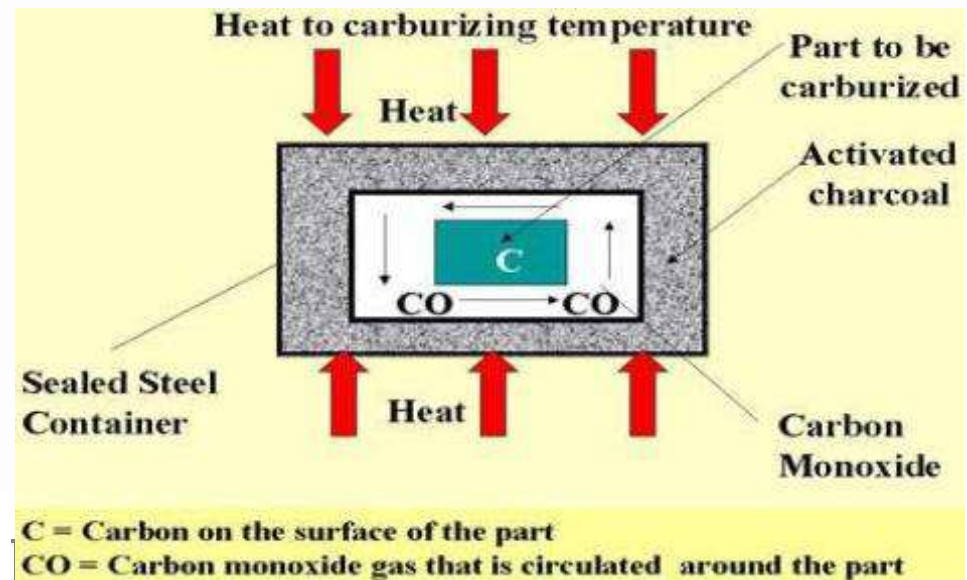
# Solid carburising

- ❖ Components to be carburised packed with a compound rich in carbon, in steel or CI boxes and sealed with clay
- ❖ **If not sealed** properly medium comes in contact with air and burns without carburising
- ❖ **Medium:** 50 to 55% hardwood charcoal, 30 to 32% coke and remaining energiser or accelerator like  $\text{BaCO}_3$
- ❖ **Process:**
  - Heating boxes in a furnace **up to 930 °C**
  - Holding for definite period till required case depth is achieved
  - Cooling
- ❖ High temperature helps in absorption of carbon on surface
- ❖ **Reactions:**



# Gas Carburising

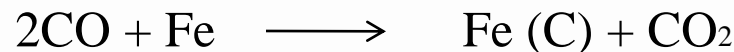
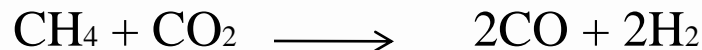
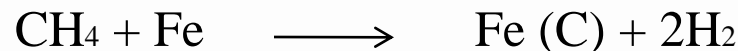
- The component is *heated above austenitising temperature* in the presence of carbon rich gases like; ***methane, propane, butane or carbon dioxide*** in a closed chamber.
- At high temperature the hydrocarbons decompose and carbon will get deposited on the surface.
- The thickness of hardened case is depend on the gas flow rate.
- Used for the hardening of ball and roller bearing, pins axles etc.
- The process is cleaner than the pack carburising process.
- Gas carburising is faster than pack carburising.
- Requires less labour and handling
- The case depth can be controlled effectively.
- Suitable for carburising in large quantities.
- Materials and gases are expensive than pack carburising.



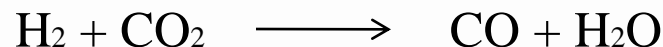
# Gas carburising

- ❖ Components heated in the range of **870 to 950° C** in the presence of **carbonaceous gases** like **methane, ethane, propane or butane** diluted with a carrier gas containing 40% N<sub>2</sub>, 40% H<sub>2</sub>, 20% CO, 0.3% CO<sub>2</sub>, 0.5% CH<sub>4</sub>, 0.8% water vapor and traces of oxygen

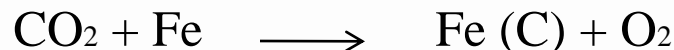
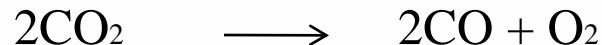
- ❖ **Reactions:**



- Carburising mainly occurs due to CO to CO<sub>2</sub> conversion
- H<sub>2</sub> reacts with CO<sub>2</sub> and increases CO concentration



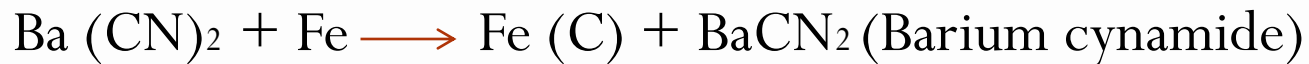
- Traces of oxygen are also present due to the following reactions;



- ❖ **To avoid dead spots and formation of soot:** Control on gas composition and proper circulation of gas is essential for constant and uniform rate of carbon

# Liquid carburising

- A liquid, rich in hydrocarbon, is used in a bath or in a pressurized system.
- Also known as salt bath carburising
- Carburising done by immersing the steel components in a carbonaceous fused salt bath **medium containing** sodium or potassium cyanide, sodium and potassium chloride and barium chloride which acts as a activator
- Bath heated in the range of **815 – 900 °C**
- **Reactions:**



- Some beneficial nitrogen may also diffuse through oxidation of sodium cyanide



- Nitriding helps in increasing hardness and wear resistance

# Liquid carburising

## Advantages

- Uniform and rapid heat transfer
- Low distortion
- Negligible surface oxidation
- High uniformity in case depth and carbon content

## Disadvantages

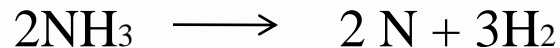
- Highly poisonous sodium cyanide; hence care should be taken while storage, use and disposal
- Salt sticks to the components and must be removed while washing

# Nitriding

- Applicable to **alloy steels** containing **nitride forming elements** like Al, Cr, Mo, V and W
- Process carried out at **550° C**; hence **no phase transformation**
- Proper heat treatment is necessary before nitriding
- All machining and grinding operations to be completed before nitriding
- Area not to be nitrified to be covered by depositing tin by electrolysis

## Two types:

- Liquid nitriding: Same reactions as that of liquid carburising except only N diffusion because of low temperatures
- Gas nitriding: Anhydrous ammonia gas is passed which dissociates into nascent nitrogen and hydrogen



- Treatment time depends upon case depth and size; usually 21hrs to 100hrs
- **Nitriding time** of 100hrs for **case depth** of 0.5mm @ 550° C
- **Case hardness:** 900-1100VHN

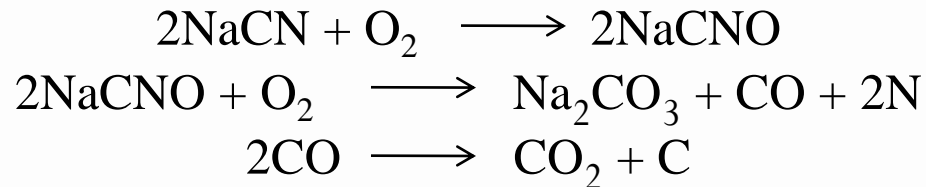
# Nitriding

- ❖ **Applications:** Precision gears, boring bars, forming rolls for paper and rubber, forming dies, camshafts, crankshafts, cylinder liners
- ❖ **Advantages:**
  - No post heat treatment; hence minimum distortions
  - High fatigue life
  - Better corrosion resistance than carburised and hardened components
  - Excellent bearing properties (Non metallic nature of nitrides, less coefficient of friction)
  - High hardness than carburised and hardened components
  - High hot hardness
- ❖ **Disadvantages:**
  - Applicable only to alloy steels containing nitriding elements
  - Thin case depth



# Cyaniding

- ❖ **Applicable** to steels with 0.3 to 0.4% C
- ❖ Surface hardened by addition by **addition of carbon and nitrogen**
- ❖ **Process:**
  - **Medium:** Parts immersed in liquid bath containing NaCN varying between 25% and 90%
  - Bath heated in the range of **800 to 960° C**
  - **Measured amount of air** passed through the molten bath
  - **Reactions:**



- C and N<sub>2</sub> so formed diffuse into steel and give thin wear resistant layer of carbonitride phase
- **Quenched** in oil or water
- Low temperature **tempering**
- ❖ **Cyaniding time** of 1.5 to 6hrs for **case depth** of 0.13 to 0.35mm @ 850° C
- ❖ Higher the temperature, higher the C diffusion (0.8 to 1.2%) on surface as compared to N (0.2 to 0.3%)

# Cyaniding

## ❖ Advantages:

- Less time consuming
- Less distortion due to use of salt bath

## ❖ Disadvantage:

- Not suitable for components subjected to shock, fatigue and impact because nitrogen has adverse effect on these properties

## ❖ Difference between cyaniding and liquid carburising:

- Absence of alkaline earth salts in cyaniding
- High % of NaCN in case of cyaniding
- High N and lower C in case of cyaniding
- Thin cases in cyaniding

# Carbonitriding

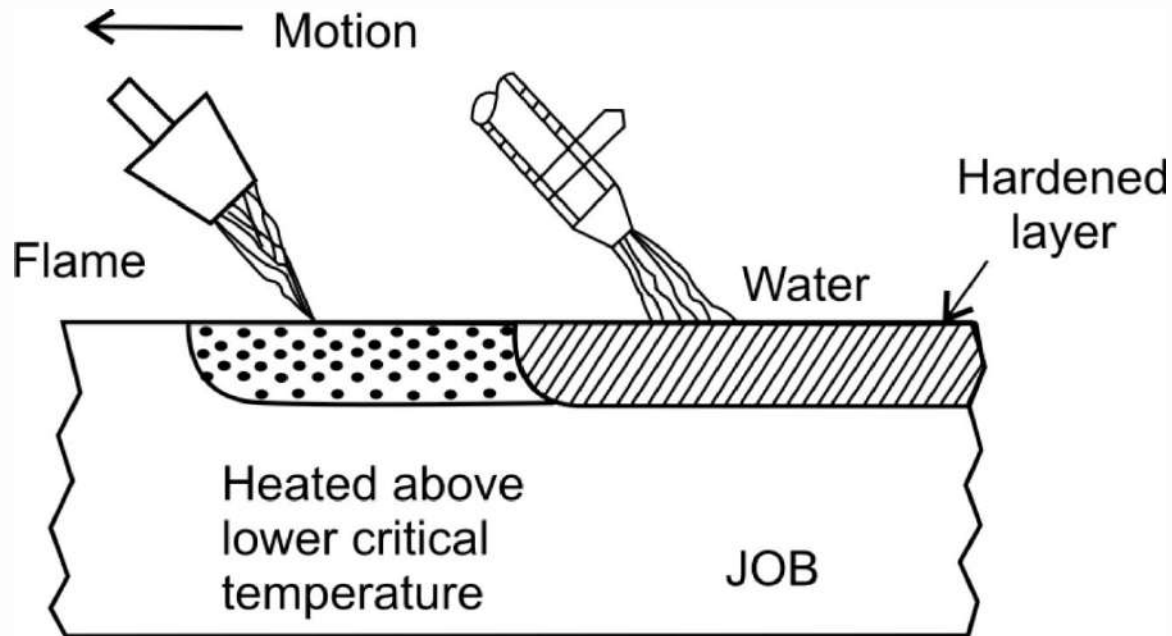
- ❖ Also known as **dry cyaniding, gas cyaniding, and ni-carbing**
- ❖ **Applicable** to steels with 0.3 to 0.4% C
- ❖ Surface hardened by addition by **addition of carbon and nitrogen**
- ❖ **Used** to improve wear resistance of mild steel and low alloy steel
- ❖ **Process:**
  - **Medium:** Gas mixture consisting of 15%  $\text{NH}_3$ , 5%  $\text{CH}_4$  and 80% neutral carrier gas
  - Heated in the range of **800 to 870° C**
  - C and  $\text{N}_2$  diffuse into steel
  - **Quenching in oil** to avoid cracking
  - **Tempering** @ 150 to 180° C
- ❖ **Case depth** : 0.05 to 0.75mm
- ❖ **Case hardness:** 850VHN
- ❖ Nitrogen is more effective in increasing hardenability as compared to carbon
- ❖ Nitrogen content depend upon ammonia and temperature
- ❖ **Advantages:**
  - Surface hardenability, wear resistance and corrosion resistance better than carburising

# Surface Hardening with no change in chemical composition

## Flame Hardening

- Heating the surface being hardened above the upper critical temperature with an oxy acetylene flame before quenching it in a spray of water.
- This is a surface hardening process resulting in a hard surface layer of about 2 mm to 6 mm deep.
- The main difference between this process and other surface hardening processes is that the composition of the steel being hardened is not changed.
- An oxy-acetylene flame is use to heat the part locally up to a temperature of 850 °C, followed by quenching using water jet.

# Flame Hardening



# Flame hardening

❖ **Applicable to steels with %C = 0.3 to 0.6**

❖ **Process:**

- Heating above upper critical temperature (here A3) by oxyacetylene flame
- Cooling by spraying of jet of water or immersion in water
- Reheating in furnace or oil bath @ 180 to 200° C for stress relieving
- Hardness in flame hardened steel is due to lower bainite or martensite structure

❖ **Case depth is up to 6 mm**

❖ **High heating rate to avoid oxidation and decarburisation**

❖ **Less distortions**

❖ **Selective areas can be hardened**

❖ **Different methods of flame hardening:**

- **Spot or stationary:** Shaft ends, large gears etc
- **Progressive:** Guideways, flat surfaces etc
- **Spinning:** Shafts, wheels, pulleys etc
- **Combination of progressive and spinning:** Piston rods, Rolls etc

❖ **Applications:** Crankshaft, axle, large gear, cam, bending roller etc

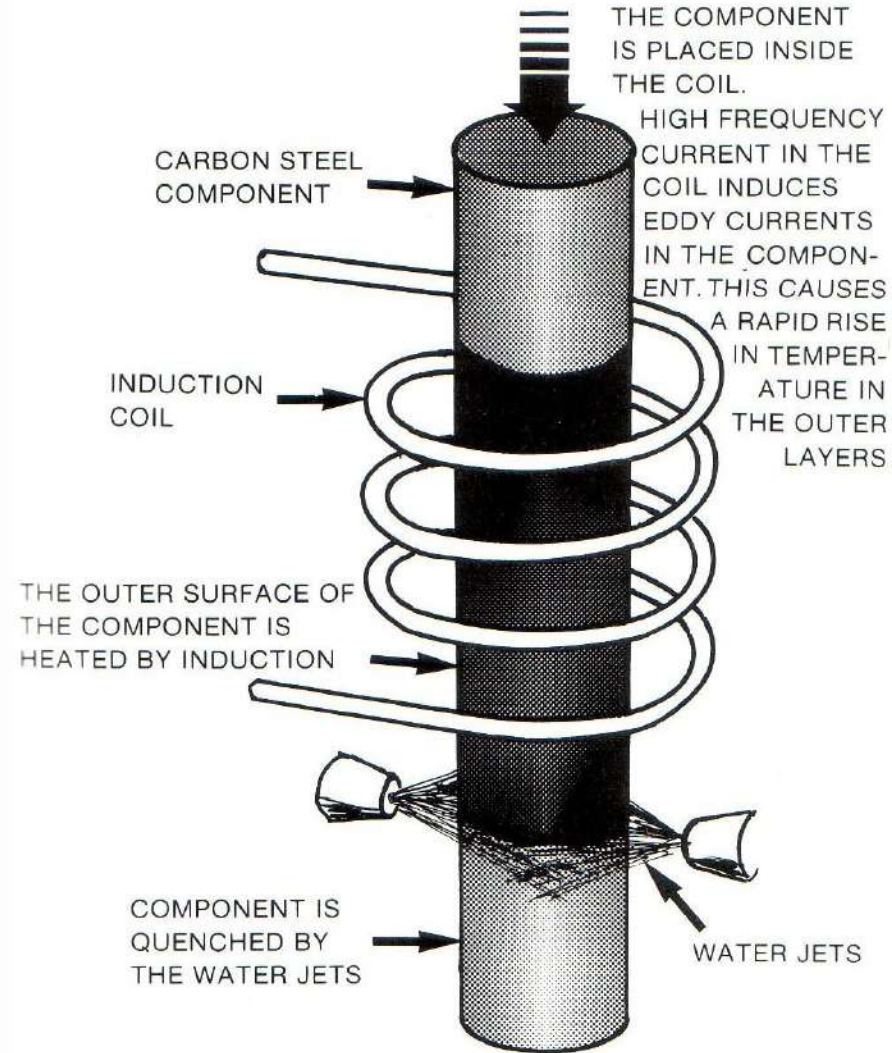
# Induction hardening

- ❖ **Hard steel at the surface and soft core .**
- ❖ **Applicable** to steels with %C = 0.4 to 0.5 and some alloy steels
- ❖ **Process:**
  - Heating done by electromagnetic induction
  - Within a short period of 2 to 5 minutes, the temperature of surface layer comes to above upper critical temperature
  - Quenched by jet of cold water
  - Temperature is 700 to 800 °C
  - Sometimes self tempering may also occur
- ❖ **Skin effect:** Depth of hardened layer is inversely proportional to square root of frequency of induced current
- ❖ In addition to the direct heating of the skin by induced current, there is also some heating of the core due to conduction of heat. Hence overall depth of hardness is increased
- ❖ **Case depth:** 0.5 to 6 mm in 1-5 seconds
- ❖ **Applications:** Crankshaft, camshaft, gears, crankpins, axles, boring bars, brake

# Induction hardening

## Advantages:

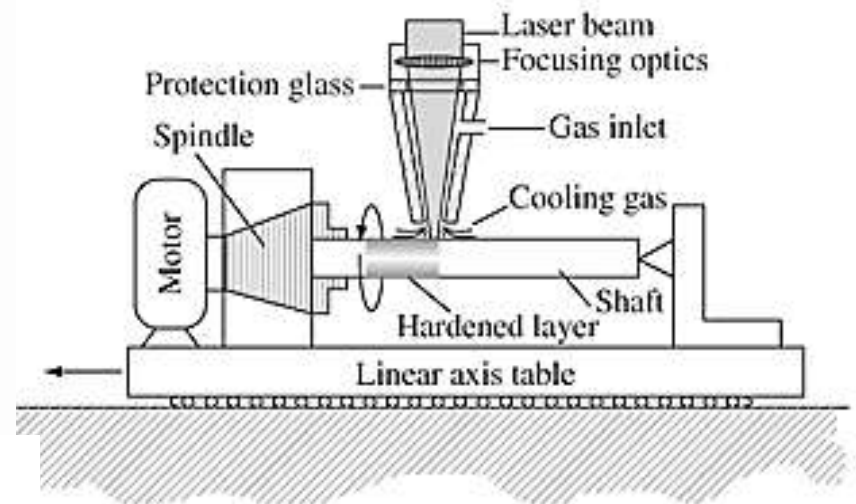
- Original toughness and ductility remain unaffected
- Fast heating and no holding leads to increase in production rates Suitable for automation.
- No scaling and decarburisation
- Less distortion because of heating of only required surface
- Easy control over the depth of hardening by control of frequency of supply voltage and/or time of holding
- Cleanliness of working conditions
- Only a light final grinding or lapping operation may be required after hardening
- Irregular shaped parts are suitable for induction hardening; cams, gear tooth, piston





# Laser beam hardening

- A laser source is used as heating source.
- A phosphate coating is applied on the work piece for the absorption of laser.
- When exposed to laser, the parts are heated 900-1400 °C locally.
- By varying the power of laser, we can control the heat absorption.
- At first, the zone to be hardened is heated to austenitizing range and the rapid cooling converts it into martensitic structure by self quenching.
- **Microstructure:** Laser heat treated steel consists of bainite + ferrite at the surface of heated spot and pearlite + ferrite in the interior.
- This process is suitable for selective heat treatment.
- Greater hardening depth requires a large volume of material to ensure the sudden dissipation of heat.
- Clean process, no work piece cleaning required.
- Suitable for steel with carbon content



# Laser beam hardening

## **Advantages:**

- High production rates
- Effect of heat on surrounding surface is less
- Less time than induction and flame hardening
- Localized treatment is possible
- No external quenching is needed; necessary only for small parts
- No contamination
- Process can be controlled by computer
- Difficult to harden areas can be hardened
- No final machining needed subsequent to hardening

# Electron beam hardening

- ✓ Similar to laser beam hardening, in which the heat source is high energy electrons.
- ✓ Austenitising occurs due to energy transferred by electrons.
- ✓ The martensite formation occurs by self quenching, once the energy transfer is stopped.
- ✓ The surface can be hardened very precisely both in depth and in location.
- ✓ The hardening process depth ranges from 0.1-1.5 mm.
- ✓ The thickness of the material should be 5 to 10 times the austenitising depth.

