Engineering of Metallurgy

ME 2304 - Engineering of Metallurgy (3-2-2-2)

Semester Offered (Fall – Spring)

Spring semester

Prerequisites:-

ME 1301 Principles of manufacturing process

Course Definition:-

Metallurgy is a domain of materials science and engineering that studies the effect of the solidification conditions and heat treatment on structure and properties of the materials. Moreover, its study the mechanical properties of metals, such as: the hardness, stress and strain, and creep. Metallurgical engineers develop ways of processing metals and converting them into useful products. It is also monitor metal corrosion and fatigue and develop ways to strengthen metals.

Course Topics:-

1-Mechanical properties

2-Thermal Equilibrium Diagrams

3-The Iron/ Carbon phase diagram

4-Cast Iron:

5- Heat Treatment

Course Description:-

Crystalline structure of metals. Grains and grain boundaries, Nucleation and dentritic growth, Influence of solidification conditions on structure and properties. Defection cast metals.

Course Objectives:-

To provide an understanding of the crystalline structure of metals. Knowing the Iron/ Carbon phase diagram and the effect of rapid cooling. To know what is the Thermal Equilibrium Diagrams? To know the Heat Treatment processes, stress relieving, Annealing, full annealing, incomplete annealing, Isothermal annealing, diffusing annealing (homogenizing) annealing of casting, spherioidosing.

Course Learning Outcomes:-

After successful completion of this course, the students will be able to:

1- explain the basic concepts of metallurgy.
2- Understand of the crystalline structure, and relate chemical composition, structure and properties of metallic materials.
3- Adjust the structure and properties of metallic materials according to their applications.
4- Describe and understand Thermal Equilibrium Diagrams, Iron/ Carbon phase diagram and Heat Treatment processes

Lab Experiments:

Microstructure's test, Hardness test, Irone phase test and heat treatment test

Recommended Textbooks

The metallurgy: structure, properties and heat treatment by D. J. D. and L. A. O.

Materials and Processes in Manufacturing by E.P Degarmo.

Materials Science and Engineering An Introduction by William D. Callister, Jr..

Introduction:-

All the things around us are made of 100 or so elements. These elements were classified by Lavoisier in to metals and non-metals by studying their properties. The metals and non-metals differ in their properties

Metals:

The valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together. Metals are usually strong, conduct electricity and heat well and are opaque to light (shiny if polished). Examples: aluminum, steel, brass, gold.

The main properties of it:-

1. The usually have a crystalline structure and are good thermal and electrical conductors.
2. Many metals have high strength and high elastic module.
3. They maintain their good strength at high and low temperature.
4. They also have sufficient ductility which is important for many engineering applications.
5. The can be strengthened by alloying and heat treatment.
6. They are last resistant to corrosion.

CRYSTAL STRUCTURE OF METALS:-

Introduction

Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another.A crystalline material is one in which the atoms are situated in a repeating or periodic array over large atomic distances; that is, long-range order exists, such that upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest-neighbor atoms. All metals, many ceramic materials, and certain polymers form crystalline structures under normal solidification conditions

crystal structure:-

Some of the properties of crystalline solids depend on the crystal structure of the material, the manner in which atoms, ions, or molecules are spatially arranged. There is an extremely large number of different crystal structures all having long range atomic order; these vary from relatively simple structures for metals to exceedingly complex ones, as displayed by some of the ceramic and polymeric materials. The present discussion deals with several common metallic crystal structures.

Crystal Structure:-

• Solid materials classified according to regularity with which atoms or ions are Arranged with respect to one another - over large atomic distances • atoms bonded to nearest neighboring atom.

• All metals, many ceramic materials, certain polymers form crystalline Structures on solidification

• Unit cell (small repeating entities) - basic structural unit or building block of the Crystal structure and defines the crystal structure by virtue of its geometry and the atom positions within.

• Solidification process

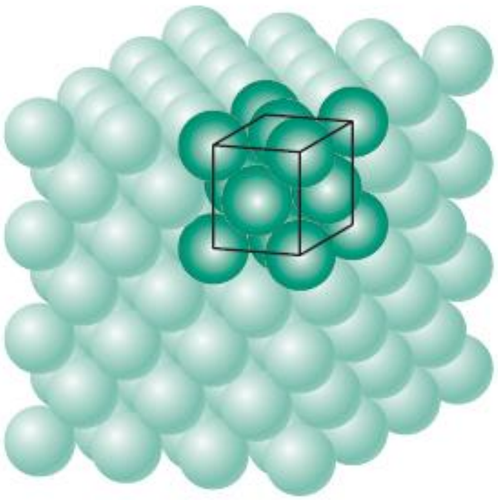
• Amorphous material (non-crystalline) - atomic structure resembles that of a liquid (super cooled liquid); rapid cooling e.g. $SiO2$, inorganic gases, polymers

• Atomic hard sphere model ; Lattice Structure, Space lattice

- Lattice parameters of a unit cell (as show)

UNIT CELLS:-

The atomic order in crystalline solids indicates that small groups of atoms form a repetitive pattern.Thus, in describing crystal structures, it is often convenient to subdivide the structure into small repeat entities called unit cells. Unit cells for most crystal structures are parallelepipeds or prisms having three sets of parallel faces; one is drawn within the aggregate of spheres (Figure 3.1c), which in this case happens to be a cube. A unit cell is chosen to represent the symmetry of the crystal structure, wherein all the atom positions in the crystal may be generated by translations of the unit cell integral distances along each of its edges. Thus, the unit cell is the basic structural unit or building block of the crystal structure and defines the crystal structure by virtue of its geometry and the atom positions within



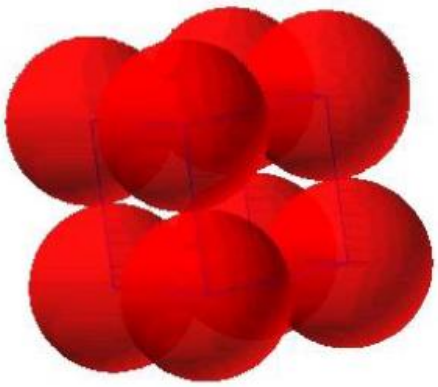
METALLIC CRYSTAL STRUCTURES:-

The atomic bonding in this group of materials is metallic and thus non directional in nature. Consequently, there are minimal restrictions as to the number and position of nearest-neighbor atoms; this leads to relatively large numbers of nearest neighbors and dense atomic packings for most metallic crystal structures. Also, for metals, using the hard sphere model for the crystal structure, each sphere represents an ion core. Table 3.1 presents the atomic radii for a number of metals. Three relatively simple crystal structures are found for most of the common metals: face centered cubic, body-centered cubic, and hexagonal close-packed.

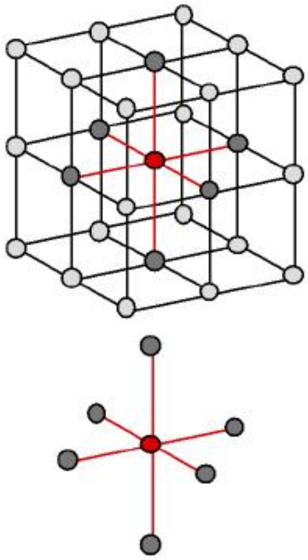
Simple Cubic Structure (SC)

Rare due to low packing density (only Po has this structure)

- Close-packed directions are cube edges



- Coordination # = 6
  (# nearest neighbors)

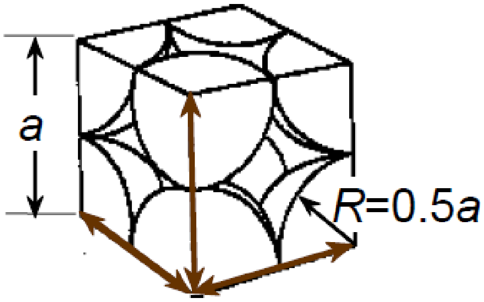


Atomic Packing Factor (APF)

$$APF = \frac{\text{Volume of atoms in unit cell*}}{\text{Volume of unit cell}}$$

*assume hard spheres

- APF for a simple cubic structure = 0.52



close-packed directions

contains 8 x 1/8 =
1 atom/unit cell

$$APF = \frac{\underset{\frac{\text{atoms}}{\text{unit cell}}}{1}\ \overset{\frac{\text{volume}}{\text{atom}}}{\frac{4}{3}\pi(0.5a)^3}}{\underset{\frac{\text{volume}}{\text{unit cell}}}{a^3}}$$

The Face-Centered Cubic Crystal Structure

The crystal structure found for many metals has a unit cell of cubic geometry, with atoms located at each of the corners and the centers of all the cube faces. It is aptly called the face-centered cubic (FCC) crystal structure. Some of the familiar metals having this crystal structure are copper, aluminum, silver, and gold (. Figure below shows a hard sphere model for the FCC unit cell, whereas in Figure 3.1b the atom centers are represented by small circles to provide a better perspective of atom positions. The aggregate of atoms in Figure 3.1c represents a section of crystal consisting of many FCC unit cells. These spheres or ion cores touch one another across a face diagonal; the cube edge length a and the atomic radius R are related through

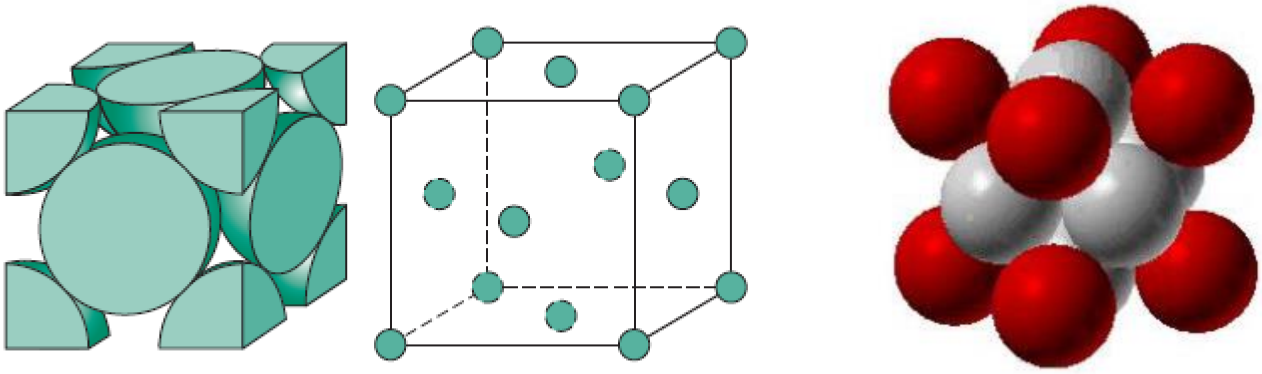


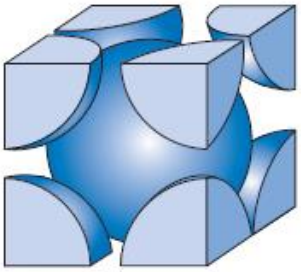
Figure : the face centered cubic crystal structure

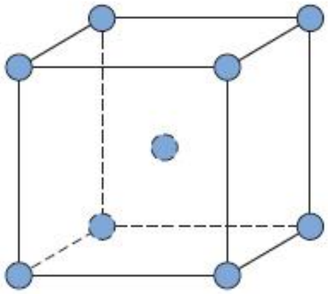
Number of Lattice Points in Cubic Crystal Systems

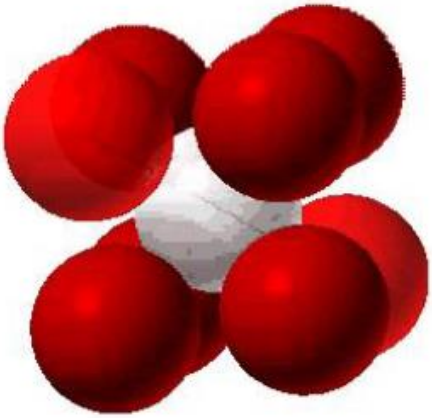
In FCC unit cells: point / unit cell = (8 corners)1/8 + (6 fces)(1/2) = 4

The Body-Centered Cubic Crystal Structure

Another common metallic crystal structure also has a cubic unit cell with atoms located at all eight corners and a single atom at the cube center. This is called a body-centered cubic (BCC) crystal structure. A collection of spheres depicting this crystal structure is shown in Figure are diagrams of BCC unit cells with the atoms represented by hard sphere and reduced-sphere models, respectively







Number of Lattice Points in Cubic Crystal Systems

In BCC unit cells: point / unit cell = (8 corners)1/8 + (1 center)(1) = 2

The Hexagonal Close-Packed Crystal Structure

Not all metals have unit cells with cubic symmetry; the final common metallic crystal structure to be discussed has a unit cell that is hexagonal. Figure shows a reduced-sphere unit cell for this structure, which is termed hexagonal close packed (HCP); an assemblage of several HCP unit cells is presented in Figure The top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the center. Another plane that provides three additional atoms to the unit cell is situated between the top and bottom planes. The atoms in this mid plane have as nearest neighbors atoms in both of the adjacent two planes. The equivalent of six atoms is contained in each unit cell; one-sixth of each of the 12 top and bottom face corner atoms, one-half of each of the 2 center face atoms, and all 3 mid plane interior atoms. If a and c represent, respectively, the short and long unit cell dimensions of, the c a ratio should be 1.633; however, for some HCP metals this ratio deviates from the ideal value.

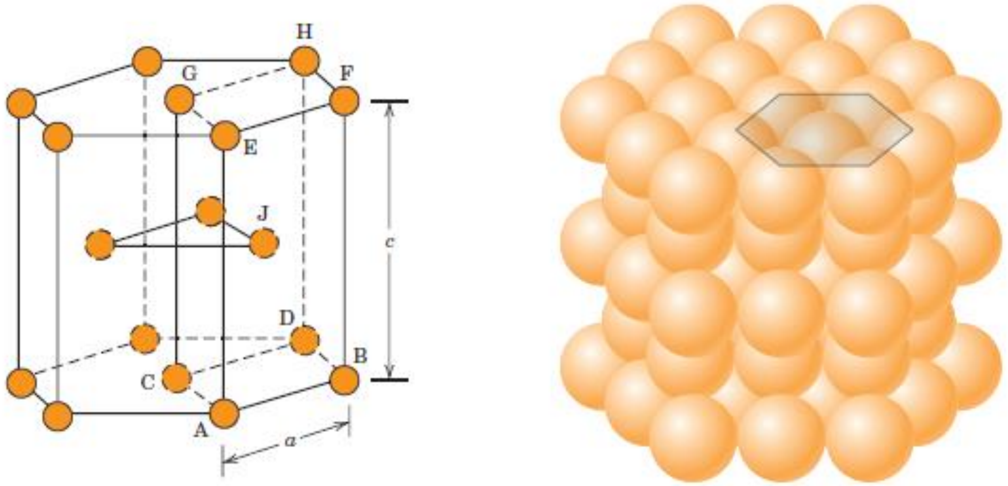


Figure: For the hexagonal close-packed crystal structure

Atomic packing factor (APF):-

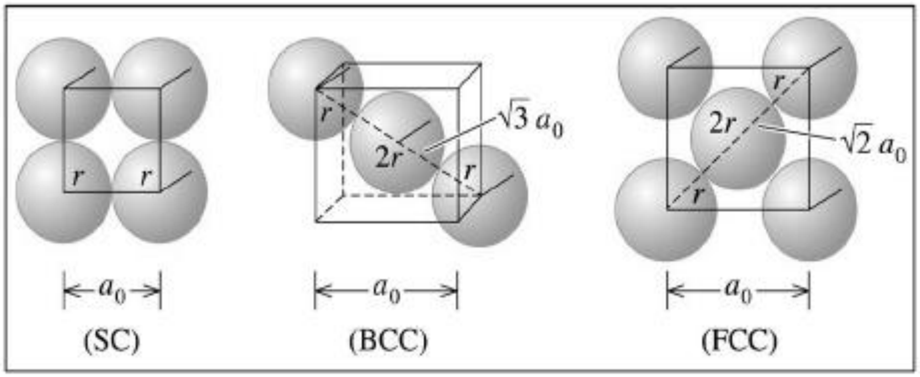
Two other important characteristics of a crystal structure are the coordination number and the atomic packing factor (APF). For metals, each atom has the same number of nearest-neighbor or touching atoms, which is the coordination number. For face-centered cubics, the coordination number is 12. This may be confirmed by examination of Figure 3.1a; the front face atom has four corner nearest-neighbor atoms surrounding it, four face atoms that are in contact from behind, and four other equivalent face atoms residing in the next unit cell to the front, which is not shown. The APF is the sum of the sphere volumes of all atoms within a unit cell (assuming the atomic hard sphere model) divided by the unit cell volume—that is

$$\text{APF} = \frac{\text{volume of atoms in a unit cell}}{\text{total unit cell volume}}$$

Crystal Structure

In SC, BCC, and FCC structures when one atom is located at each lattice point.

Relationship between Atomic Radius and Lattice Parameters

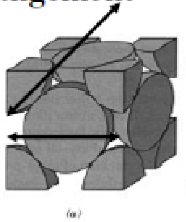


Atomic Packing Fraction for FCC

$$APF = \frac{\text{vol. of atomic spheres in unit cell}}{\text{total unit cell vol.}}$$

No. of atoms per unit cell = 4/cell
Volume of one atom= $4\pi R^3/3$
Volume of cubic cell = a^3
"R" related to "a" by $\boxed{\sqrt{2}a = 4R}$

Face-Centered-Cubic Arrangement



Unit cell contains:
6 x 1/2 + 8 x 1/8
= 4 atoms/unit cell

$$APF = \frac{\underbrace{4}_{\frac{\text{atoms}}{\text{unit cell}}} \; \underbrace{\frac{4}{3}\pi(\sqrt{2}a/4)^3}_{\frac{\text{volume}}{\text{atom}}}}{\underbrace{a^3}_{\frac{\text{volume}}{\text{unit cell}}}}$$

$\boxed{= 0.74}$

DENSITY COMPUTATIONS

A knowledge of the crystal structure of a metallic solid permits computation of its theoretical density through the relationship

$$\rho = \frac{nA}{V_C N_A}$$

where

n = number of atoms associated with each unit cell
A = atomic weight
V_C = volume of the unit cell
N_A = Avogadro's number (6.023×10^{23} atoms/mol)

EXAMPLE PROBLEM

Theoretical Density Computation for Copper

Copper has an atomic radius of 0.128 nm, an FCC crystal structure, and an atomic weight of 63.5 g/mol. Compute its theoretical density and compare the answer with its measured density.

Solution

Equation 3.5 is employed in the solution of this problem. Since the crystal structure is FCC, n, the number of atoms per unit cell, is 4. Furthermore, the atomic weight A_{Cu} is given as 63.5 g/mol. The unit cell volume V_C for FCC was determined in Example Problem 3.1 as $16R^3\sqrt{2}$, where R, the atomic radius, is 0.128 nm.

Substitution for the various parameters into Equation 3.5 yields

$$\rho = \frac{nA_{Cu}}{V_C N_A} = \frac{nA_{Cu}}{(16R^3\sqrt{2})N_A}$$

$$= \frac{(4 \text{ atoms/unit cell})(63.5 \text{ g/mol})}{[16\sqrt{2}(1.28 \times 10^{-8} \text{ cm})^3/\text{unit cell}](6.023 \times 10^{23} \text{ atoms/mol})}$$

$$= 8.89 \text{ g/cm}^3$$

The literature value for the density of copper is 8.94 g/cm^3, which is in very close agreement with the foregoing result.

Crystallographic Points, Directions, and Planes-

Procedure:

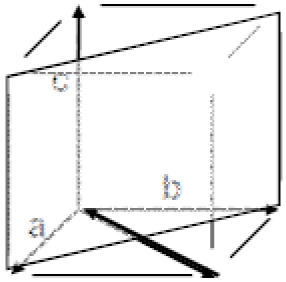
1. Any line (or vector direction) is specified by 2 points.

- The first point is, typically, at the origin (000).

2. Determine length of vector projection in each of 3 axes in units (or fractions) of a, b, and c.

- X (a), Y(b), Z(c)

1 1 0



3. Multiply or divide by a common factor to reduce the lengths to the smallest integer values, u v w.

4. Enclose in square brackets: [u v w]: [110] direction.

DIRECTIONS will help define PLANES (Miller Indices or plane normal).

5. Designate negative numbers by a bar $[\bar{1}\bar{1}0]$

- Pronounced "bar 1", "bar 1", "zero" direction.
    1. "Family" of [110] directions is designated as <110>.

Miller Indices:-

Definition

Miller indices are used to specify directions and planes.

•These directions and planes could be in lattices or in crystals.

•The number of indices will match with the dimension of the lattice or the crystal.

•E.g. in 1D there will be 1 index and 2D there will be two indices etc

Notation Summary

•(h,k,l) represents a point – note the exclusive use of commas

•Negative numbers/directions are denoted with a bar on top of the number

•[hkl] represents a direction

•<hkl> represents a family of directions

•(hkl) represents a plane

•{hkl} represents a family of planes

Miller Indices for Planes: Procedure

1.Identify the plane intercepts on the x, y and z-axes.

2.Specify intercepts in fractional coordinates.

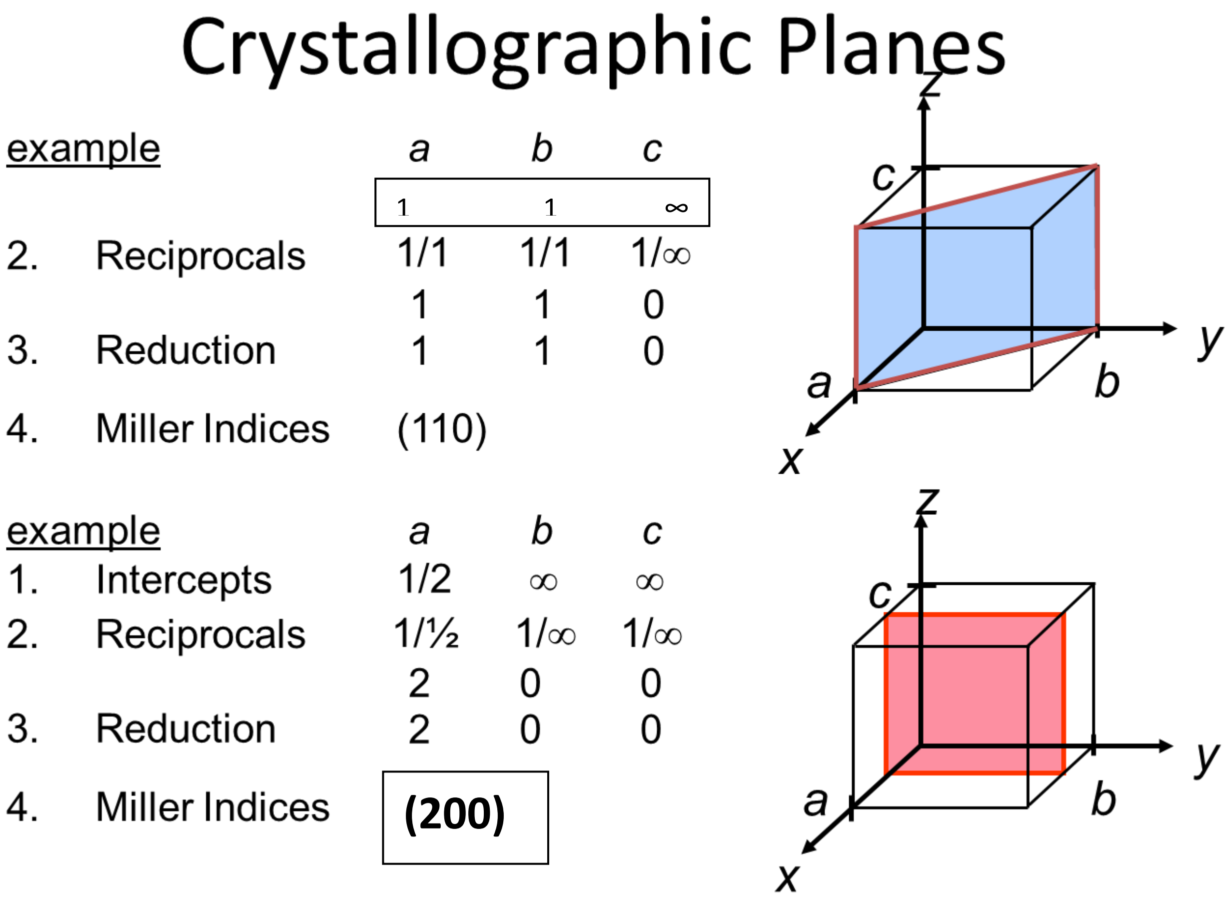
3.Take the reciprocals of the fractional intercepts

Miller Indices for Planes

•Consider the plane in pink, which is one of an infinite number of parallel plane each a consistent distance (“a”) away from the origin (purple planes) Crystallographic Planes Miller Indices: Reciprocals of the (three) axial intercepts for a plane, cleared of fractions & common multiples. All parallel planes have same Miller indices.

Algorithm

1. Read off intercepts of plane with axes in terms of a, b, c
2. Take reciprocals of intercepts
3. Reduce to smallest integer values
4. Enclose in parentheses, no
   commas i.e., (hkl)



Crystallographic Planes

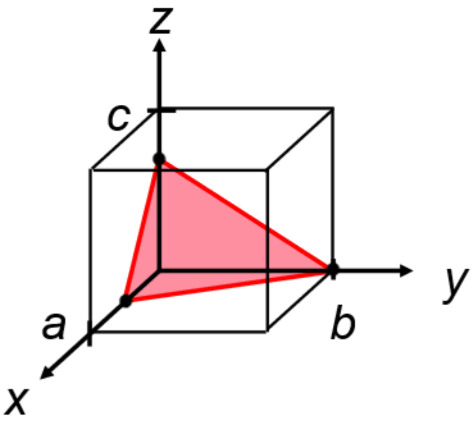
example	a	b	c
	1	1	∞
2. Reciprocals	1/1	1/1	1/∞
	1	1	0
3. Reduction	1	1	0
4. Miller Indices	(110)		

example	a	b	c
1. Intercepts	1/2	∞	∞
2. Reciprocals	1/½	1/∞	1/∞
	2	0	0
3. Reduction	2	0	0
4. Miller Indices	**(200)**		

example

	a	b	c
1. Intercepts	1/2	1	3/4
2. Reciprocals	1/½	1/1	1/¾
	2	1	4/3
3. Reduction	6	3	4

4. Miller Indices (634)



Miller Indices are the reciprocals of the parameters of each crystal face. Thus:

- Pink Face

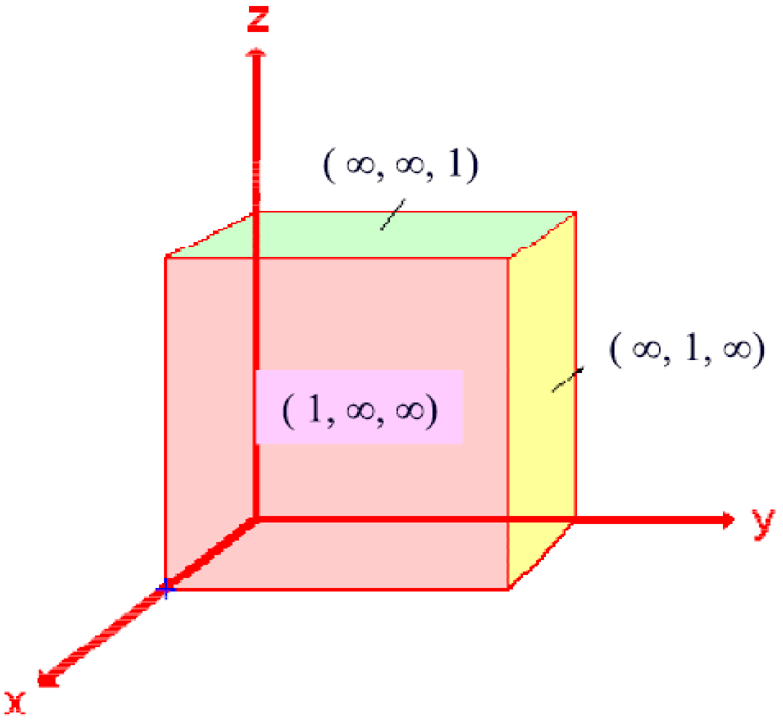
= (1/1, 1/∞, 1/∞) = (100)

- Green Face

= (1/∞, 1/∞, 1/1) = (001)

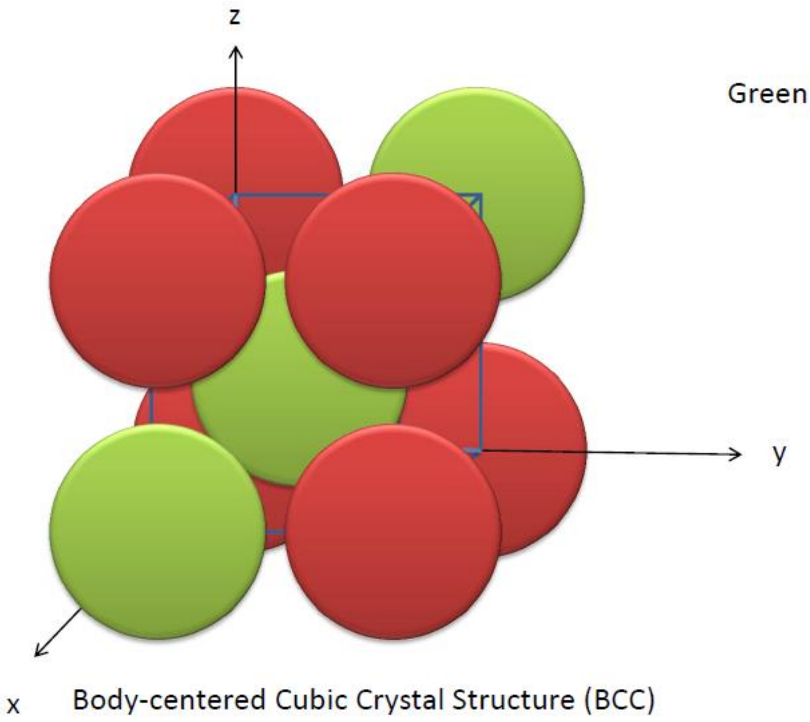
- Yellow Face

= (1/∞, 1/1, 1/∞) = (010)



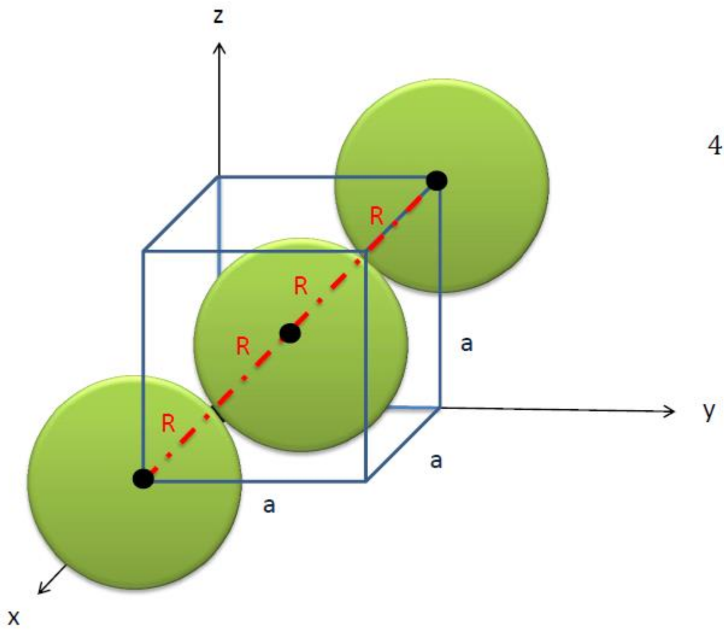
Linear Density and Planar Density

First, we should find the lattice parameter(a) in terms of atomic radius(R). Then, we can find linear density or planar density



Green ones touches each other.

Body-centered Cubic Crystal Structure (BCC)



$$4R = \sqrt{a^2 + a^2 + a^2}$$

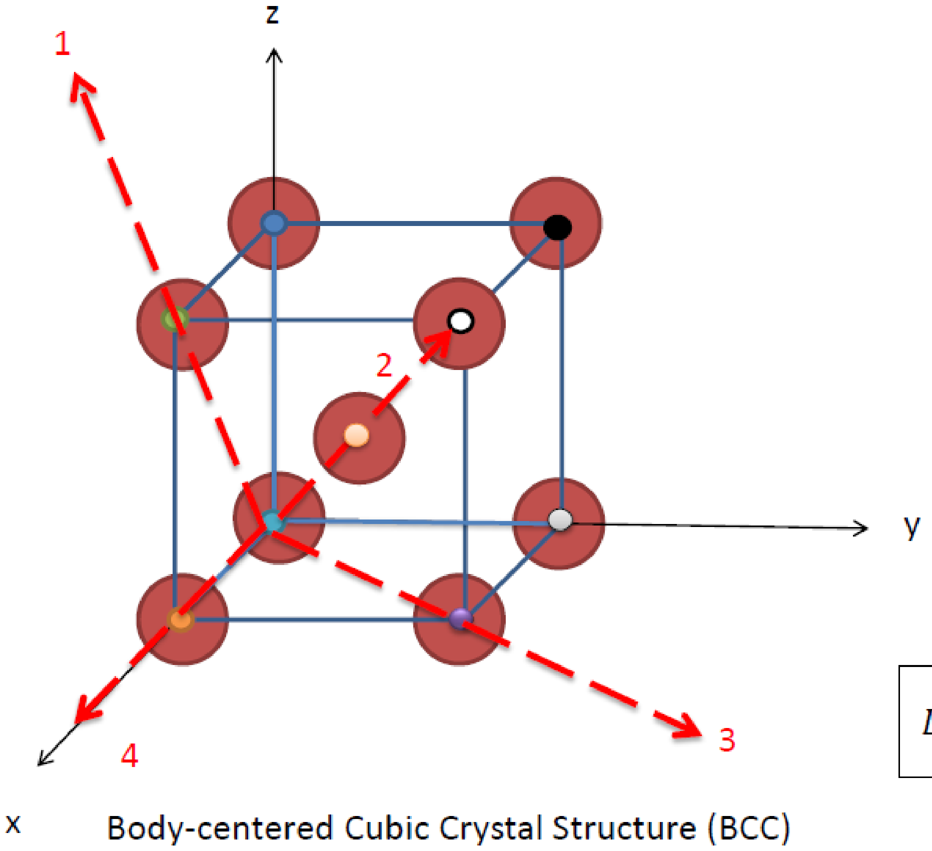
$$\rightarrow a = \frac{4R}{\sqrt{3}}$$

We found the lattice parameter in terms of atomic radius.

Linear Density:-

1.Draw the atoms on the direction, and use the formula;

$$LD = \frac{\#\ of\ atoms\ on\ the\ line}{the\ length\ of\ the\ line}$$



Body-centered Cubic Crystal Structure (BCC)

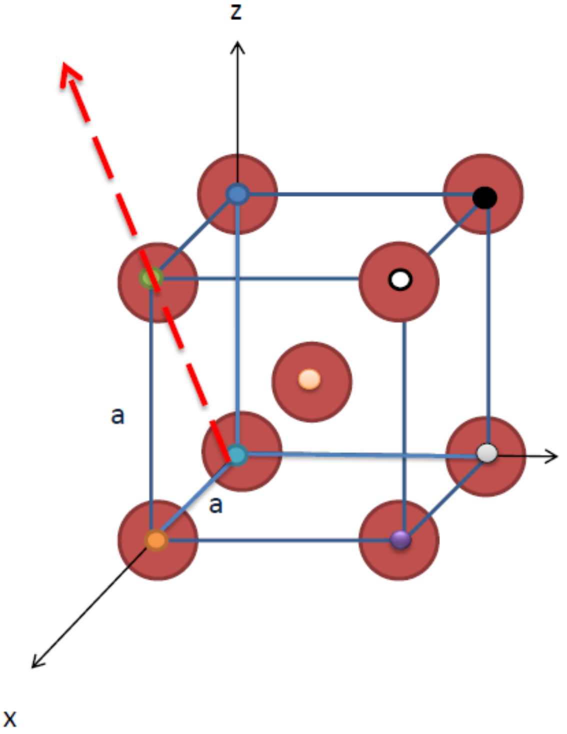
Directions

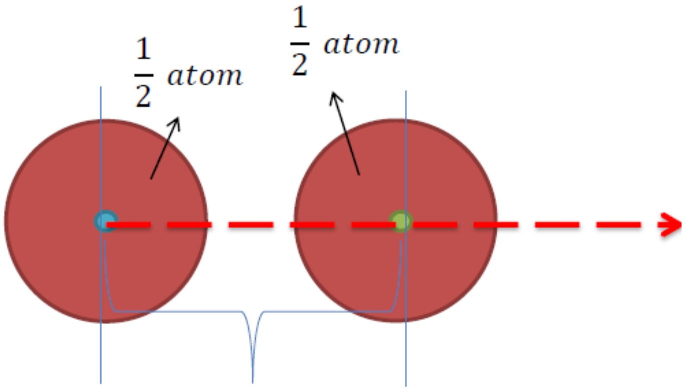
1 [1 0 1]
2 [1 1 1]
3 [1 1 0]
4 [1 0 0]

Let's apply the formula below for [101] and [111].

$$\boxed{LD = \frac{\#\ of\ atoms\ on\ the\ line}{the\ length\ of\ the\ line}}$$

[1 0 1] direction for BCC and Linear Density



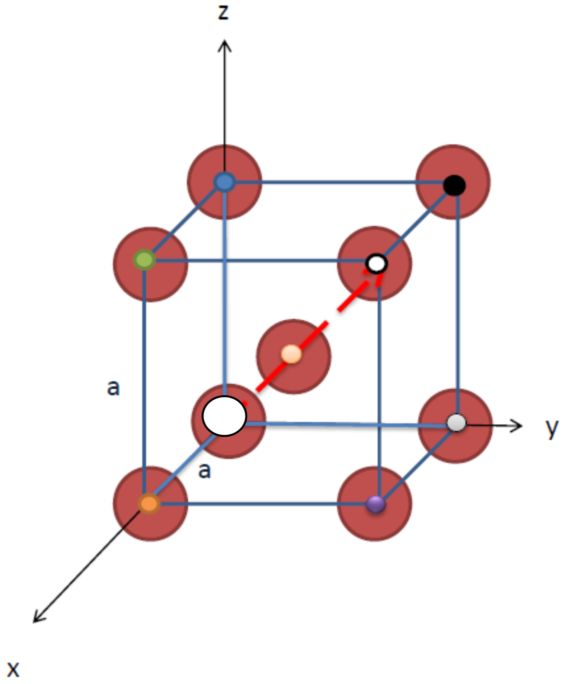


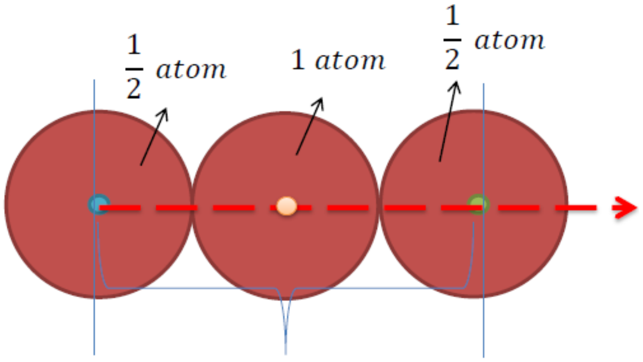
$$L = a\sqrt{2} = \frac{4\sqrt{2}R}{\sqrt{3}}$$

$$LD = \frac{\#\ of\ atoms\ on\ the\ line}{the\ length\ of\ the\ line}$$

$$LD = \frac{\frac{1}{2}+\frac{1}{2}}{\frac{4\sqrt{2}R}{\sqrt{3}}} = \frac{\sqrt{3}}{4\sqrt{2}R}$$

[1 1 1] direction for BCC and Linear Density





$$L = a\sqrt{3} = 4R$$

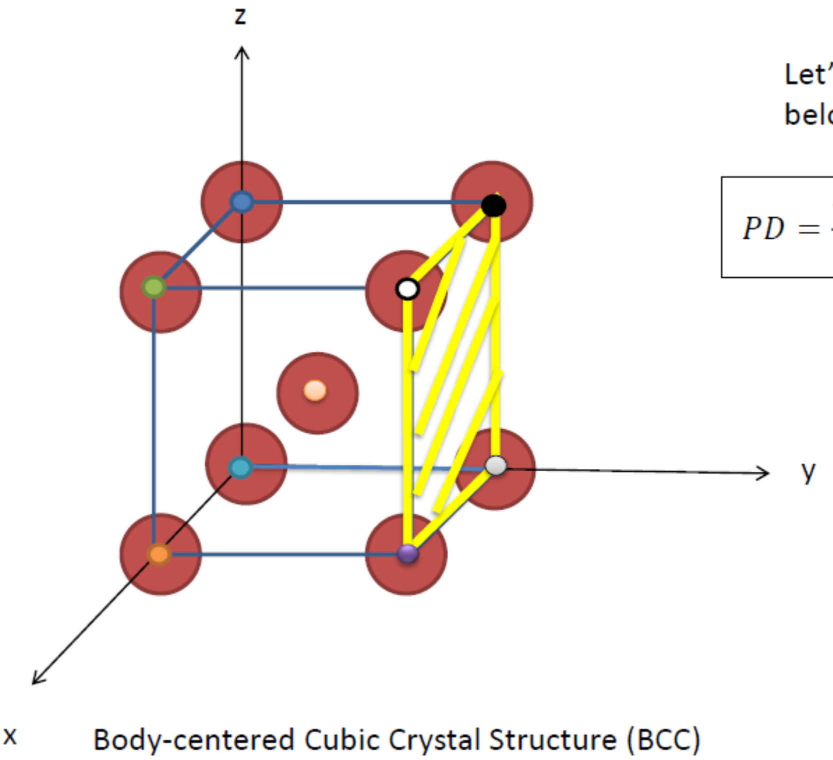
$$LD = \frac{\#\ of\ atoms\ on\ the\ line}{the\ length\ of\ the\ line}$$

$$LD = \frac{\frac{1}{2}+1+\frac{1}{2}}{4R} = \frac{1}{2R}$$

Planar Density

1.Draw the atoms on the plane, and use the formula;

$$PD = \frac{\#\ of\ atoms\ on\ the\ plane}{the\ area\ of\ the\ plane}$$



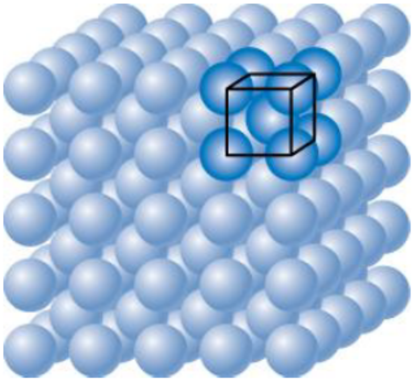
Body-centered Cubic Crystal Structure (BCC)

Let's apply the formula below for (0 1 0).

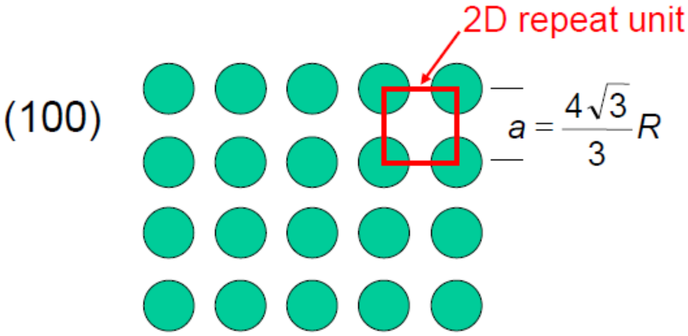
$$PD = \frac{\#\ of\ atoms\ on\ the\ plane}{the\ area\ of\ the\ plane}$$

Planar Density of (100) Iron

Solution: At T < 912°C iron has the BCC structure.



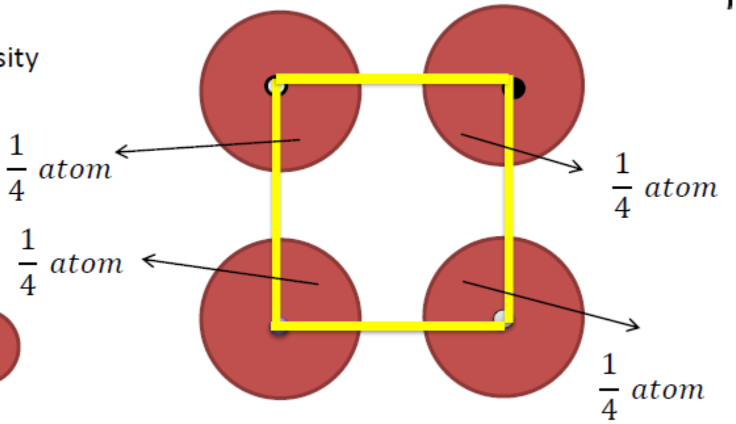
Adapted from Fig. 3.2(c), *Callister 7e.*

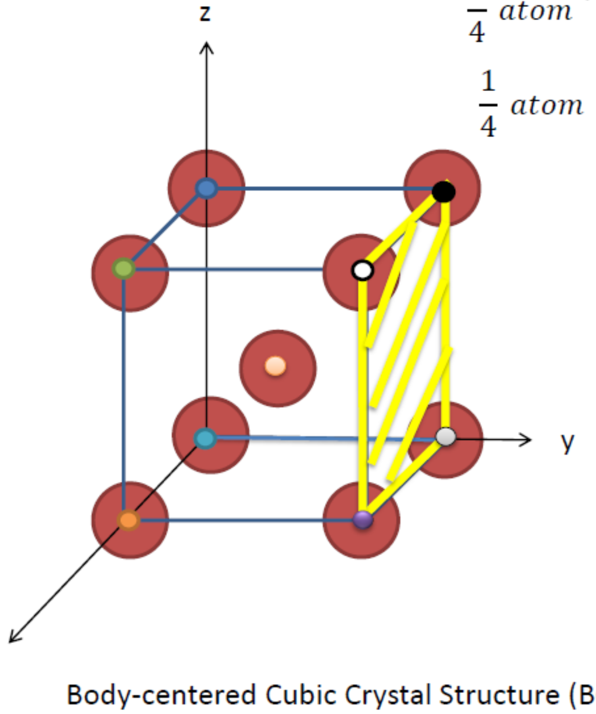


Radius of iron R = 0.1241 nm

$$\text{Planar Density} = \frac{\overset{\text{atoms / 2D repeat unit}}{1}}{\underset{\text{area / 2D repeat unit}}{a^2}} = \frac{1}{\left(\frac{4\sqrt{3}}{3}R\right)^2} = 12.1\,\frac{\text{atoms}}{\text{nm}^2} = \boxed{1.2 \times 10^{19}\,\frac{\text{atoms}}{\text{m}^2}}$$

(0 1 0) plane for BCC and Planar Density





Body-centered Cubic Crystal Structure (BCC)

$$PD = \frac{\#\ of\ atoms\ on\ the\ plane}{the\ area\ of\ the\ plane}$$

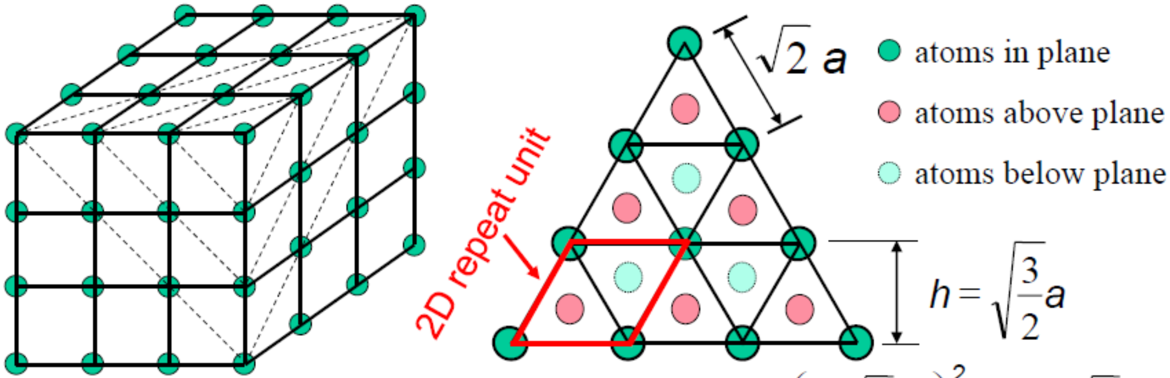
$$PD = \frac{\frac{1}{4}+\frac{1}{4}+\frac{1}{4}+\frac{1}{4}}{a^2}$$

$$PD = \frac{1}{\left(\frac{4R}{\sqrt{3}}\right)^2} = \frac{3}{16R^2}$$

Planar Density of (111) Iron

Solution (cont): (111) plane

1 atom in plane/ unit surface cell



$$\text{area} = \sqrt{2}\,ah = \sqrt{3}\,a^2 = \sqrt{3}\left(\frac{4\sqrt{3}}{3}R\right)^2 = \frac{16\sqrt{3}}{3}R^2$$

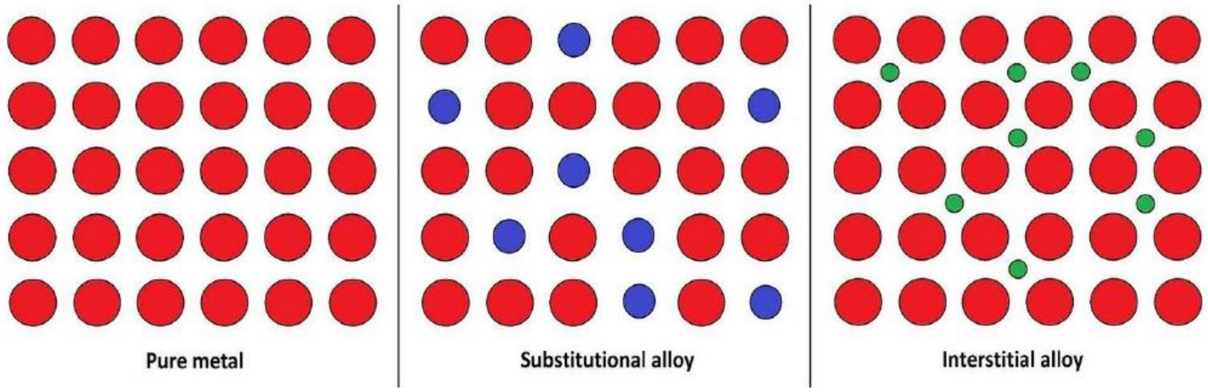
$$\text{Planar Density} = \frac{\dfrac{\text{atoms}}{\text{2D repeat unit}}}{\dfrac{\text{area}}{\text{2D repeat unit}}} = \frac{1}{\dfrac{16\sqrt{3}}{3}R^2} = 7.0\,\frac{\text{atoms}}{\text{nm}^2} = \boxed{0.70 \times 10^{19}\,\frac{\text{atoms}}{\text{m}^2}}$$

Alloying:-

Alloys consist of a combination of two or more metal elements in the solid state. In engineering work, alloys, rather than pure metals, are generally used because of their superior properties. Ordinary steels, for example, are alloys of iron and carbon and are preferred to pure iron because of strength and other considerations. Important mechanical properties of alloys are related to the solid phases, or homogenous parts, that form from the combination of elements. Such phases are observable on the microscopic scale, and their study is important in understanding alloy properties.

Types of Alloying :-

Interstitial is where the alloy elements are located in spaces between atoms in the unit cell. For instance, when carbon (Atomic radius 0.129 nm) is added to iron (0.075nm), the carbon fits into the gap between the Fe atoms (interstitial site). The solubility depends on the size of these gaps and the crystal structure. Substitutional is where the alloying elements are located in vacancies in the unit cell. An atom of one element substitutes for another in the crystal structure.



Hume-Rothery Rules for Alloying;-

It is not possible for every combination of materials to form an alloy. The following rules are for maximum solubility in substitutional alloying:

1. Same Crystal Structure (BCC, FCC, HCP for instance)

2. Same Valency Factor

3. Similar Electronegativity – the tendancy for the atom to attract a shared pair of electrons. This depends on the atomic number and the distance at which the valence electrons are from the nucleus.

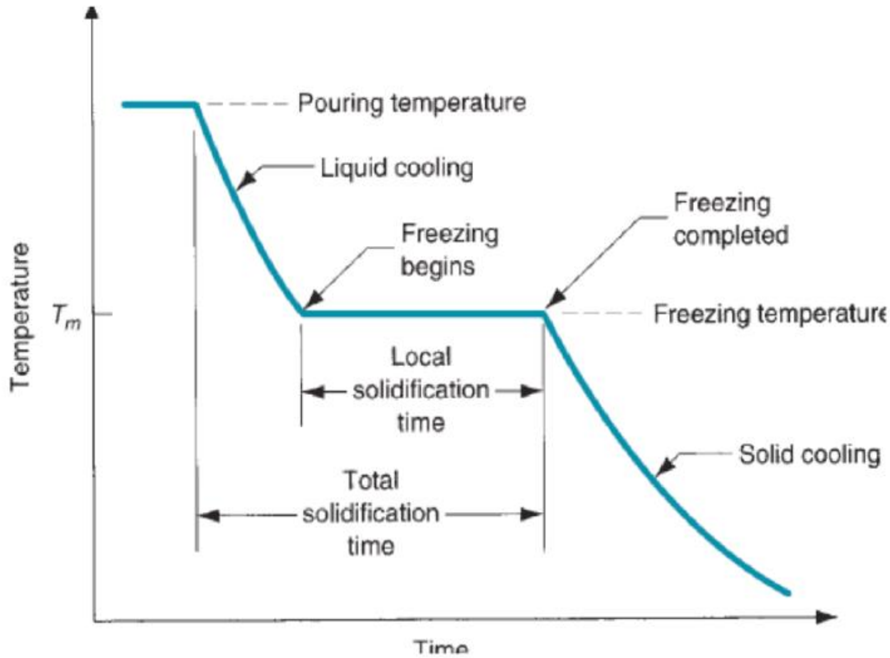
4. Difference in atomic radius <= 15% In interstitial alloying, the solute atoms should be <= 59% of the atomic radius of the solvent atoms.

SOLIDIFICATION OF METALS

Solidification involves the transformation of the molten metal back into the solid state. The solidification process differs depending on whether the metal is a pure element or an alloy.

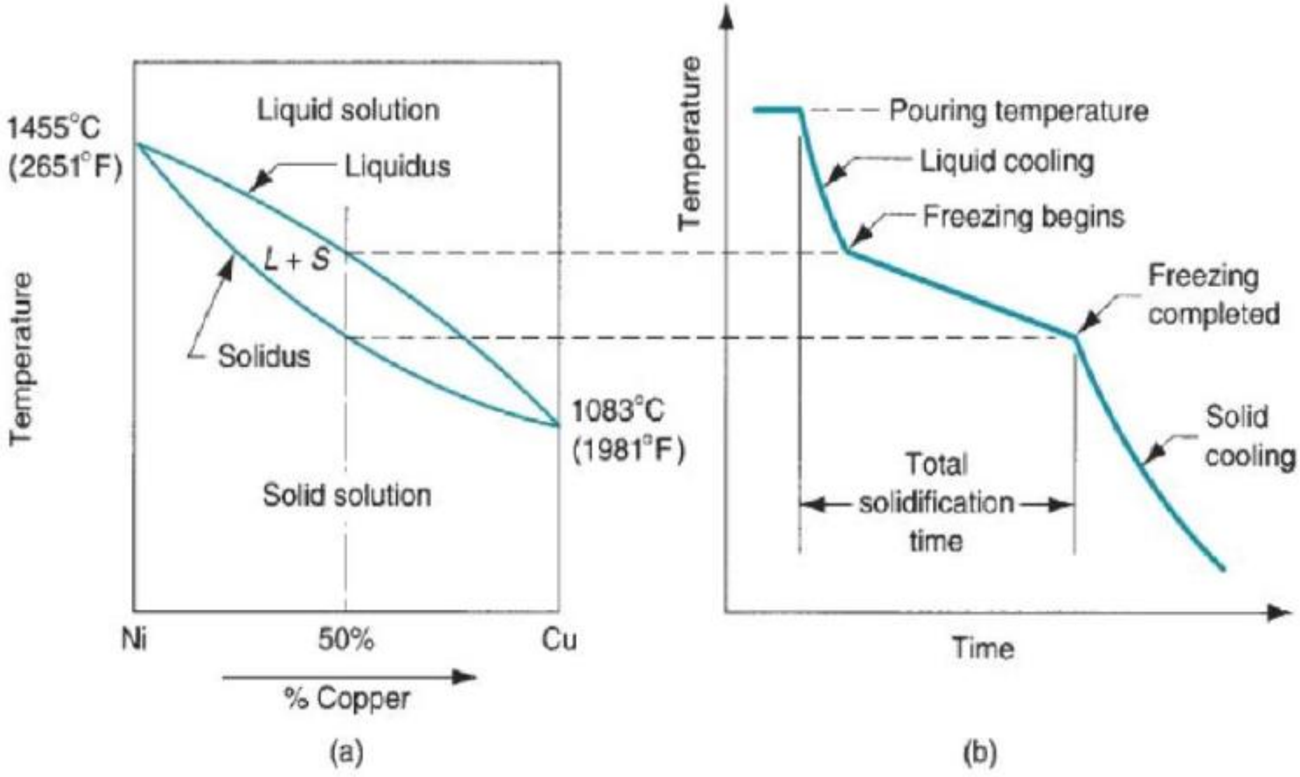
Pure Metals

A pure metal solidifies at a constant temperature equal to its freezing point, which is the same as its melting point. The melting points of pure metals are well known and documented. The process occurs over time as shown in the plot below, called a cooling curve. The actual freezing takes time, called the local solidification time in casting, during which the metal's latent heat of fusion is released into the surrounding mold. The total solidification time is the time taken between pouring and complete solidification After the casting has completely solidified, cooling continues at a rate indicated by the downward slope of the cooling curve.



Alloy Metal

Most alloys freeze over a temperature range rather than at a single temperature. The exact range depends on the alloy system and the particular composition



Solid-Solution Strengthening:-

Adding another element that goes into interstitial or substitution positions in a solution increases strength. The impurity atoms cause lattice strain. which can "anchor" dislocations. This occurs when the strain caused by the alloying element compensates that of the dislocation, thus achieving a state of low potential energy. It costs strain energy for the dislocation to move away from this state (which is like a potential well). The scarcity of energy at low temperatures is why slip is hindered. Pure metals are almost always softer than their alloys.

Solid Solutions

A solid solution may be formed when impurity atoms are added to a solid, in which case the original crystal structure is retained and no new phases are formed.

1. Substitution solid solutions: impurity atoms substitute for host atoms, and appreciable solubility is possible only when atomic diameters and electro negativities for both atom types are similar, when both elements have the same crystal structure, and when the impurity atoms have a valence that is the same as or less than the host material
2. Interstitial solid solutions: These form for relatively small impurity atoms that occupy interstitial sites among the host atoms.

Phase Diagrams

Equilibrium Phase Diagrams:-

Give the relationship of composition of a solution as a function of temperatures and the quantities of phases in equilibrium. These diagrams do not indicate the dynamics when one phase transforms into another. Sometimes diagrams are given with pressure as one of the variables. In the phase diagrams we will discuss, pressure is assumed to be constant at one atmosphere.

Binary Isomorphous Systems:-

This very simple case is one complete liquid and solid solubility, an isomorphism system. The example is the Cu-Ni alloy of Fig. 9.2a. The complete solubility occurs because both Cu and Ni have the same crystal structure (FCC), near the same radii, electro negativity and valence. The liquids line separates the liquid phase from solid or solid + liquid phases. That is, the solution is liquid above the liquidus line. The solidus line is that below which the solution is completely solid (does not contain a liquid phase.)

Development of microstructure in isomorphous alloys

a)Equilibrium cooling:-

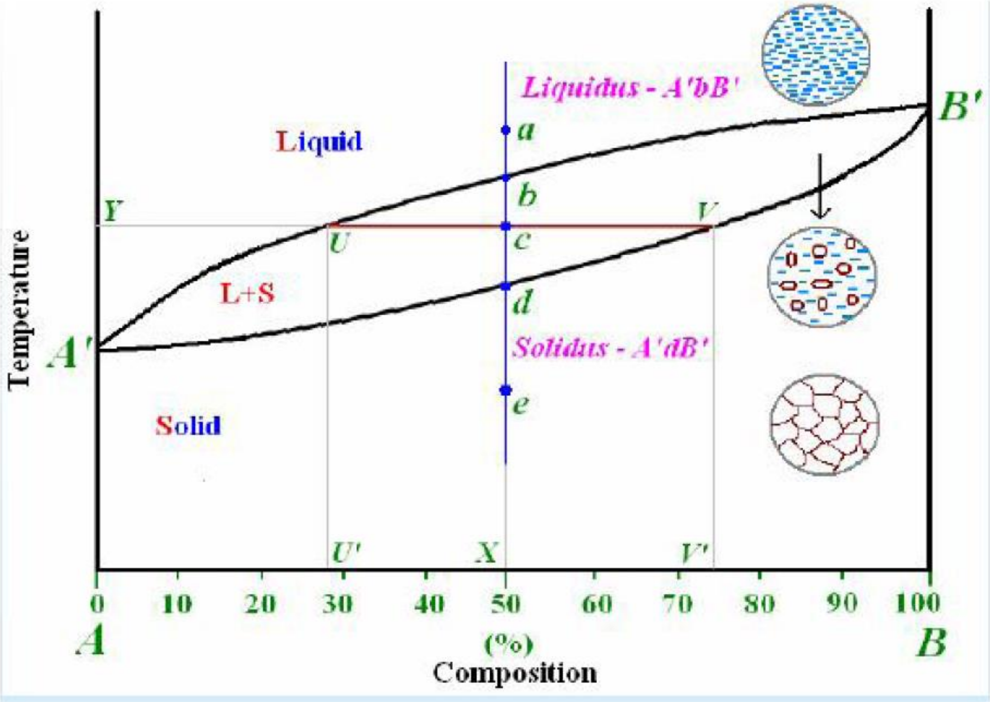
Solidification in the solid + liquid phase occurs gradually upon cooling from the liquids line. The composition of the solid and the liquid change gradually during cooling (as can be determined by the tie-line method.) Nuclei of the solid phase form and they grow to consume all the liquid at the solidus line.

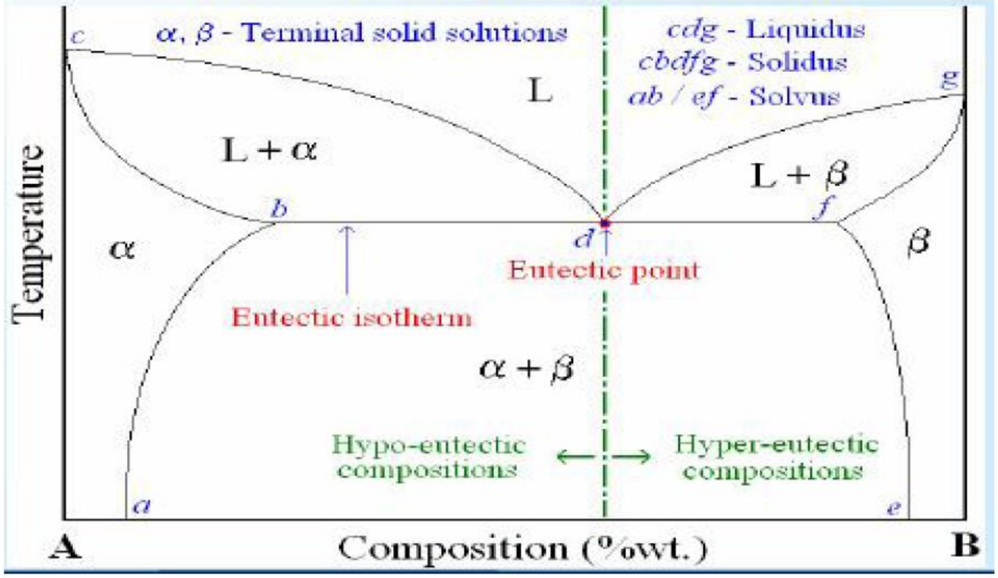
b) Non-equilibrium cooling:-

Solidification in the solid + liquid phase also occurs gradually. The composition of the liquid phase evolves by diffusion, following the equilibrium values that can be derived from the tie-line method. However, diffusion in the solid state is very slow. Hence, the new layers that solidify on top of the grains have the equilibrium composition at that temperature but once they are solid their composition does not change. This lead to the formation of layered (cored) grains and to the invalidity of the tie-line method to determine the composition of the solid phase (it still works for the liquid phase, where diffusion is fast.)

Binary Eutectic Systems:-

Interpretation: Obtain phases present, concentration of phases and their fraction (%). Solvus line: limit of solubility Eutectic or invariant point. Liquid and two solid phases exist in equilibrium at the eutectic composition and the eutectic temperature. The melting point of the eutectic alloy is lower than that of the components (eutectic = easy to melt in Greek).• At most two phases can be in equilibrium within a phase field.• Single-phase regions are separated by 2-phase regions.





Development of microstructure in eutectic alloys:-

Case of lead-tin alloys, A layered, eutectic structure develops when cooling below the eutectic temperature. Alloys which are to the left of the eutectic concentration (hypoeutectic) or to the right (hypereutectic) form a proeutectic phase before reaching the eutectic temperature, while in the solid + liquid region. The eutectic structure then adds when the remaining liquid is solidified when cooling further. The eutectic microstructure is lamellar (layered) due to the reduced diffusion distances in the solid state. To obtain the concentration of the eutectic microstructure in the final solid solution, one draws a vertical line at the eutectic concentration and applies the lever rule treating the eutectic as a separate phase.

Eutectic reaction: - (eutectic means easily melted), and C_E and T_E represent the eutectic composition and temperature, respectively; $C_{\alpha E}$ and $C_{\beta E}$ are the respective compositions of the α and β phases at T_E Thus, for the copper–silver system.

Eutectoid and Peritectic Reactions:-

The eutectoid (eutectic-like) reaction is similar to the eutectic reaction but occurs from one solid phase to two new solid phases. It also shows as V on top of a horizontal line in the phase diagram. There are associated eutectoid temperature (or temperature), eutectoid phase, eutectoid and proeutectoid microstructures. The peritectic reaction also involves three solid in equilibrium, the transition is from a solid + liquid phase to a different solid phase when cooling. The inverse reaction occurs when heating.

The Iron–Carbon System

A portion of the iron–carbon phase diagram is presented in the Figure Pure iron, upon heating, experiences two changes in crystal structure before it melts. At room temperature the stable form, called ferrite, or α iron, has a BCC crystal structure.

Ferrite experiences a polymorphic transformation to FCC austenite, or γ iron, at 912°C. This austenite persists to (1394°C), at which temperature the FCC austenite reverts back to a BCC phase known as d ferrite, which finally.

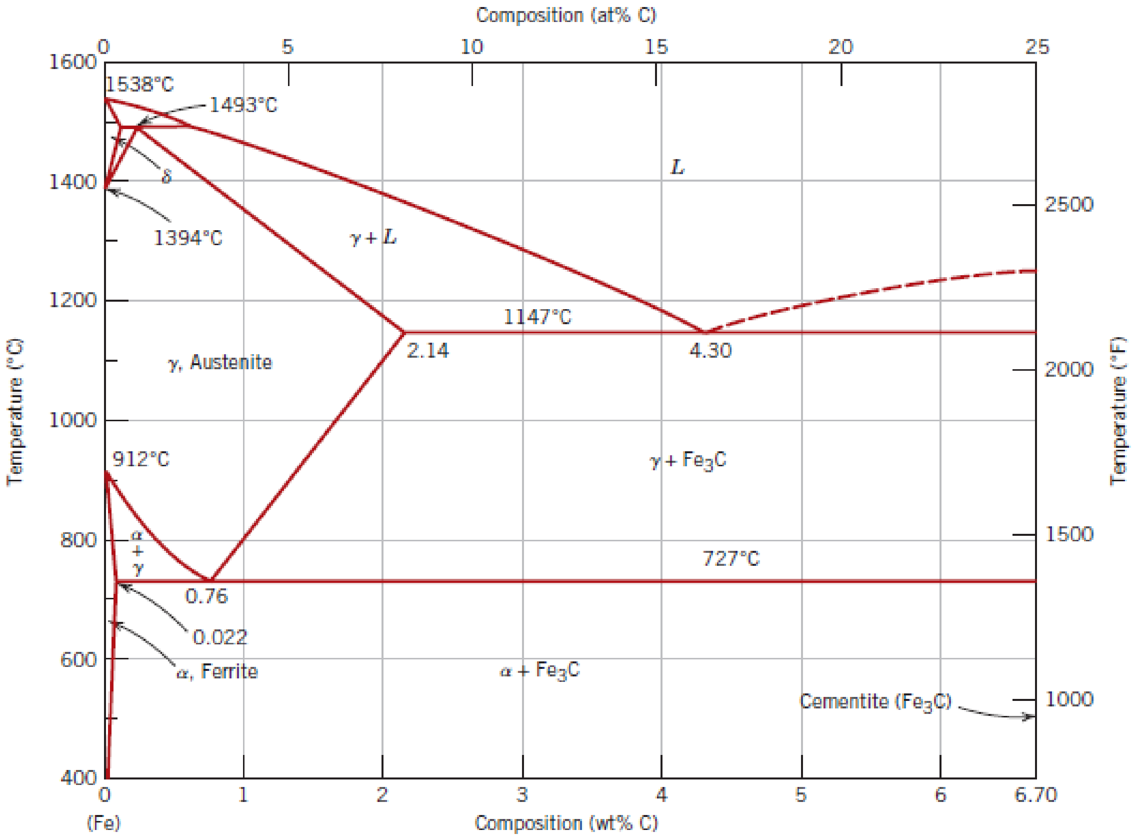


Fig (1) The Iron–Carbon System

A portion of the iron–carbon phase diagram is presented in Figure above. Pure iron, upon heating, experiences two changes in crystal structure before it melts. At room temperature the stable form, called **ferrite,** or **α** iron, has a BCC crystal structure. Ferrite experiences a polymorphic transformation to FCC **austenite,** or **γ** iron, at (912°C). This austenite persists to (1394°C), at which temperature the FCC austenite reverts back to a BCC phase known as d ferrite, which finally melts at (1539°C). All these changes are apparent along the left vertical axis of the phase diagram.

Carbon is an interstitial impurity in iron and forms a solid solution with each of α and δ ferrites, and also with austenite, as indicated by the α,γ and δ single-phase fields in Figure (1). In the BCC ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at (727°C). 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 temperatures below (768°C), and has a density of 7.88 g/cm3.

The austenite, or phase of iron, when alloyed with carbon alone, is not stable below (727°C), as indicated in Figure (1). The maximum solubility of carbon in austenite, 2.14 wt%, occurs at (1147°C). This solubility is approximately 100 times greater than the maximum for BCC ferrite, since the FCC interstitial positions are larger, and, therefore, the strains imposed on the surrounding iron atoms are much lower. As the discussions that follow demonstrate, phase transformations involving austenite are very important in the heat treating of steels. In passing, it should be mentioned that austenite is nonmagnetic.

The δ ferrite is virtually the same as α ferrite, except for the range of temperatures over which each exists. Since the δ ferrite is stable only at relatively high temperatures, it is of no technological importance and is not discussed further. Cementite (Fe_3C) forms when the solubility limit of carbon in ferrite is exceeded below (727°C) (for compositions within the {$\alpha+Fe_3C$} phase region). As indicated in Figure (1), Fe_3C will also coexist with the phase γ between (727°C) and (1341 and (1147°C). Mechanically,

cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence cementite is only metastable; that is, it will remain as a compound indefinitely at room temperature. However, if heated to between 650°C and 700°C for several years, it will gradually change or transform into α iron and carbon, in the form of graphite, which will remain upon subsequent cooling to room temperature. Thus, the phase diagram in Figure (1) is not a true equilibrium one because cementite is not an equilibrium compound. However, inasmuch as the decomposition rate of cementite is extremely sluggish, virtually all the carbon in steel will be as Fe_3C instead of graphite, and the iron–iron carbide phase diagram is, for all practical purposes, valid. addition of silicon to cast irons greatly accelerates this cementite decomposition reaction to form graphite.

peritectic reaction :- The peritectic reaction is yet another invariant reaction involving three phases at equilibrium. With this reaction, upon heating, one solid phase transforms into a liquid phase and another solid phase

Eutectoid reaction: - that one solid phase instead of a liquid transform into two other solid phases at a single temperature. A eutectoid reaction is found in the iron–carbon system. that is very important in the heat treating of steels.

It may be noted that a eutectoid invariant point exists at a composition of 0.76 wt% C and a temperature of (727°C).This eutectoid reaction may be represented by

Eutectoid reaction
for the iron-iron
carbide system

$$\gamma(0.76\ \mathrm{wt\%\ C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\ \mathrm{wt\%\ C}) + \mathrm{Fe_3C}\ (6.7\ \mathrm{wt\%\ C})$$

or, upon cooling, the solid γ phase is transformed into α iron and cementite. (Eutectoid phase transformations) The eutectoid phase changes described above are very important, being fundamental to the heat treatment of steels, as explained in subsequent discussions. Ferrous alloys are those in which iron is the prime component, but carbon as well as other alloying elements may be present. In the classification scheme of ferrous alloys based on carbon content, there are three types: iron, steel, and cast iron. Commercially pure iron contains less than 0.008 wt% C and, from the phase diagram, is composed almost exclusively of the ferrite phase at room temperature. The iron–carbon alloys that contain between 0.008 and 2.14 wt% C are classified as steels. In most steels the microstructure consists of both α and Fe_3C phases. Upon cooling to room temperature, an alloy within this composition range must pass through at least a portion of the -phase field; distinctive microstructures are subsequently produced, as discussed below. Although a steel alloy may contain as much as 2.14 wt% C, in practice, carbon concentrations rarely exceed 1.0 wt%. Cast irons are classified as ferrous alloys that contain between 2.14 and 6.70 wt% C. However, commercial cast irons normally contain less than 4.5 wt% C.

The Iron–Carbon Diagram:-

The Iron–Iron Carbide (Fe–Fe3C) Phase Diagram This is one of the most important alloys for structural applications. The diagram Fe—C is simplified at low carbon concentrations by assuming it is the Fe—Fe3C diagram. Concentrations are usually given in weight percent. The possible phases are:

- α-ferrite (BCC) Fe-C solution
- γ-austenite (FCC) Fe-C solution
- δ-ferrite (BCC) Fe-C solution
- liquid Fe-C solution
- Fe3C (iron carbide) or cementite. An intermetallic compound.

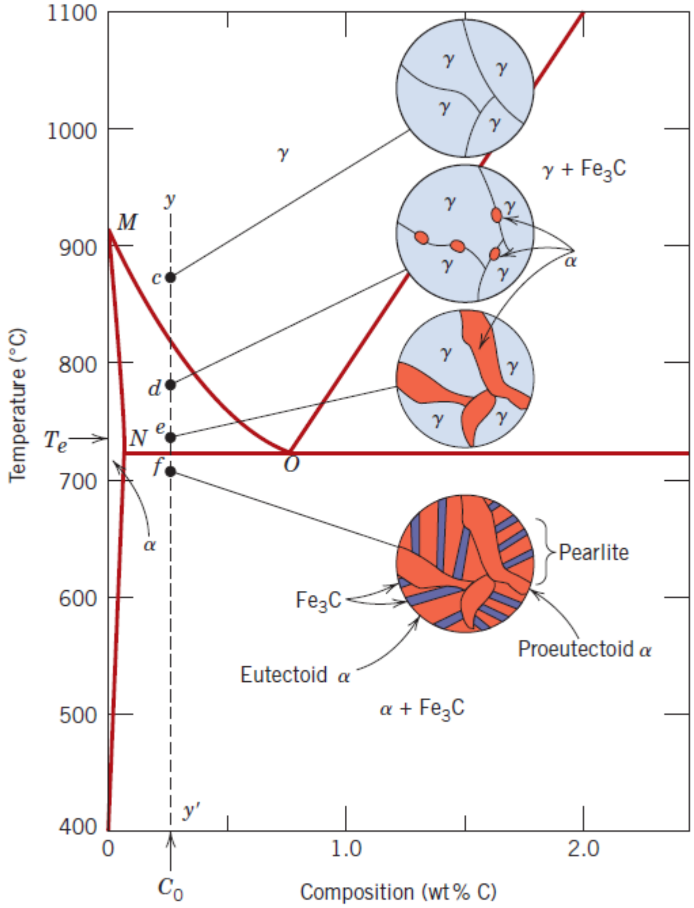
the maximum solubility of C in α- ferrite is 0.022 wt%. δ–ferrite is only stable at high temperatures. It is not important in practice. Austenite has a maximum C concentration of 2.14 wt %. It is not stable below the eutectic temperature (727 C) unless cooled rapidly Cementite is in reality metastable, decomposing into α-Fe and C when heated for several years between 650°C and 770°C.

- α -ferrite: – It is solid solution of carbon in δ-iron. Maximum concentration of carbon in α - ferrite is 0.09% at 2719 ºF (1493ºC) which is the temperature of the peritectic transformation. The crystal structure of δ-ferrite is BCC (cubic body centered).
- γ Austenite: – Austenite is interstitial solid solution of carbon in γ-iron. Austenite has FCC (cubic face centered) crystal structure, permitting high solubility of carbon i.e. up to 2.06% at 2097 ºF (1147 ºC). Austenite does not exist below 1333 ºF (723ºC) and maximum carbon concentration at this temperature is 0.83%.
- α-ferrite: – It is solid solution of carbon in α-iron. α-ferrite has BCC crystal structure and low solubility of carbon – up to 0.025% at 1333 ºF (723ºC). α-ferrite exists at room temperature.
- Cementite – Cementite is also known as iron carbide, is an intermetallic compound of iron and carbon, having fixed composition Fe3C. Cementite is a hard and brittle substance, influencing the properties of steels and cast irons.

Development of Microstructures in Iron—Carbon Alloys:-

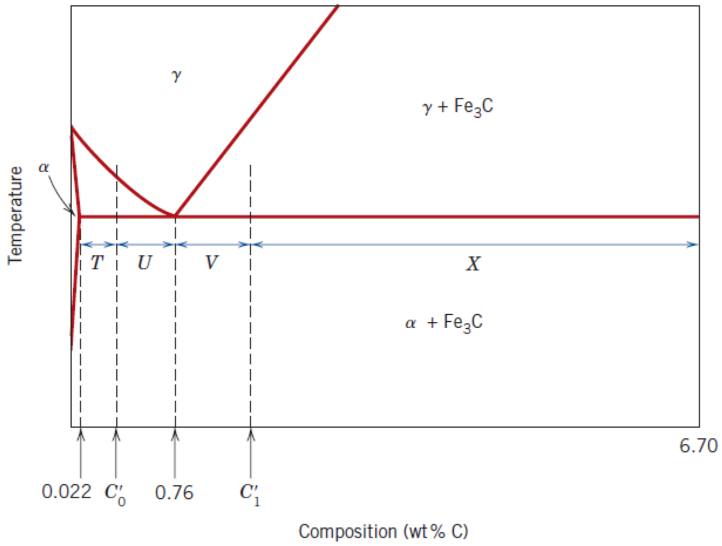
1- Hypoeutectoid Alloys: -

Microstructures for iron–iron carbide alloys having other than the eutectoid composition are now explored 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 in Figure 9.29. At about , point c, the microstructure will consist entirely of grains of the g phase, as shown in the Fig schematically in the figure. In cooling to point *d*, about , which is within α+γ the phase region, both these phases will coexist as in the schematic microstructure. Most of the small α particles will form along the original γ grain boundaries. The compositions of both and phases may be determined using the appropriate tie line; these compositions correspond, respectively, to about 0.020 and 0.40 wt% C. While cooling an alloy through the phase α+γ region, the composition of the ferrite phase changes with temperature along the α—(α+γ) 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 (α+γ) -γ 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 α phase and a microstructure similar to that also shown: the α particles will have grown larger. At this point, the compositions of the α and γ phases are determined by constructing a tie line at the temperature T_e the α phase will contain 0.022 wt% C, while the phase will be of the eutectoid composition, 0.76 wt% C.

The relative amounts of the proeutectoid and pearlite may be determined in a manner for primary and eutectic microconstituents. We use the lever rule in conjunction with a tie line that extends from α-(α + Fe_3C) the phase boundary (0.022 wt% C) to the eutectoid composition (0.76 wt% C), inasmuch as pearlite is the transformation product of austenite having this composition. For example, let us consider an alloy of composition C_o in Figure. Thus, the fraction of pearlite W_p, may be determined according to



Lever rule expression for computation of pearlite mass fraction (composition *C*0.,

$$W_p = \frac{T}{T + U}$$

$$= \frac{C'_0 - 0.022}{0.76 - 0.022} = \frac{C'_0 - 0.022}{0.74}$$

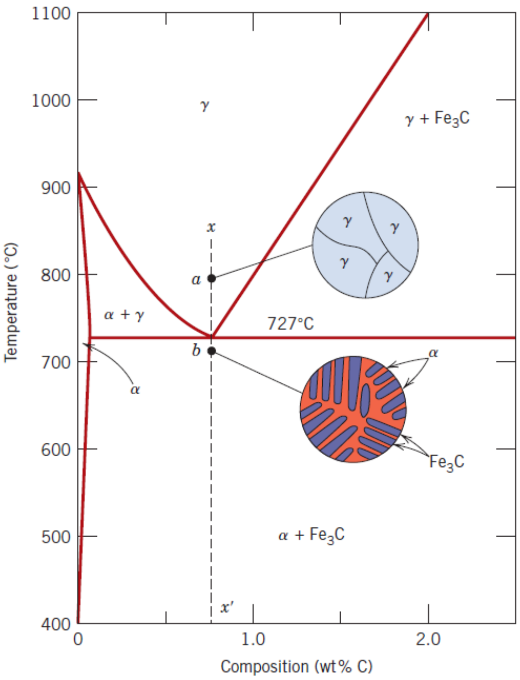
Lever rule expression for computation of proeutectoid ferrite mass fraction

$$W_{\alpha'} = \frac{U}{T + U}$$

$$= \frac{0.76 - C_0'}{0.76 - 0.022} = \frac{0.76 - C_0'}{0.74}$$

2- Eutectoid Alloys

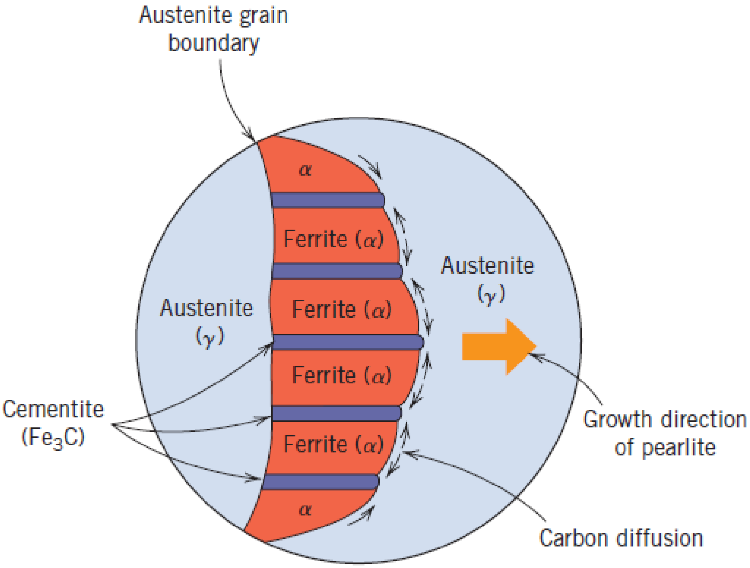
Eutectoid composition (0.76 wt% C) as it is cooled from a temperature within the γ phase region, say, 800_C—that is, beginning at point *a* in Figure , and moving down the vertical line xx' Initially, the alloy is composed entirely of the austenite phase having a composition of 0.76 wt% C and corresponding microstructure, also indicated in Figure As the alloy is cooled, there will occur no changes until the eutectoid temperature(727°C) is reached. Upon crossing this temperature to point *b*, the austenite transforms according to Equation



Eutectoid reaction for the iron-iron carbide system

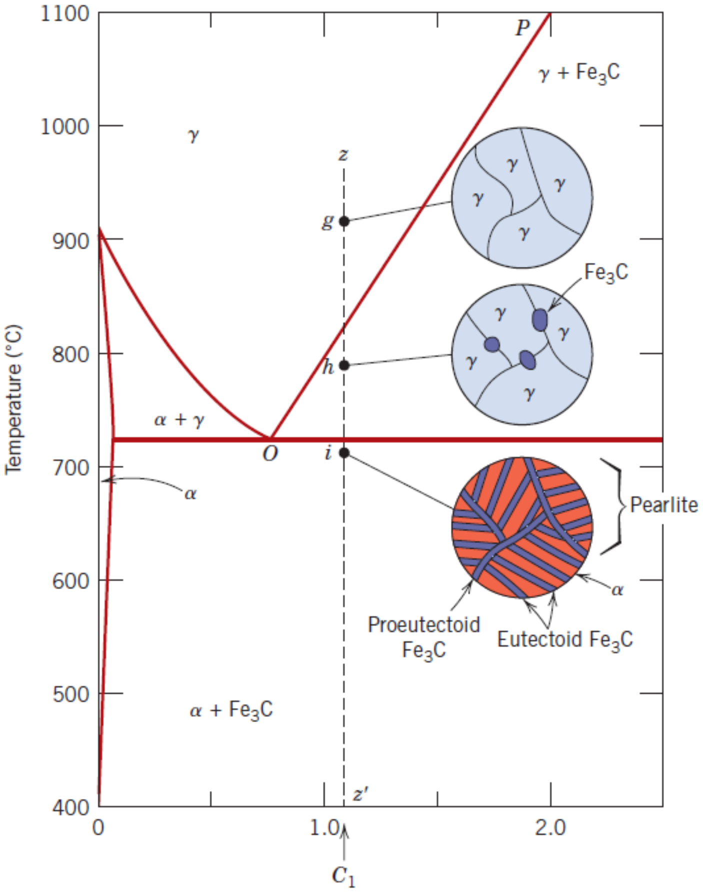
$$\gamma(0.76\text{ wt\% C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\text{ wt\% C}) + Fe_3C\,(6.7\text{ wt\% C})$$

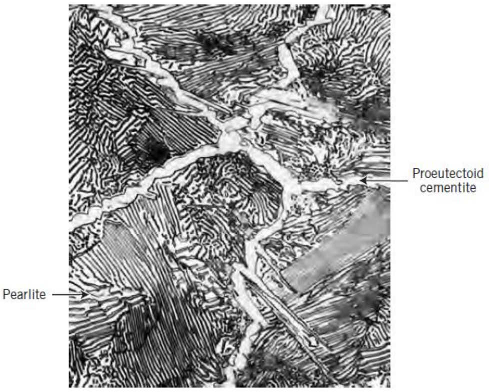
The microstructure for this eutectoid steel that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases (αand Fe_3C) that form simultaneously during the transformation. In this case, the relative layer thickness is approximately 8 to 1. This microstructure, represented schematically in Figure above, point *b*, is called **pearlite** because it has the appearance of mother of pearl when viewed under the microscope at low magnifications in the Fig.



3- **Hypereutectoid Alloys: -**

Analogous transformations and microstructures result for **hypereutectoid alloys,** those containing between 0.76 and 2.14 wt% C, which are cooled from temperatures within the phase field. Consider an alloy of composition C_1in Figure that, upon cooling, moves down the line zz' At point *g* only the γ phase will be present with a composition C_1 of the microstructure will appear as shown, having only γ grains. Upon cooling into the $\gamma+Fe_3C$ phase field—say, to point *h*—the cementite phase will begin to form along the initial grain boundaries, similar to the phase in **Hypoeutectoid Alloys**, point *d*. This cementite is called **proeutectoid cementite**—that which forms before the eutectoid reaction. Of course, the cementite composition remains constant (6.70 wt% C) as the temperature changes. However, 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 (Figure). In the photomicrograph of a 1.4 wt% C steel (Figure 9.33), note that the proeutectoid cementite appears light. Since it has much the same appearance as proeutectoid ferrite (Figure), there is some difficulty in distinguishing between hypoeutectoid and hypereutectoid steels on the basis of microstructure.





Relative amounts of both pearlite and proeutectoid Fe3C microconstituents may be computed for hypereutectoid steel alloys in a manner analogous to that for hypoeutectoid materials; the appropriate tie line extends between 0.76 and 6.70 wt% C.Thus, for an alloy having composition C_1’ in Figure above, fractions of W_p pearlite and proeutectoid cementite Fe_3C are determined from the following lever rule expressions:

$$W_p = \frac{X}{V + X} = \frac{6.70 - C_1'}{6.70 - 0.76} = \frac{6.70 - C_1'}{5.94}$$

and

$$W_{Fe_3C'} = \frac{V}{V + X} = \frac{C_1' - 0.76}{6.70 - 0.76} = \frac{C_1' - 0.76}{5.94}$$

EXAMPLE PROBLEM

Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:

(a) The fractions of total ferrite and cementite phases

(b) The fractions of the proeutectoid ferrite and pearlite

(c) The fraction of eutectoid ferrite

Solution

(a) This part of the problem is solved by application of the lever rule expressions employing a tie line that extends all the way across the $\alpha + Fe_3C$ phase field. Thus, C_0' is 0.35 wt% C, and

$$W_\alpha = \frac{6.70 - 0.35}{6.70 - 0.022} = 0.95$$

and

$$W_{Fe_3C} = \frac{0.35 - 0.022}{6.70 - 0.022} = 0.05$$

(b) The fractions of proeutectoid ferrite and pearlite are determined by using the lever rule and a tie line that extends only to the eutectoid composition (i.e., Equations 9.20 and 9.21). Or

$$W_p = \frac{0.35 - 0.022}{0.76 - 0.022} = 0.44$$

and

$$W_{\alpha'} = \frac{0.76 - 0.35}{0.76 - 0.022} = 0.56$$

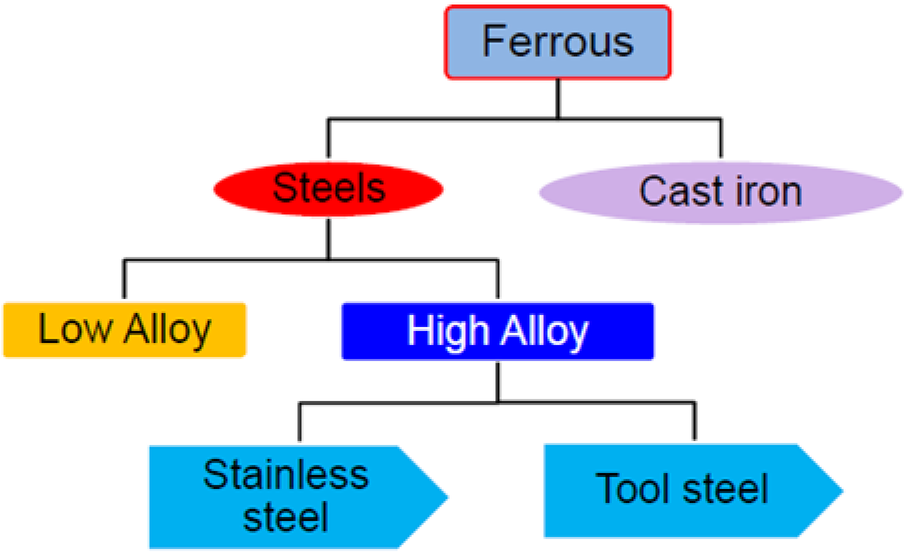
(c) All ferrite is either as proeutectoid or eutectoid (in the pearlite). Therefore, the sum of these two ferrite fractions will equal the fraction of total ferrite; that is,

$$W_{\alpha'} + W_{\alpha e} = W_{\alpha}$$

where $W_{\alpha e}$ denotes the fraction of the total alloy that is eutectoid ferrite. Values for W_{α} and $W_{\alpha'}$ were determined in parts (a) and (b) as 0.95 and 0.56, respectively. Therefore,

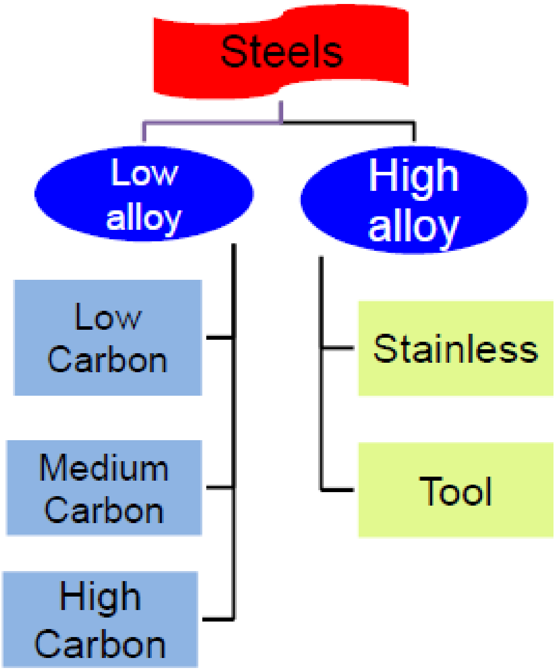
$$W_{\alpha e} = W_{\alpha} - W_{\alpha'} = 0.95 - 0.56 = 0.39$$

Ferrous Materials



Ferrous Materials - Steels

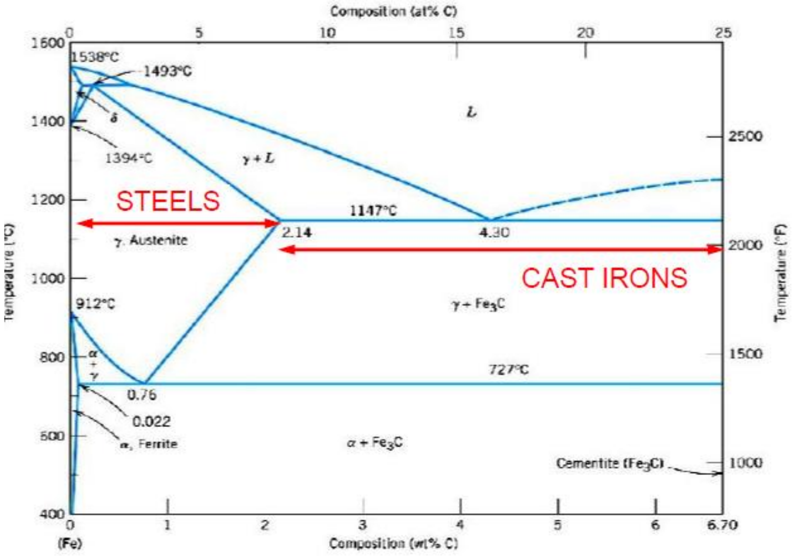
- Steels - alloys of iron-carbon. May contain other alloying elements.
- Several grades are available.
- Low Alloy (<10 wt%)
  - –Low Carbon (<0.25 wt% C)
  - –Medium Carbon (0.25 to 0.60 wt%)
  - –High Carbon (0.6 to 1.4 wt%)
- High Alloy
  - –Stainless Steel (> 11 wt% Cr)
  - –Tool Steel



Cast Iron

Cast Iron: typical properties: -

- ❖ High Hardness and brittleness
- ❖ Low ductility
- ❖ Cannot be cold worked/deformed at room temperature
- ❖ Easily melt and can be cast to the desired shape (can be sand cast to intricate shapes)
- ❖ Cheapest alloy



Depends on :-

1.Carbon content

2.Presence of alloying elements

3.Cooling rate before and after casting

4.Heat Treatment

Types of Cast Iron

1- White Cast Iron
2- Grey Cast Iron
3- Malleable Cast Iron
4- Nodular/ductile Cast Iron
5- Alloy Cast Iron

White Cast Iron

- Very hard but Brittle
- High wear and abrasion resistance
- Extremely difficult to machine
- Is used to produce malleable cast iron
- Heat treatment to 800 – 900 °C causes decomposition of Fe_3C - graphite clusters

- Very hard but Brittle
- High wear and abrasion resistance
- Extremely difficult to machine

- Is used to produce malleable cast iron

- Heat treatment to 800 – 900 oC causes decomposition of Fe_3C - graphite clusters

- Typical applications: rollers in rolling mills, brake shoes, extrusion nozzles

Malleable Cast Iron

1-Produced by annealing White Cast Iron at *900 –1060oC for 50-80hrs* (slow cooling to room temperature)

2-C is in the form of *irregular spheroid*

3-Typical Applications: Casting mould, railroad, pipe fittings and bridges, connecting rods

Grey Cast Iron

- Least expensive of metals
- High fluidity: complex shapes can be cast
- Graphite flakes: high damping capacity and good machineability
- Typical applications: cylinder blocks, base structure for machines and heavy equipment

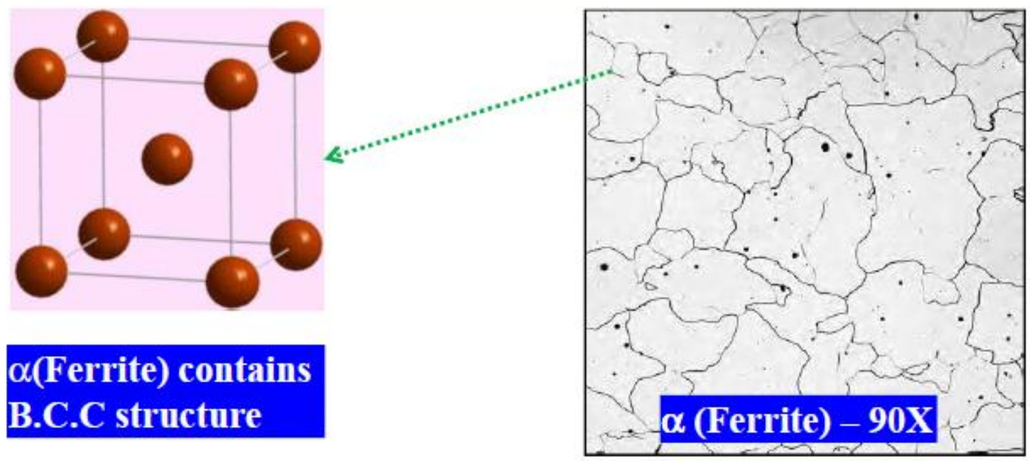
Ductile Cast Iron

- Ductile cast iron is produce by adding magensium (Mg) / cerium (Ce) to grey cast iron: graphite forms as spheres rather than flakes
- Removing the graphite flakes improves the tensile strength, toughness and ductility
- crankshafts, camshafts, gears and valves

Properties of steel phase

Ferrite (α)

- It is an interstitial solid solution of a small amount of carbon dissolved in α iron. The maximum solubility is 0.025%C at 723ºC and it dissolves only 0.008%C at room temperature. *It is the softest structure that appears on the diagram.*
- *Ferrite is ferromagnetic at low temperatures but loses its magnetic properties with the rise of temperatures with major loss at curies temperatures, 768*ºC and above this temperature, it becomes nonmagnetic (paramagnetic).
- **The crystal structure of ferrite (α) is B.C.C**
- **Tensile strength – 245 Mpa, Yield strength 118 Mpa**
- **Elongation – 40-50% in 2 in.**
- **Hardness - 95 HRB**



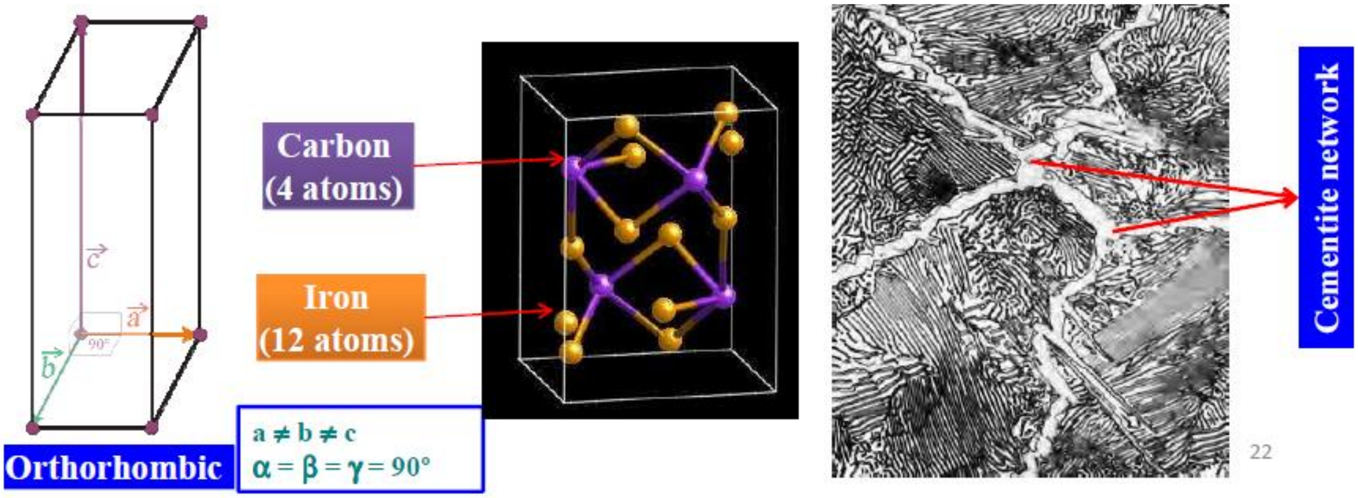
α(Ferrite) contains B.C.C structure

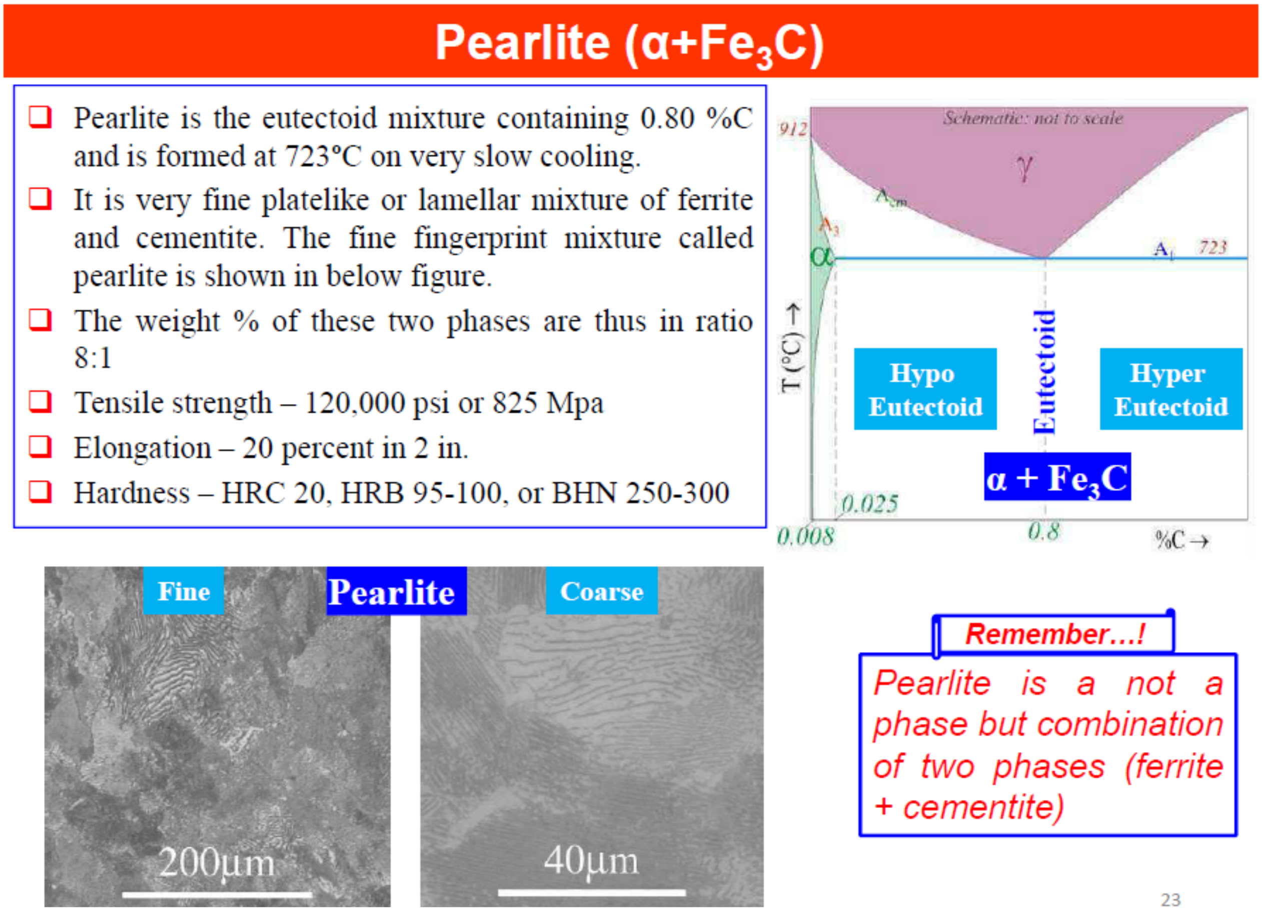
α (Ferrite) – 90X

Cementite (Fe_3C)

- Cementite or iron carbide, chemical formula Fe3C, contains 6.67%C by weight and it is a metastable phase.
- It is typically hard and brittle interstitial compound of low tensile strength (350 Mpa) but high compressive strength and high hardness ~64 HRC.

- It is the hardest structure that appears on the diagram.
- It has a complex orthorhombic crystal structure with 12 iron atoms and 4 carbon atoms per unit cell.
- It is slightly ferromagnetic up to 210ºC and paramagnetic above it. Melting point around 1227ºC.





Pearlite ($\alpha + Fe_3C$)

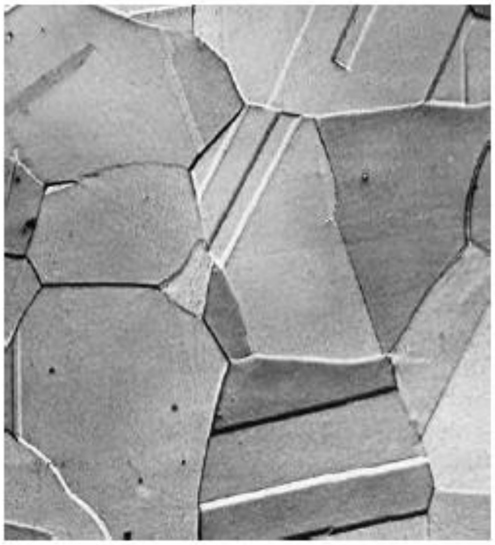
- ❑ Pearlite is the eutectoid mixture containing 0.80 %C and is formed at 723°C on very slow cooling.
- ❑ It is very fine platelike or lamellar mixture of ferrite and cementite. The fine fingerprint mixture called pearlite is shown in below figure.
- ❑ The weight % of these two phases are thus in ratio 8:1
- ❑ Tensile strength – 120,000 psi or 825 Mpa
- ❑ Elongation – 20 percent in 2 in.
- ❑ Hardness – HRC 20, HRB 95-100, or BHN 250-300

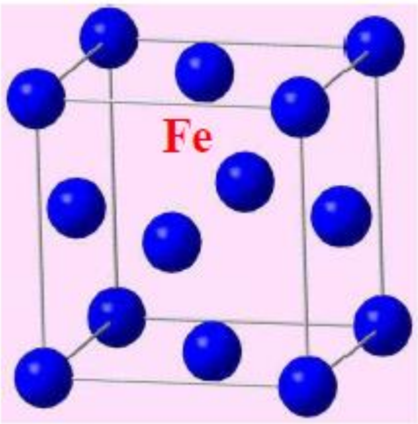
Remember…!

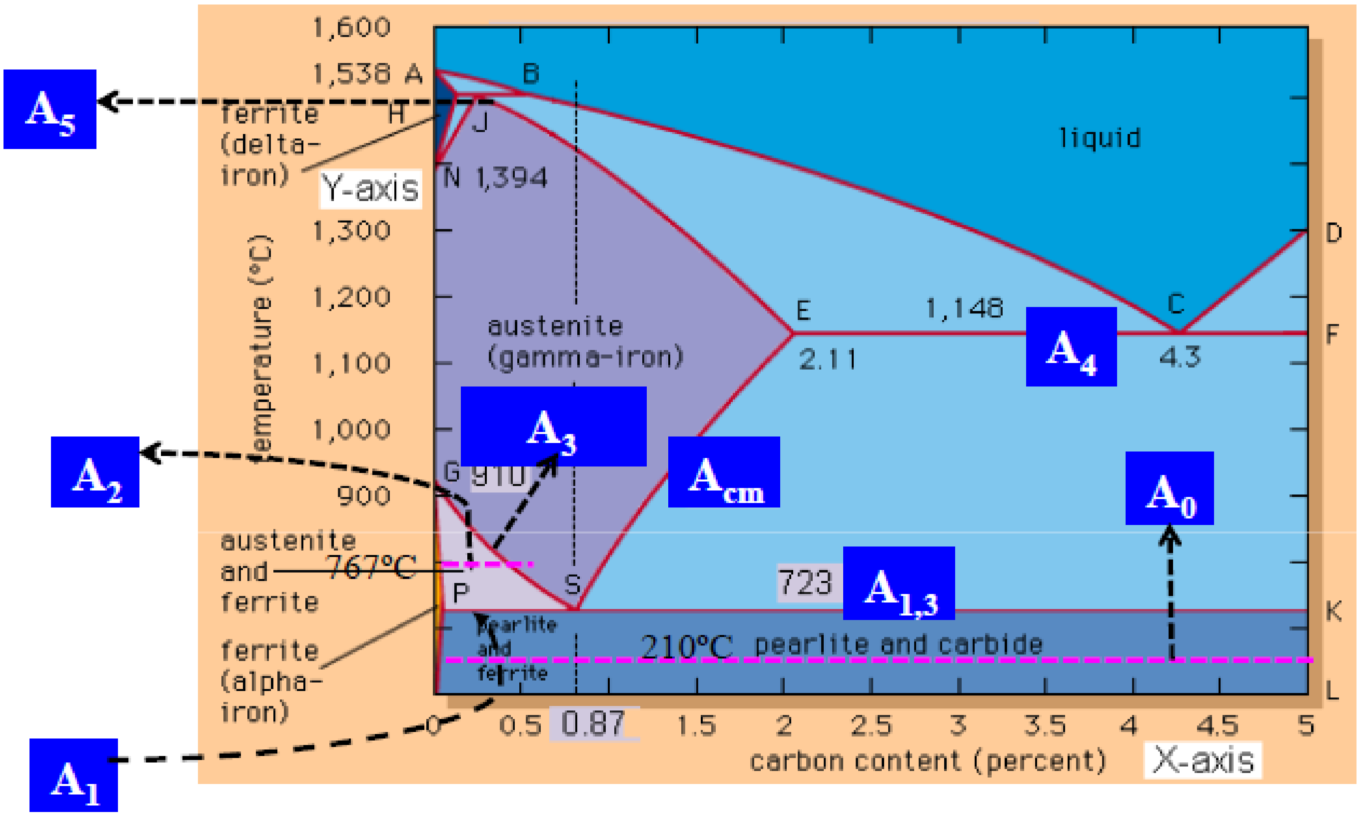
Pearlite is a not a phase but combination of two phases (ferrite + cementite)

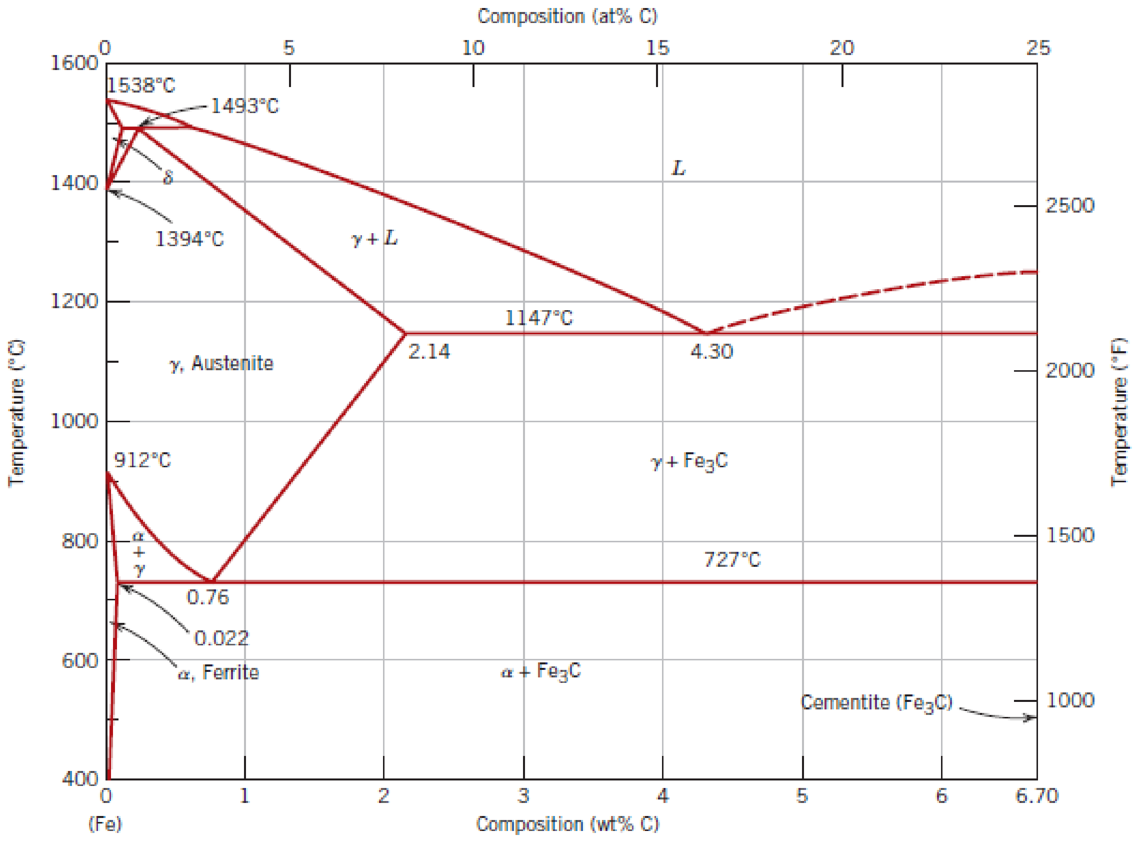
Austenite (γ)

- It is an interstitial solid solution of a small amount of carbon dissolved in γ iron and has FCC crystal structure. The maximum solubility is 2.1%C at 1147ºC.
- Austenite is soft, ductile tough and malleable (FCC structure) and non-magnetic (paramagnetic).
- Steels are commonly rolled and forged above about 1100ºC when they are in austenite state due to its high ductility and malleability, which is also due to its FCC structure.
    - Tensile strength – 150,000 psi or 1035 Mpa
    - Elongation – 10% in 2 in.
    - Hardness – 40 HRC and Toughness is high






A_5
1,600
1,538 A
B
ferrite (delta-iron)
H
J
N 1,394
Y-axis
liquid
D
1,300
1,200
1,100
1,000
900
temperature (°C)
austenite (gamma-iron)
E
1,148
C
F
2.11
4.3
A_4
A_3
A_{cm}
A_0
A_2
G 910
austenite and ferrite
767°C
P
S
723
$A_{1,3}$
K
ferrite (alpha-iron)
pearlite and ferrite
210°C
pearlite and carbide
L
A_1
0
0.5
0.87
1.5
2
2.5
3
3.5
4
4.5
5
carbon content (percent)
X-axis


Composition (at% C)
0
5
10
15
20
25
1600
1538°C
1493°C
L
δ
1400
1394°C
γ + L
2500
1200
1147°C
2.14
4.30
γ, Austenite
2000
1000
912°C
γ + Fe_3C
Temperature (°C)
Temperature (°F)
800
α + γ
727°C
1500
0.76
0.022
600
α, Ferrite
α + Fe_3C
Cementite (Fe_3C)
1000
400
0
1
2
3
4
5
6
6.70
(Fe)
Composition (wt% C)

Heat Treatment

The heat treatment includes heating and cooling operations or the sequence of two or more such operations applied to any material in order to modify its metallurgical structure and alter its physical, mechanical and chemical properties. Usually, it consists of heating the material to some specific temperature, holding at this temperature for a definite period and cooling to room temperature or below with a definite rate.

ANNEALING:-

There are two types of annealing processes applied to commercial plain-carbon steels.

- As the name suggests, this process is employed to relieve internal stresses. No microstructural changes occur during the process.
- Internal stresses are those stresses which can exist within a body in the absence of external forces. These are also known as residual stresses are locked-in stresses.
- These stresses are developed in operations like:

Solidification of castings, welding, machining, grinding, shot peening, surface hammering, cold working, case hardening, electroplated coatings, precipitation and phase transformation.

a) Full Annealing

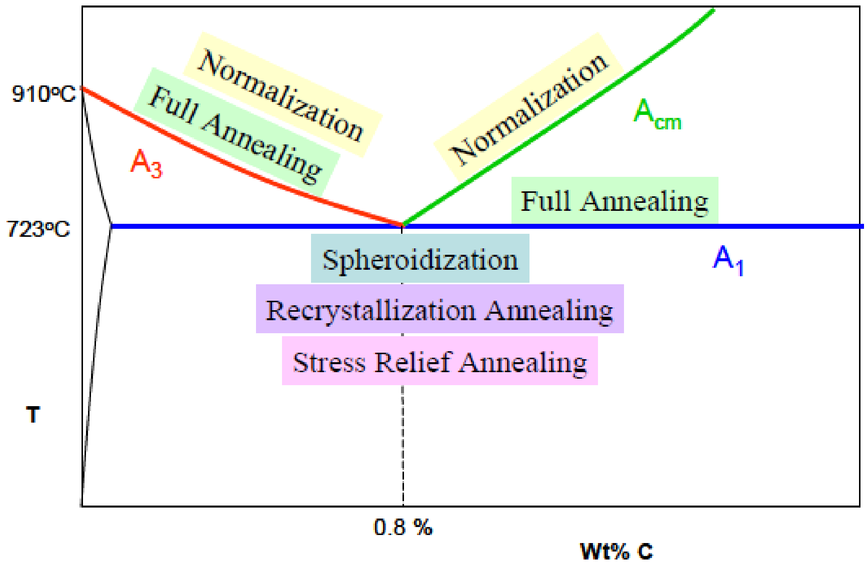
In full annealing, hypoeutectoid and eutectoid steels are heated in the austenite region, about40°Cabovetheupper-critical line, held the necessary time and then slowly cooled to room temperature, usually in the furnace. Resulting microstructure is consisting of small grainsofpro-eutectoidferriteandsmallareasofcoarselamellarpearlite.

For hypereutectoid steels, the material will be heated to the two-phase(γ+Fe3C) region 40°C above the eutectoid temperature.

Heating above this temperature coarsen the austenitic grains, which on cooling will transform to large pearlitic areas. The microstructure of full annealed hypereutectoid steels will consist of coarse lamellar pearlite areas surrounded by a network of pro-eutectoid cementite. Because the excess cementite network is brittle, annealing should never be a final heat treatment for hypereutectoid steels.

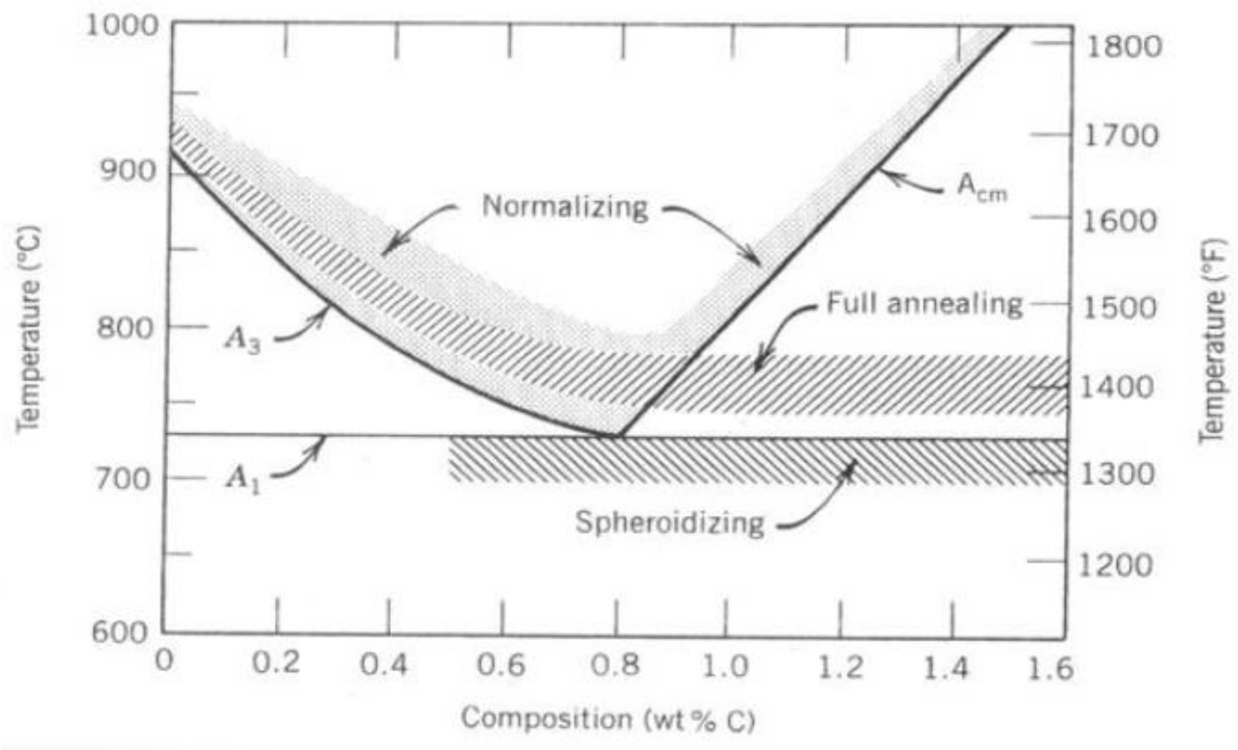
b) Process Annealing

This process is sometimes called as stress relief annealing. This treatment is carried out at a temp. below the eutectoid temperature usually between550-650°C for hypoeutectoid steels.



SPHERODIZING

High carbon hypereutectoid steels, which contain a large amount of Fe_3C, have poor machining characteristics. During the sherardizing treatment, which requires several hours at about 30 C below the eutectoid temperature, the Fe3C changes into large spherical particles in order to reduce boundary area. The microstructure, known as spherulite, has a continuous matrix of soft machinable ferrite.



Normalizing

Normalized treatment is frequently applied to steel in order to achieve any one or more of the objectives, namely

- To refine the grain structure,
- To obtain uniform structure,
- To decrease residual stresses,
- To improve Machinability.

QUENCHING

•Quenching is a heat treatment in which the steel is heated up to austenite(g) region and then rapidly cooled in water or oil.

•The hardening of steel requires the formation of martensite phase. This can be accomplished by quenching. Martensite is a meta-stable phase consisting of super-saturated interstitial solid solution of carbon in BCC or BCT iron.

•Quenching in water gives higher hardness than quenching in oil.

Hardening

- Hardening and Hardness are two very different things. One is a process of heat treatment and other is a extrinsic property of a material.
- Hardening is a heat treatment process in which steel is rapidly cooled from austenitising temperature. As a result of hardening, the hardness and wear resistance of steel are improved.
- Hardening treatment generally consists of heating to hardening temperature, holding at that temperature, followed by rapid cooling such as quenching in oil or water or salt baths.

- Hardening is applied to cutting tools and machine parts where high hardness and wear resistance are important.
- The Process Variables:

Hardening Temperature: The steel should be heat treated to optimum austenitising temperature. A lower temperature results lower hardness due to incomplete transformation t austenite. If this temperature is too high will also results lower hardness due to a coarse-grained structure.

Soaking Time: Soaking time at hardening temperature should be long enough to transform homogenous austenite structure. Soaking time increases with increase in section thickness and the amount of alloying element.

Delay in quenching: After soaking, the steel is immediately quenched. Delay in quenching may reduce hardness due to partial transformation of austenite.

Type of quenching medium also has a profound effect, which will be discussed briefly.

- The main purpose of hardening tool steel is to develop high hardness. This enables tool steel to cut other metals. High hardness developed by this process also improves wear resistance. Gears, shafts and bearings. Tensile strength and yield strength are improved considerably y hardening structural steels.
- Because of rapid cooling, high internal stresses are developed in the hardened steel. Hence these steels are generally brittle. Hardening in general is followed by another treatment known as tempering which reduces internal stresses and makes the hardened steel relatively stable,

Isothermal transformation diagram

Isothermal transformation diagrams (also known as **time-temperature-transformation** (**TTT**) **diagrams**) are plots of temperature versus time (usually on a logarithmic scale). They are generated from percentage transformation-vs time measurements, and are useful for understanding the transformations of an alloy steel at elevated temperatures.

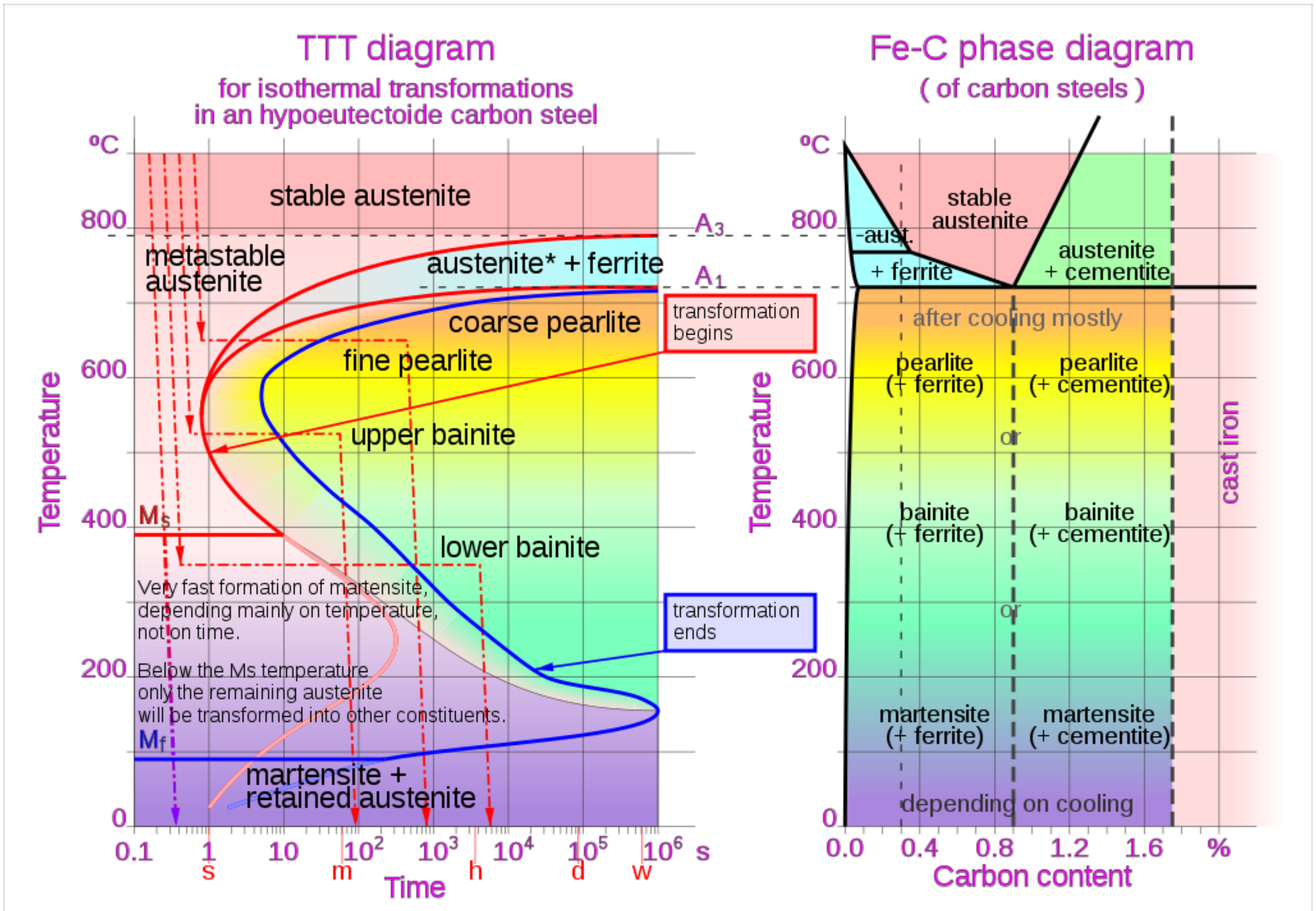
An isothermal transformation diagram is only valid for one specific composition of material, and only if the temperature is held constant during the transformation, and strictly with rapid cooling to that temperature. Though usually used to represent transformation kinetics for steels, they also can be used to describe the kinetics of crystallization in ceramic or other materials. Time-temperature-precipitation diagrams and time-temperature-embrittlement diagrams have also been used to represent kinetic changes in steels.

Isothermal transformation (**IT**) diagram or the C-curve is associated with mechanical properties, microconstituents/microstructures, and heat treatments in carbon steels. Diffusional transformations like austenite transforming to a cementite and ferrite mixture can be explained using the sigmoidal curve; for example the beginning of pearlitic transformation is represented by the pearlite start (P_s) curve. This transformation is complete at P_f curve. Nucleation requires an incubation time. The rate of nucleation increases and the rate of microconstituent growth decreases as the temperature decreases from the liquidus temperature reaching a maximum at the bay or nose of the curve. Thereafter, the decrease in diffusion rate due to low temperature offsets the effect of increased driving force due to greater difference in free energy. As a result of the transformation, the microconstituents, pearlite and bainite, form; pearlite forms at higher temperatures and bainite at lower.

TTT diagram of isothermal transformations of a hypoeutectoid carbon steel; showing the main components obtained when cooling the steel and its relation with the Fe-C phase diagram of carbon steels.

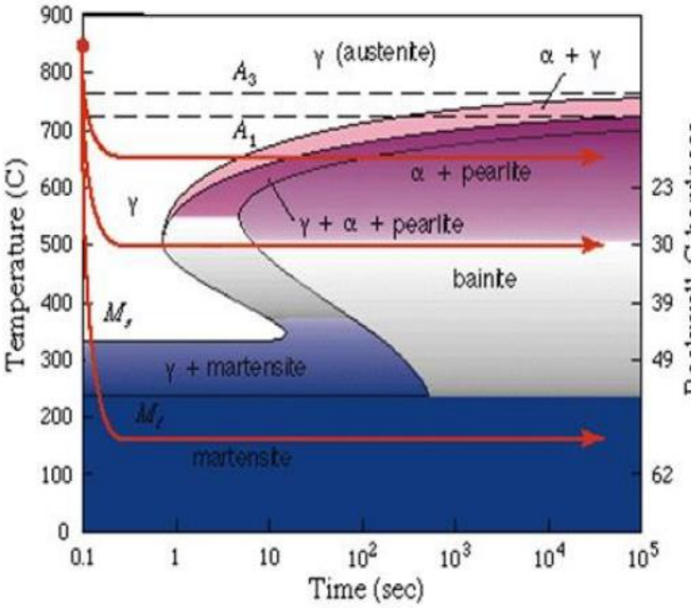
Austenite is slightly undercooled when quenched below Eutectoid temperature. When given more time, stable microconstituents can form: ferrite and cementite. Coarse pearlite is produced when atoms diffuse rapidly after phases that form pearlite nucleate. This transformation is complete at the pearlite finish time (P_f).

However, greater undercooling by rapid quenching results in formation of martensite or bainite instead of pearlite. This is possible provided the cooling rate is such that the cooling curve intersects the martensite start temperature or the bainite start curve before intersecting the P_s curve. The martensite transformation being a diffusion less shear transformation is represented by a straight line to signify the martensite start temperature.



(*) stable at these temperatures, but it will be transformed after further cooling

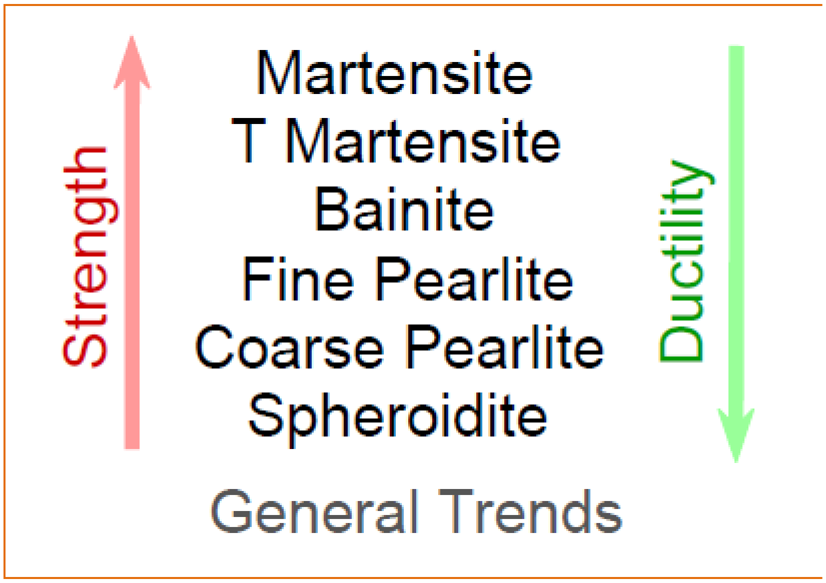
- TTT diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition.



- It is used to determine when transformations begin and end for an isothermal heat treatment of a previously **austenitized** alloy.

- TTT diagram indicates when a specific transformation starts and ends and it also shows what percentage of transformation of austenite at a particular temperature is achieved.

Depending on the type of heat treatment, time and temperature, final microstructure of the steel, or any Iron carbon will be changed and so does the properties.



Strength

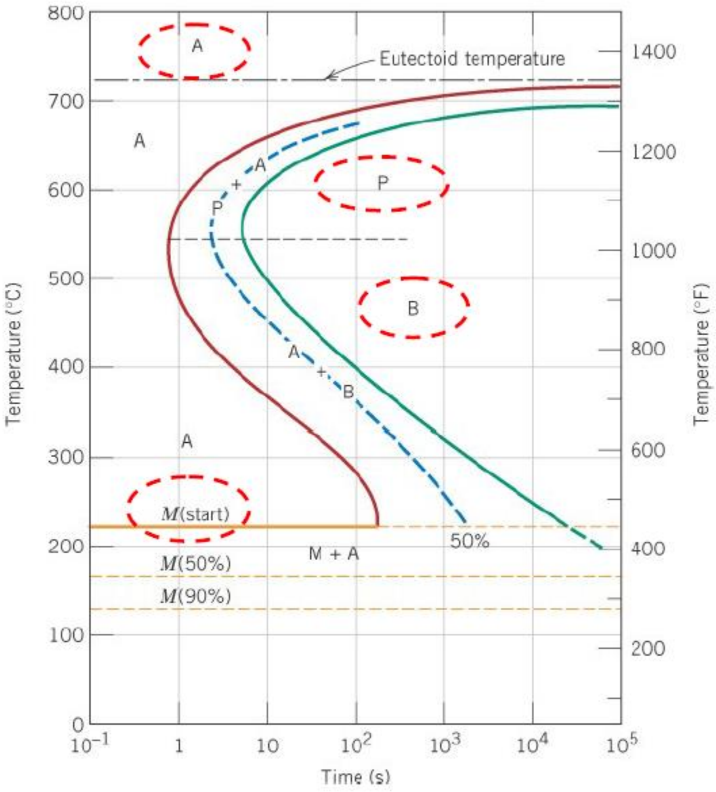
Martensite
T Martensite
Bainite
Fine Pearlite
Coarse Pearlite
Spheroidite

Ductility

General Trends

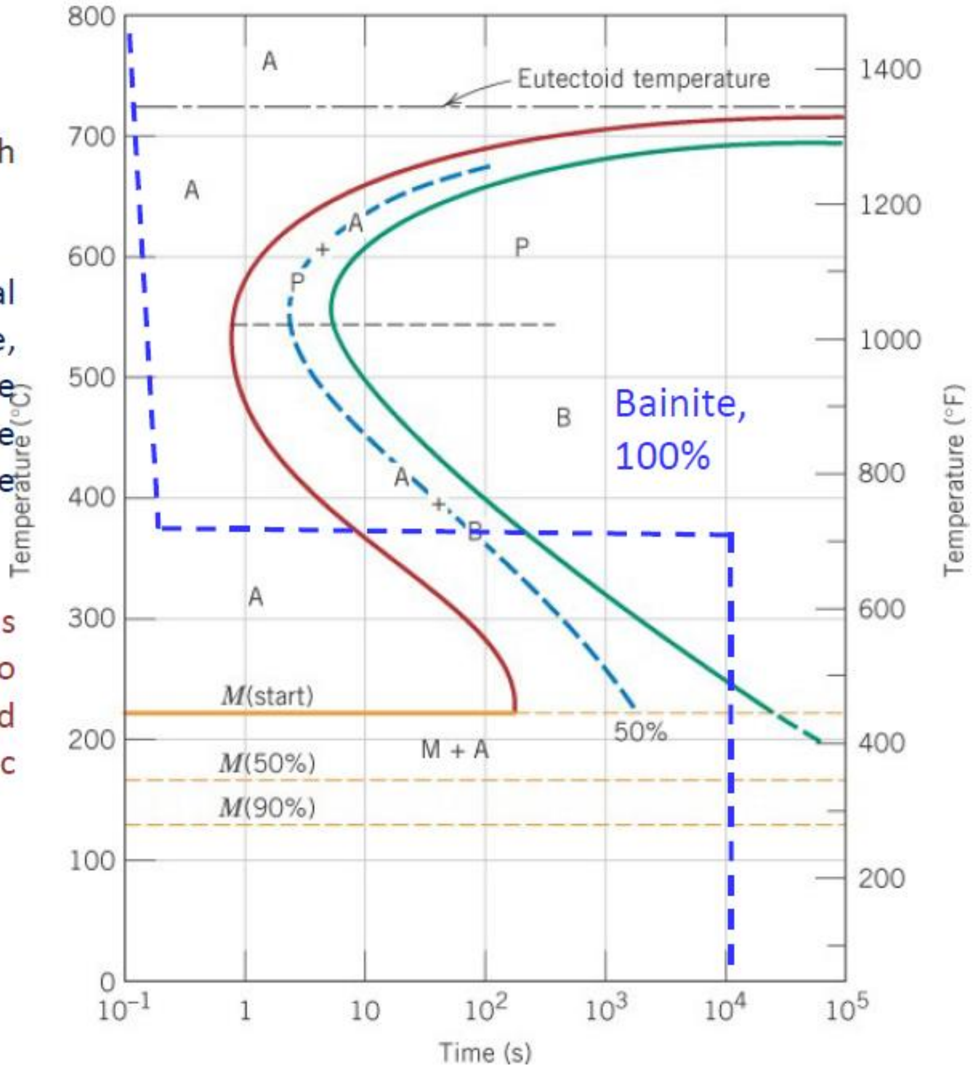
Iron-carbon alloy with Eutectoid (0.8 % C) composition.

- A: Austenite
- P: Pearlite
- B: Bainite
- M: Martensite



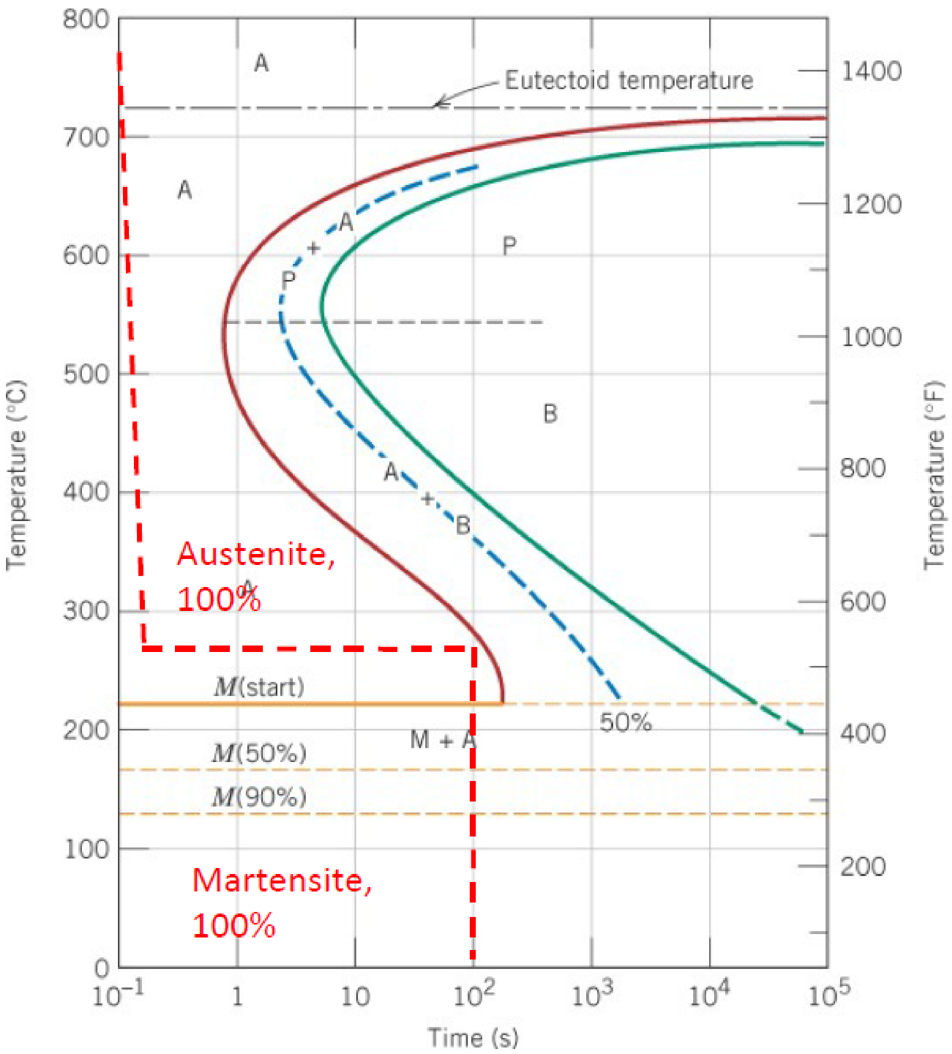
Example 1:

- 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˚C and has been held long enough to achieve a complete and homogeneous austenitic structure.
- Treatment (a)
- Rapidly cool to 350 ˚C
- Hold for 10^4 seconds
- Quench to room temperature



Example 2:

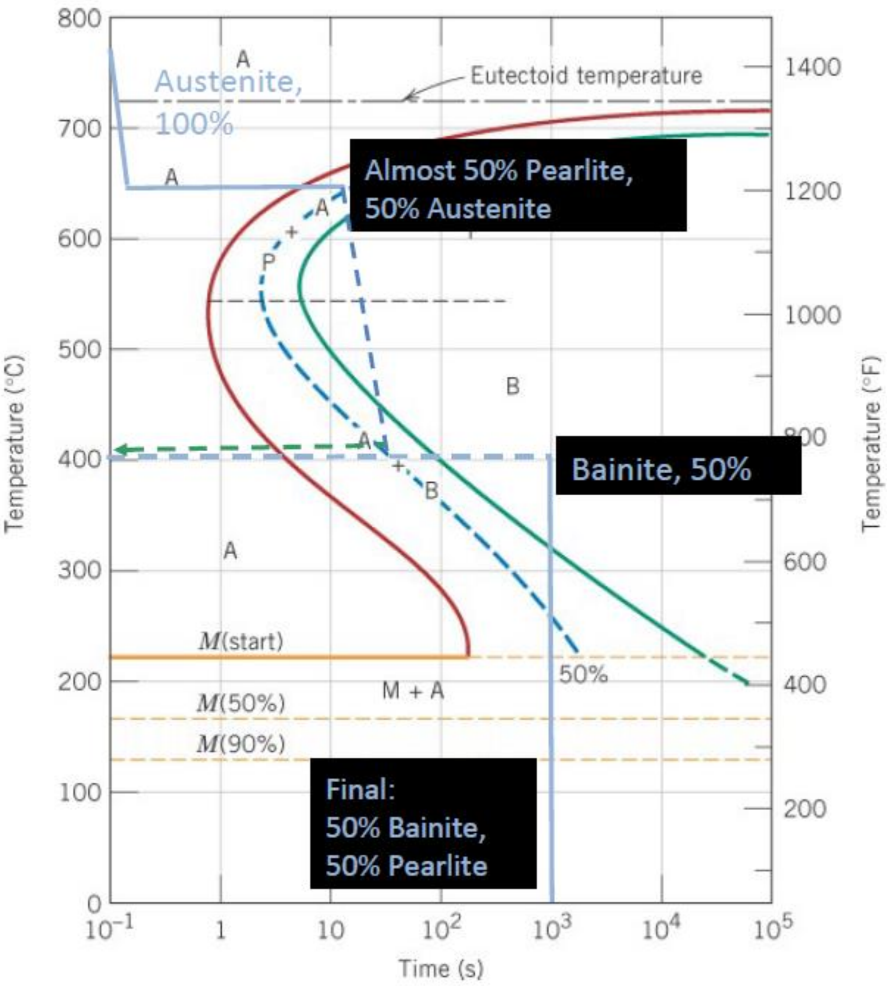
- Iron-carbon alloy with eutectoid composition.
- Specify the nature of the final microstructure (% bainite, martensite, pearlite etc) for the alloy that is subjected to the following time–temperature treatments:
- Alloy begins at 760˚C and has been held long enough to achieve a complete and homogeneous austenitic structure.
- Treatment (b)
- Rapidly cool to 250 ˚C
- Hold for 100 seconds
- Quench to room temperature



Example 3:

- 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˚C and has been held long enough to achieve a complete & homogeneous austenitic structure.

- Treatment (c)
- Rapidly cool to 650˚C
- Hold for 20 seconds
- Rapidly cool to 400˚C
- Hold for 10^3 seconds
- Quench to room temperature



Almost 50% Pearlite, 50% Austenite

Bainite, 50%

Final:
50% Bainite,
50% Pearlite