Northern Technical University

Technical engineering College Mosul

Applied Mechanics
second Level
Engineering Materials

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Weekly Syllabus

1- Introduction to engineering materials
2- Types of engineering materials
3- Properties of engineering materials
4- Crystalline structure and Non crystalline structure of metals
5- Atom binding: Ionic bond, covalent bond, metallic bond, Van der Waals forces
6- Crystal defects, different crystals from an ingot, Crystal imperfections
7- Solidification: different crystals form in an ingot
8- Mechanical properties, hardness, Brinell hardness, Vickers hardness, and Rockwell Hardness
9- Tensile test, fatigue test, Impact test and Creep test
10- Cooling curves for metals and alloys, Solid solution,
11- Two metals completely soluble in each other in solid state
12- Two metals completely insoluble in each other in solid state
13- Two metals partially soluble in each other in solid state
14- Iron making. Steel making
15- Thermal equilibrium diagram for Iron-Iron carbide, Types of steel Impurities (alloying elements) in steel, Cast Iron, Types of cast Iron
16- Heat treatments of steel
17- Surface hardening of steel
18- Preparatory week before the final Exam

References

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Engineering Materials Technology, W. Bolton 3rd edition, 1998 - 2

Fundamentals of Materials Science and Engineering, William D. Callister, 2001 - 3

The science and engineering of materials, Donald r. askeland, 3rd edition, 2001 - 4

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Introduction to engineering materials

Engineering materials form the foundation of all engineering applications. The choice of material directly impacts the performance, durability, cost, and safety of any product or structure. Understanding the various classes of materials, their properties, and their applications is essential for engineers across disciplines.

Classification of Engineering Materials (Materials Types)

Engineering materials are broadly classified into four main categories:

1- **Metals**: Strong, ductile, and conductive materials commonly used in construction, machinery, and electronics. They are subdivided into:
a- Ferrous metals: Contain iron (e.g., steel, cast iron).
b-Non-ferrous metals: Do not contain iron (e.g., aluminum, copper).
2- **Polymers**: Organic materials composed of long molecular chains. Polymers can be flexible, lightweight, and resistant to corrosion. They are widely used in packaging, insulation, and consumer products.
a- Thermoplastics: Can be remolded by heating (e.g., polyethylene).
b- Thermosets: Harden irreversibly upon curing (e.g., epoxy resins).
3- **Ceramics**: Inorganic, brittle, heat-resistant materials such as glass, porcelain, and advanced ceramics like silicon carbide. These materials excel in high-temperature environments and applications where wear resistance is crucial.
4- **Composites**: Made by combining two or more different materials to achieve properties superior to individual components. Common composites include fiberglass and carbon fiber-reinforced plastics.

3-Properties of Engineering Materials

Each material class has specific properties that determine its suitability for various applications.
These properties are divided into:

1- Mechanical Properties: Determine the material's response to physical forces.

- Strength: The ability to withstand an applied force without failure.
- Ductility: The capacity of a material to deform under tensile stress.
- Hardness: Resistance to deformation or scratching.
- Toughness: The ability to absorb energy before fracturing.

2- Thermal Properties: The material's response to heat.

- Thermal conductivity: The rate at which heat passes through a material.
- Melting point: The temperature at which a material changes from solid to liquid.

3- Electrical Properties: Critical for materials used in electronics.

- Conductivity: The ability of a material to conduct electric current.
- Resistivity: The material's opposition to electric current.

4- Crystalline and non crystalline materials :

Structure of materials: materials can be classified into two types of structure

1-Crystalline structure: -consists of atoms or ions, arranged according to some regular geometrical pattern. This pattern varies from one substance to another. All metals are crystalline in nature.

2-Amorphous structure: -is typical of all liquids in that the atoms or molecules. of which they are composed can be moved easily with respect to each other, since they do not conform to any fixed pattern. Some materials, like glasses, plastics, amorphous silicon and tar are called amorphous because the atoms exist in a random pattern just as in liquid.

1-The crystal structure of metals

Crystalline structure of metals: there are several types of pattern or space lattice in which metallic atoms can arrange themselves on solidification, but the three most common are: -

1- **The body-centered cubic lattice: -**has eight atoms at the corners of a cube **.**and one atom at the center. Iron (alpha) at room temperature, chromium, vanadium and tungsten are a few of the more important metals with this lattice Structure.

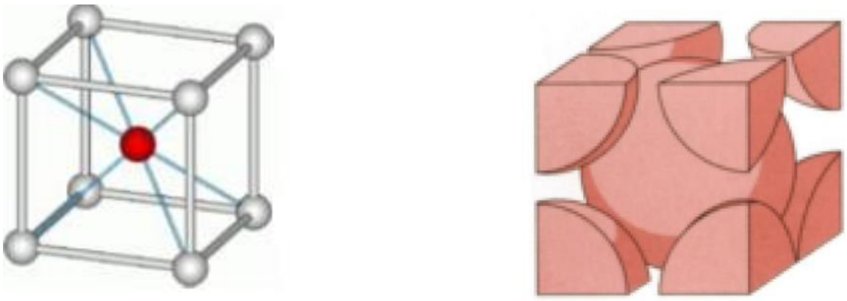


Figure 1. Body centered cubic lattice structure

2- **The face – centered cubic lattice: -** has eight atoms at the corners of a cube and an atom in the center of each face. Iron (gamma) at elevated temperature, aluminum, silver, copper and gold are examples of this lattice structure.

Figure 2. Face centered cubic lattice structure

3- **The hexagonal close – packed lattice: -** this space lattice structure is geometrically described by the figure shown below. This type of structure has 17 atoms. The metals cadmium, magnesium and titanium have the hexagonal structure.

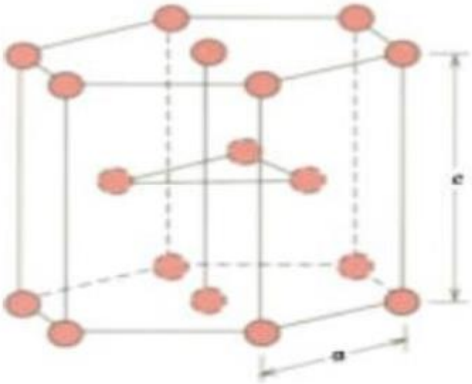
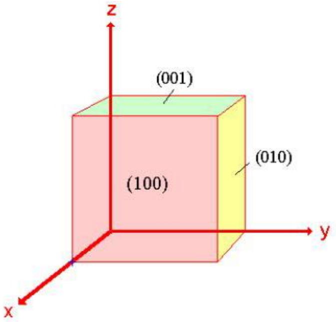


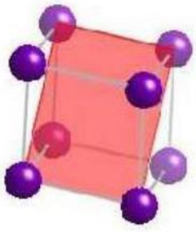
Figure 3. hexagonal close – packed lattice

1- Crystalline planes and directions .Atomic packing factor.

Crystallograhic planes and direction :

1- The unit cell :is building block for crystal.repetition of unit cell generates entire crystal.
2- Crystallograhic lanes :the layers of atoms or the planes along which atoms are arranged are known as atomic or crystallograhic planes.
3- Miller indices :the relation of aset of planes to the axes of the unit cell is designated by miller indices.
   One corner of the unit cell is assumed to be the origin of the space coordinates , and any set of lanes is identified by the recirocals of its intersections with these cooordinates .if aplane is parallel too an axis ,it intersects it at infinity.





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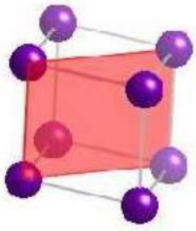

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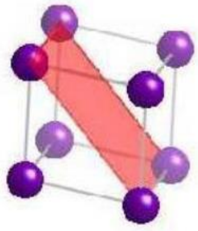
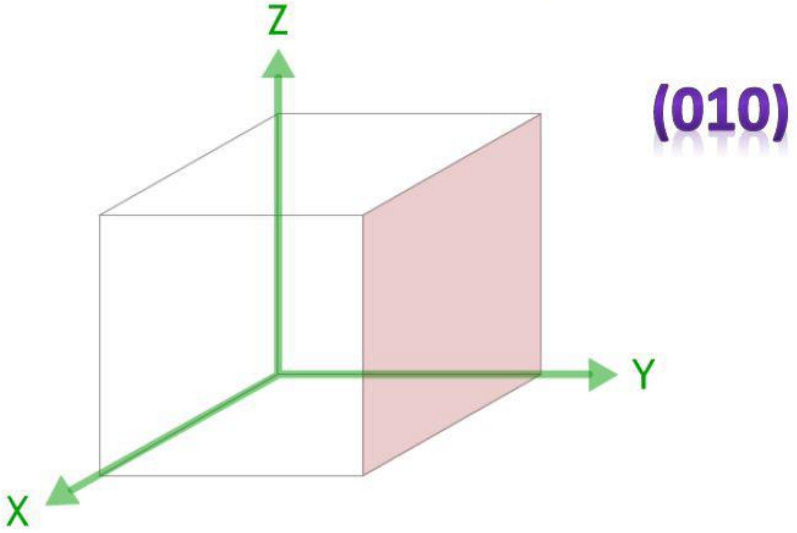


(011)

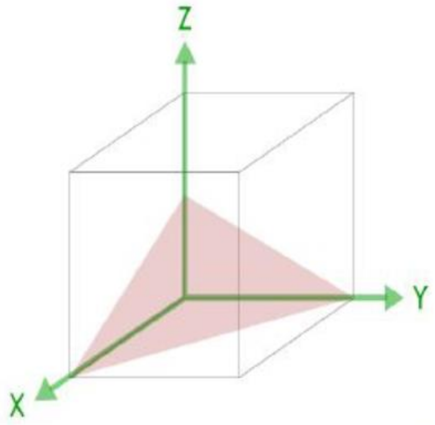
The plane (010) intersects the y-axis at one unit from the origin and is parallel to the x and z axes or intersects them at infinity. Therefore,



Process	x	y	z
Intersection	∞	1	∞
Reciprocal	1/∞	1/1	1/∞
Miller indices	0	1	0

The illustrated plane has Miller indices of (010).

As another illustration, the Miller indices of the plane (112) may be determined as follows:-



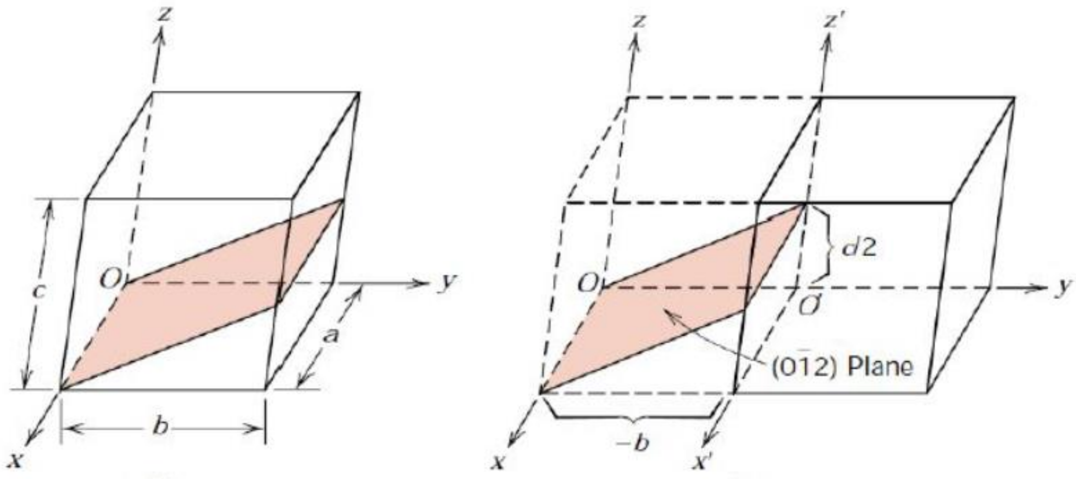
(112)

	x	y	z
Intersection	1	1	1/2
Reciprocal	1/1	1/1	1/1/2
Miller indices	1	1	2

This plane has Miller indices of (112).

EXAMPLE :

Determine the Miller indices for the plane shown in the accompanying sketch (*a*).

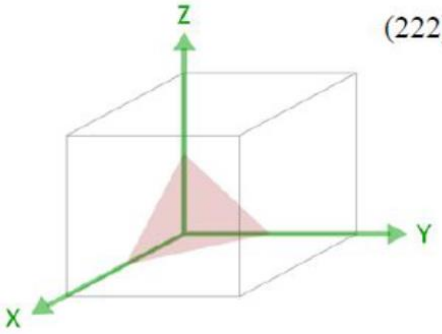


(*a*) (*b*)

SOLUTION:

Since the plane passes through the selected origin *O*, a new origin must be chosen at the corner of an adjacent unit cell, taken as *O* and shown in sketch (*b*). This plane is parallel to X axis and the intersections are ∞, -1, and ½.

As another illustration, the Miller indices of the plane shown below may be determined as follows:-

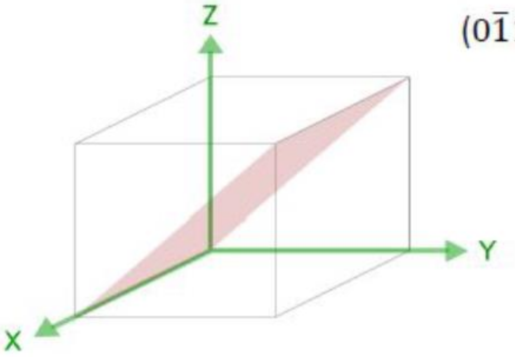


(222)

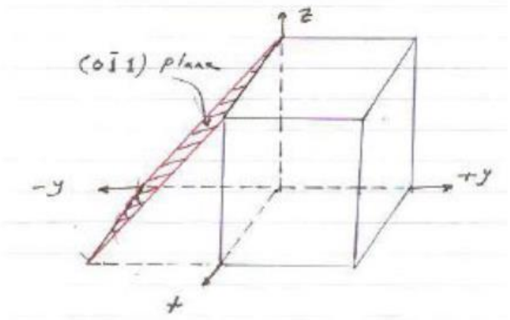
process	x	y	Z
Intersection	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
Reciprocal	1/1/2	1/1/2	1/1/2
Miller indices	2	2	2

This plane has Miller indices of (222).

As another illustration, the Miller indices of the plane shown below may be determined as follows:-



$(0\bar{1}1)$



process	x	y	Z
Intersection	∞	-1	1
Reciprocal	1/∞	1/-1	1/1
Miller indices	0	$\bar{1}$	1

The plane has Miller indices of

(0 $\bar{1}$ 1).

As another illustration, the Miller indices of the plane shown below may be determined as follows:-

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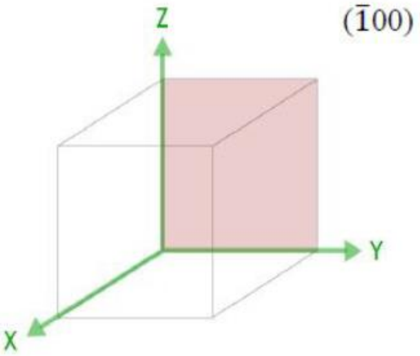
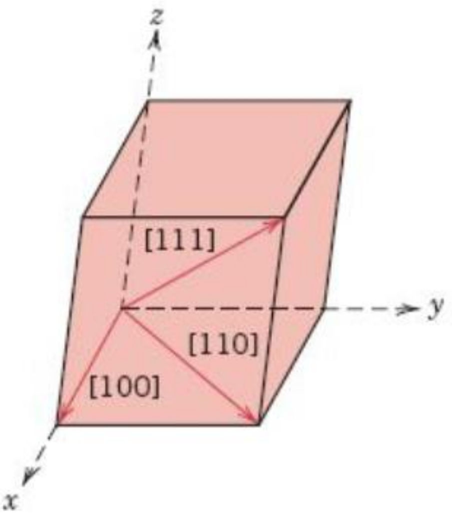


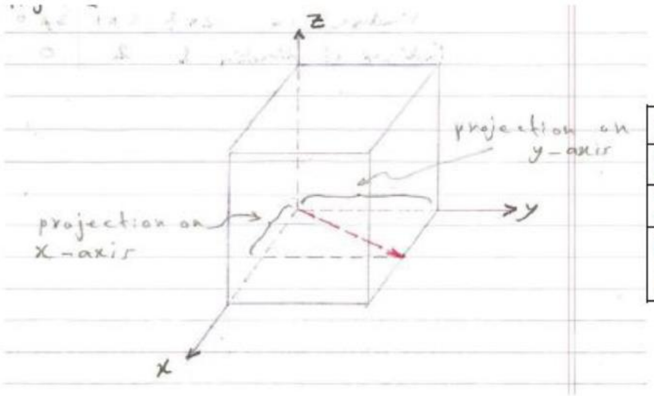
process	x	y	Z
Intersection	**-1**	∞	∞
Reciprocal	1/-1	1/∞	1/∞
Miller indices	$\bar{1}$	0	0

This plane has Miller indices of ($\bar{1}$00).

The indices of the direction:- for example, to determine the direction of [110], (Reciprocal are not used to determine the indices of direction), starting at the origin, it is necessary to move one unit along the x-axis and one unit in the direction of the y-axis. In a cubic crystal, a direction has the same indices as the plane to which it is perpendicular.



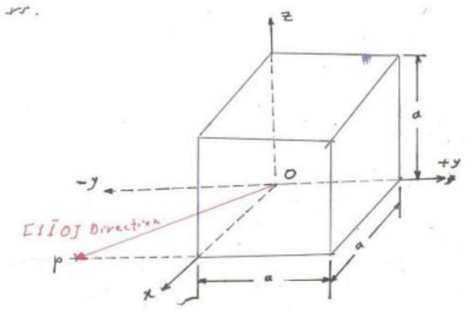
Example: Determine the indices for the direction shown in the figure below:



process	x	y	Z
Projection	**1/2**	1	0
Reduction	2*1/2	2*1	2*0
Indices of direction	1	2	0

This direction has indices of (120).

Example: Determine the indices for the direction shown in the figure below:



process	x	y	Z
Projection	1	-1	0
Reduction	1	-1	0
Indices of direction	1	$\bar{1}$	0

This direction has indices of $(1\bar{1}0)$.

Packing of atoms: An approximate idea of the packing of atoms on a particular plane may be obtained by visualizing a single unit cell of the BCC and FCC structure.

Considering The atoms as the lattice points, the number of atoms on a particular plane would be:

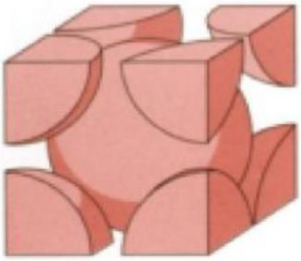
Plane	BCC	FCC
(100)	4	5
(110)	5	6
(111)	3	6
(120)	2	3
(221)	1	1

Packing factor: In BCC the center atom touches each corner atom but these do not touch each other. Since each corner atom is shared by eight adjacent cubes and the atom in center cannot be shared by any other cube, the unit cell of the BCC

$8 \text{ atoms at the corners x } \frac{1}{8} = 1\ atom$

$1 \text{ center atom} = 1\ atom$

$\text{Total} = 2\ atoms$

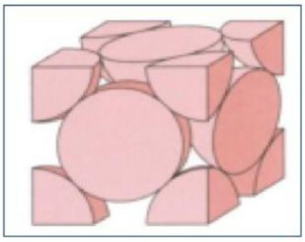


In FCC, each face atom touches its nearest corner atom. Since each corner atom is shared by eight adjacent cubes and each face atom is shared by only one adjacent Cube, the unit cell contains:

$8 \text{ atoms at the corners x } \frac{1}{8} = 1\ atom$

$6 \text{ face-centered atoms x } \frac{1}{2} = 3\ atom$

$\text{Total} = 4\ atoms$



This indicates that the FCC structure is more densely packed than the BCC structure.

Another way to show the difference in packing is to calculate the fraction of the volume of a FCC cell that is occupied by atoms and compare it to that of a BCC cell. Since there are four atoms per unit cell and each atom is a sphere of radius r_a, then:

$$V_{atoms} = 4\left(\frac{4}{3}\pi r_a^3\right)$$

And

$$V_{cell} = a^3$$

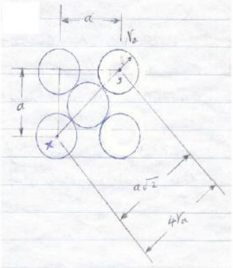
Where a is the lattice parameter. It is now necessary to find the cell volume in terms of r_a. Consider a cube face of FCC structure as shown below:

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

$$4r_a = \sqrt{2a^2}$$

$$4r_a = \sqrt{2}\ a$$

$$\sqrt{2}\,a = 4r_a$$



$$a = \frac{4\mathrm{r_a}}{\sqrt{2}}$$

$$a = 2\sqrt{2}\ \mathrm{ra}$$

$$packing\ factor = \frac{\mathrm{V_{atoms}}}{\mathrm{V_{cell}}}$$

$$packing\ factor = \frac{\frac{16}{3}\pi\,\mathrm{r_a}^{3}}{(2\sqrt{2}\ \mathrm{ra})^{3}}$$

$$packing\ factor = \frac{\pi}{3\sqrt{2}}$$

$$packing\ factor = 0.74$$

The packing factor for the BBC structure can be calculated as follows:

$$(4r_a)^2 = a^2 + x^2$$

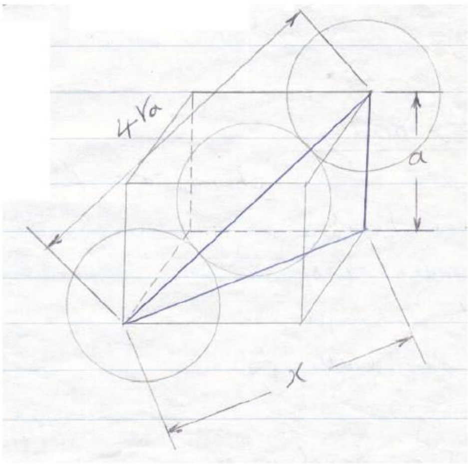
$$x^2 = 16ra^2 - a^2$$

but $x^2 = 2a^2$

$\therefore$ $3a^2 = 16ra^2$

$$a^2 = \frac{16}{3} r_a^2$$

$\therefore$ $a = \frac{4}{\sqrt{3}} r_a$



$$packing\ factor = \frac{V_{atoms}}{V_{cell}}$$

$$packing\ factor = \frac{2\frac{4}{3}\pi {r_a}^3}{a^3}$$

$$packing\ factor = \frac{2\frac{4}{3}\pi {r_a}^3}{(\frac{4}{\sqrt{3}}r_a)^3}$$

$$packing\ factor = \frac{\pi\sqrt{3}}{8}$$

$$packing\ factor = 0.68$$

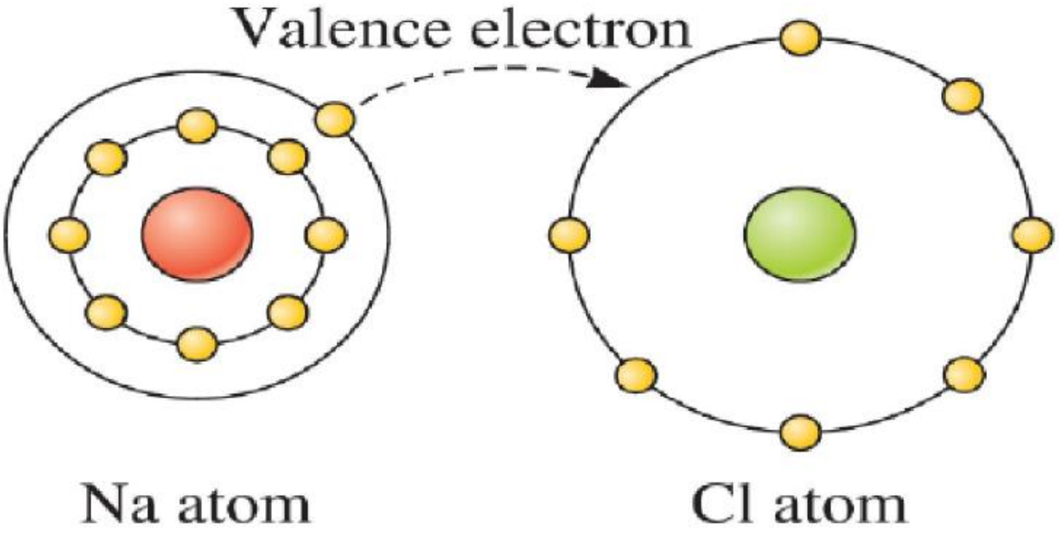
5-Atom binding:

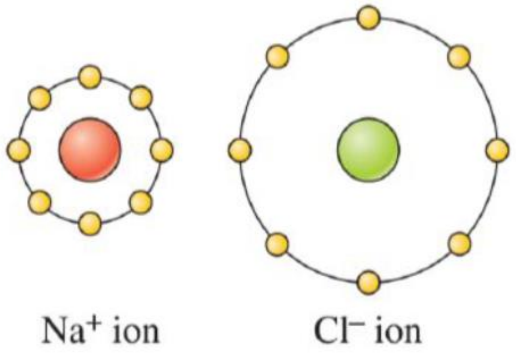
1- Ionic bond.
2- covalent bond.
3- metallic bond.
4- Van der Waals forces.

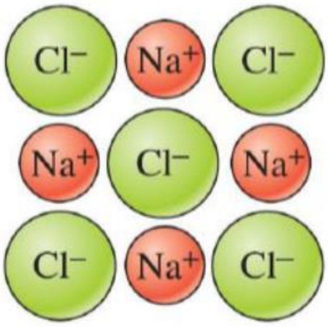
1-Ionic bond

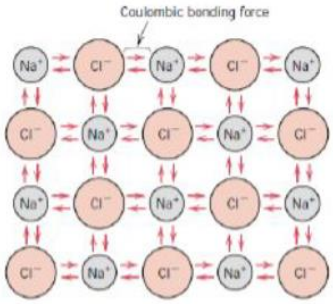
The electron structure of atoms is relatively stable when the outer shells contains eight. (or two in the case of the first shell) An element like sodium with one excess electron will readily give it up so that it has a completely filled outer shell. Atom binding: Ionic bond, covalent bond, metallic bond, Van der Waals forces. An atom of chlorine, on the other hand, with seven electrons in its outer shell, would. Like to accept one electron.

When sodium and chlorine atoms are placed together, there is a transfer of electrons from the sodium to the chlorine atoms, resulting in a strong electrostatic attraction between the positive sodium ions and the negative chlorine ions as shown below:



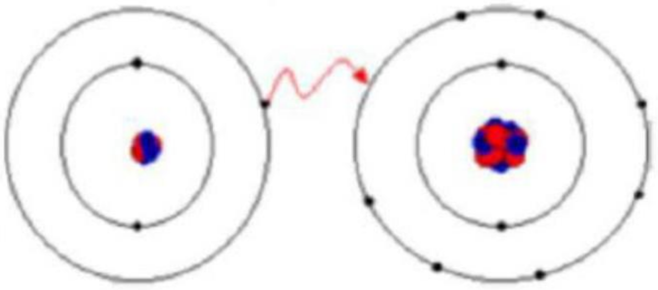






$Na + Cl \rightarrow Na^+ + Cl^- \rightarrow NaCl$

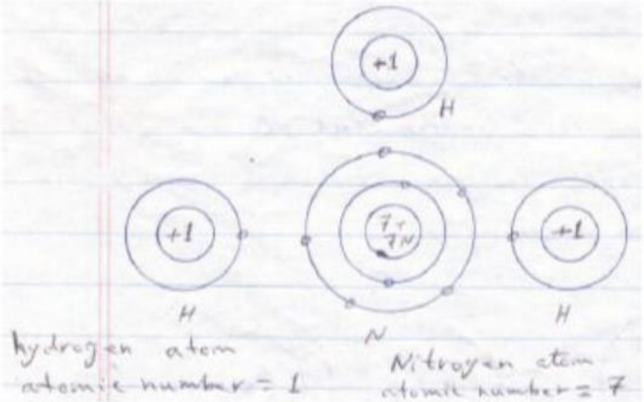
Another example for ionic bond is lithium and fluorine. Lithium has 1 electron in its outer shell and fluorine carries 7 electrons in its outer shell. When one electron moves from lithium to fluorine, each ion acquires the noble gas configuration.

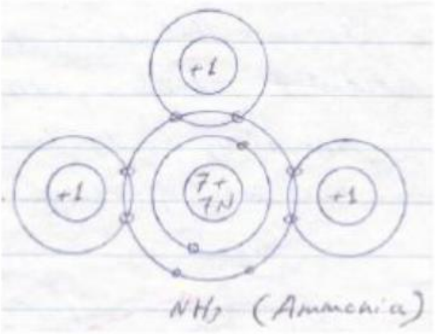


Lithium, atomic No = 3   Fluorine, atomic No = 9

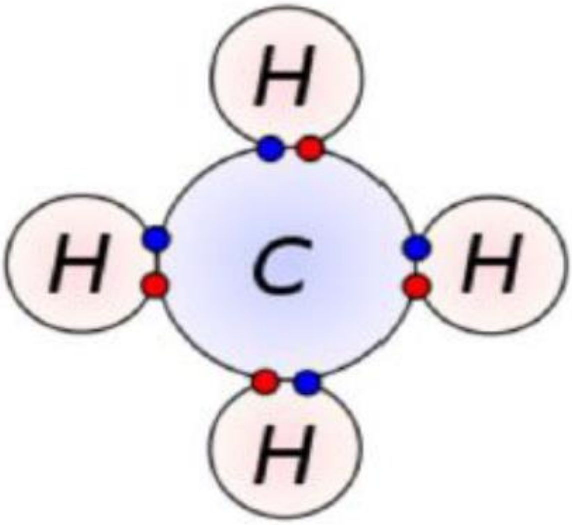
2- Covalent bond

Atom of some elements may attain a stable electron structure by sharing one or more. electrons with adjacent atoms As shown in figure below, nitrogen has 5 electrons in the outer shell and need 3 more to. complete that shell. Hydrogen has 1 electron in the outer shell A nitrogen atom shares the electrons of three hydrogen atoms and in turns share three. of its electrons with the three hydrogen atoms to form the compound ammonia NH3.





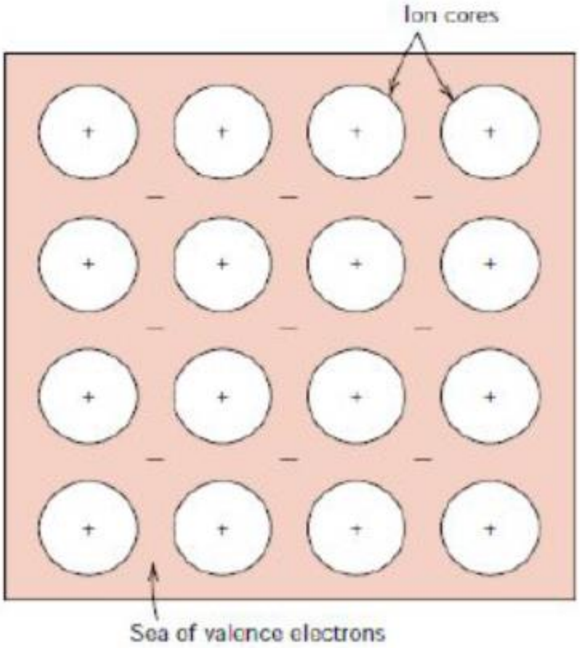
Another example for covalent bond is methane:



CH4 , covalent bond

3- Metallic bond

Each of the atoms of the metal contributes its valence electrons to the formation of a negative electron cloud. These electrons are not associated with a particular ion but are. free to move among the positive metallic ions the metallic bond may be thought of as an extension of the covalent bond to a large. number of atoms.

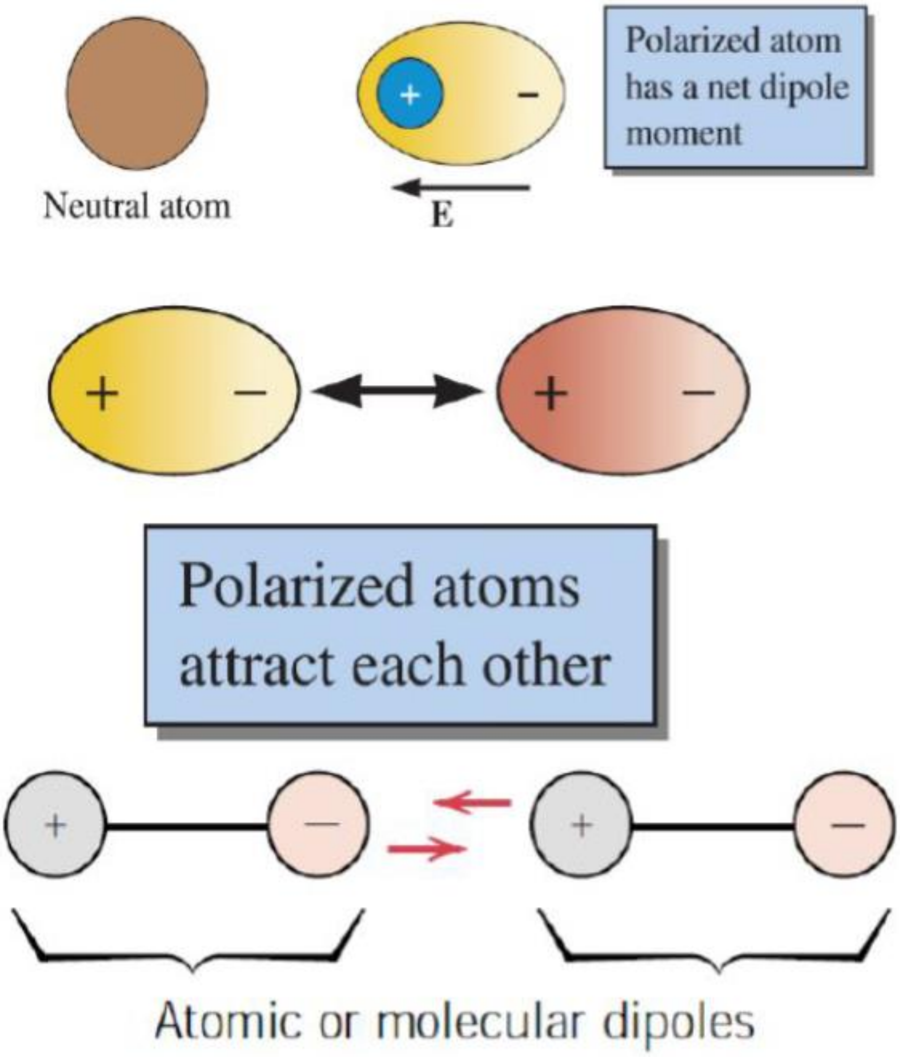


The metallic bond theory of metals explains many of the main characteristics of metallic elements:

1- All metals are good conductors of electricity.
2- Metals are good conductors of heat.
3- Most metals are ductile because layers of ions can be made to slide over each other.
4- by the application of shearing force. Metals are lustrous in appearance.

4- Van der Waals forces.

This type of bond arises in neutral atoms such as the inert gases (neon, argon and helium). When the atoms are brought close together there is a separation of the. centers of positive and negative charges, and a weak attractive force result.



6- Crystal defects, different crystals from an ingot

Crystal imperfections (micro-defects)

It is apparent from the preceding section that most materials when solidified consist of. many crystals or grains all these atoms must be laid down in exactly the right sort of order for the crystal to be perfect. It is therefore not surprising that few crystals are perfect and that imperfections. exist It is interesting to realize the amount of activity that is occurring on the surface of a crystal during growth. A very slow growth rate, such as 1 mm per day, requires the deposition of. about one hundred layers of atoms per second on the surface.

Types of Crystal imperfections:

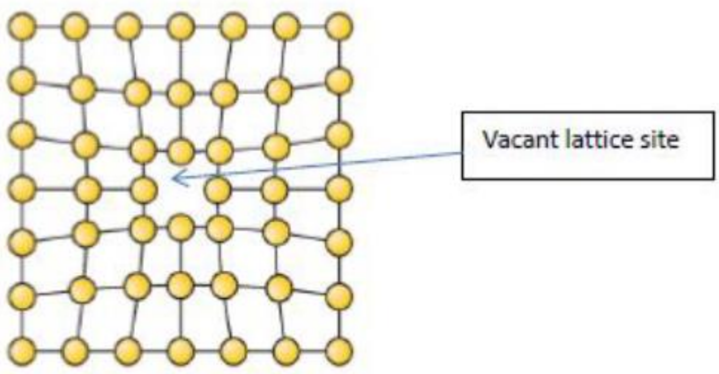
The most important types of crystal imperfection are

1- Point defects
a. Vacancies.
b. Interstitial atoms
2- Line defects
a. Edge dislocation
b. Screw dislocation.

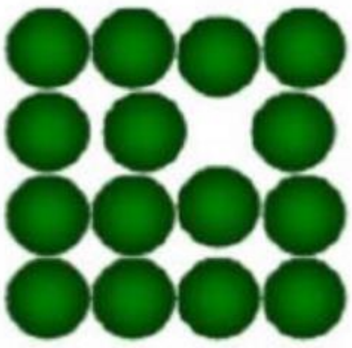
1- Point defects:

a. Vacancies

are simply empty atom sites. It is possible for a vacancy to move in the lattice structure and therefore play an important part in diffusion of atoms through the lattice.



Notice that the atoms surrounding a vacancy tend to be closer together, distorting the lattice planes.



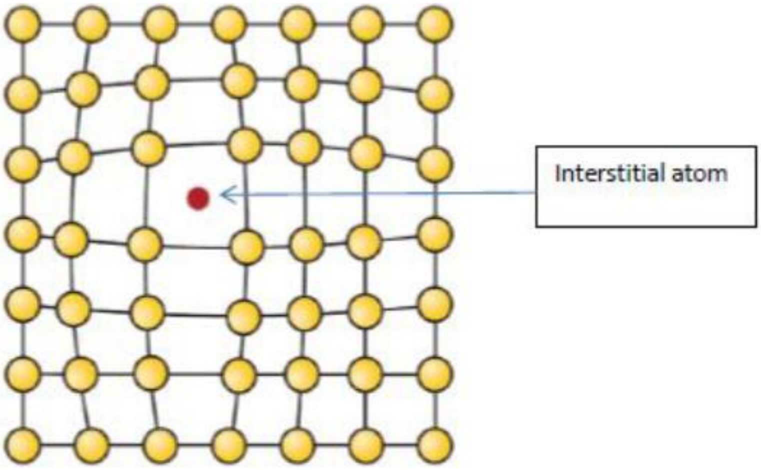
Vacancy

Vacancy – missing atom at a certain crystal lattice position
Vacancies may be occurred as a result of one of the following conditions:

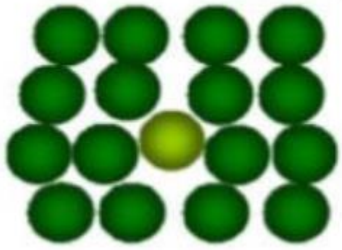
a. Solidification
b. Raising the temperature
c. Irradiation

b- Interstitial atoms.

It is possible, particularly in lattice structures that are not close-packed and in alloys between metals that have atoms widely different in atomic diameter, that some atoms may fall into interstitial positions or in the spaces of the lattice structure as shown below:

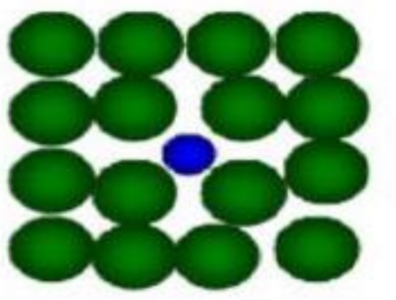


Interstitial atoms tend to push the surrounding atoms farther apart and also produce distortion of the lattice planes



Self-interstitial

Self-interstitial atom: extra atom in an interstitial position



Interstitial impurity

Interstitial impurity atom: extra impurity atom in an interstitial position.

Interstitial atoms may be produce by

a. Solidification

b. The severe local distortion during plastic deformation

c. Irradiation

2- Line defects

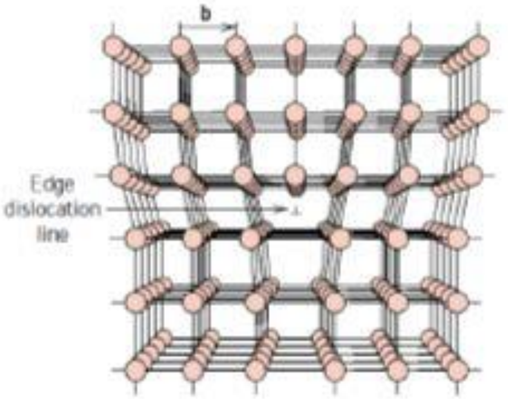
There are two types of line defects:

a. Edge dislocation.

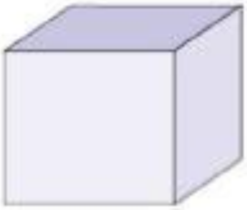
b. Screw dislocation.

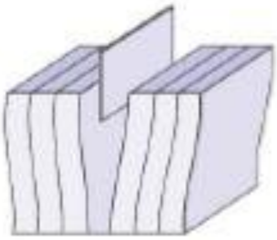
a. Edge dislocation.

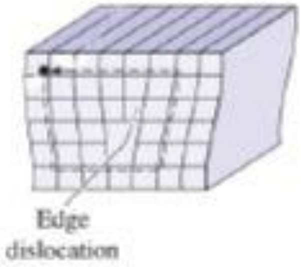
is an extra half plane of atoms “inserted” into the crystal lattice. Due to the edge dislocations metals possess high plasticity characteristics: ductility and malleability.




Edge dislocation


a

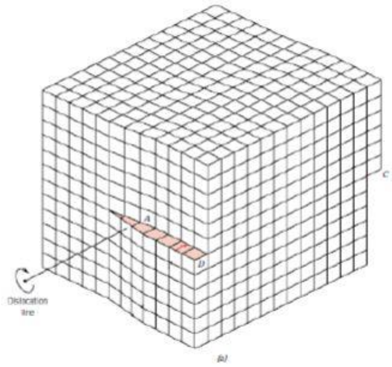

b



c

b- Screw dislocation.

forms when one part of crystal lattice is shifted (through shear) relative to the other crystal part. It is called screw as atomic planes form a spiral surface around the dislocation line.



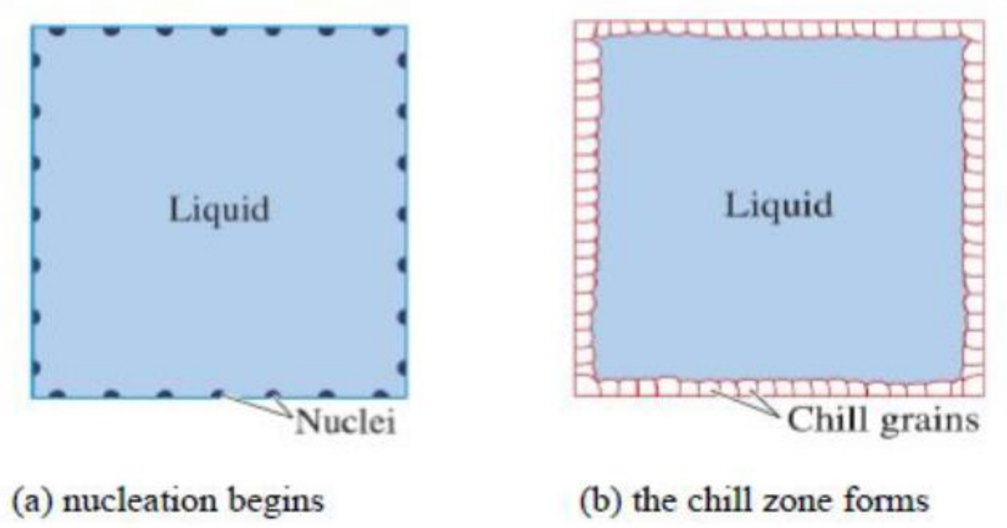
7- Solidification: different crystals form in an ingot

The grain structure in the cast product is determined by the rate of cooling, there are three types of crystals may be produced during the solidification of a casting:

1- Chill crystals.
2- Columnar crystals.
3- Equiaxed crystals

1- Chill crystals .

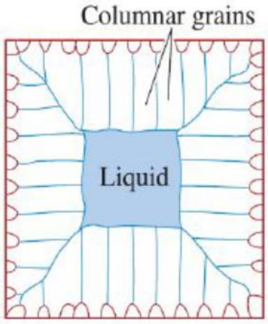
The metal in contact with the mould surfaces cools faster than that in the center of the casting. As a result, small crystals, termed chill crystals, start to form at the surfaces these are small because the metal has cooled too rapidly for them to grow to any size.



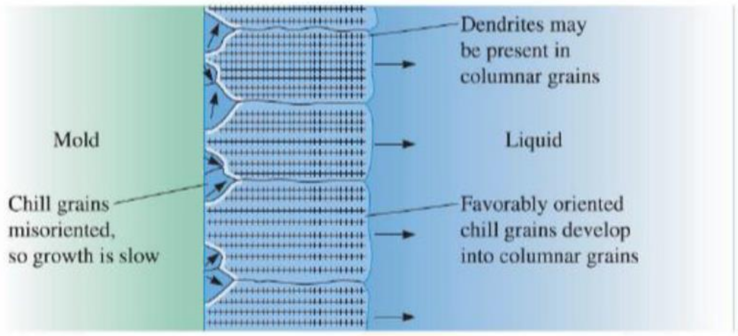
(a) nucleation begins (b) the chill zone forms

2- Columnar crystals .

The cooling rate nearer the center is, however, much slower and so some of the chill crystals have time to grow into large elongated crystals perpendicular to the mould wall, these being called columnar crystals.



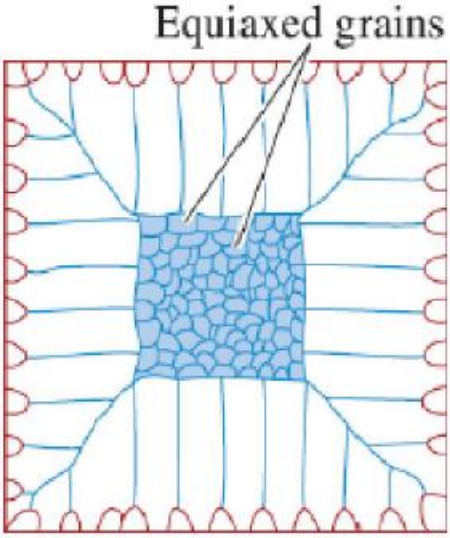
(c) Preferred growth produces the columnar zone.



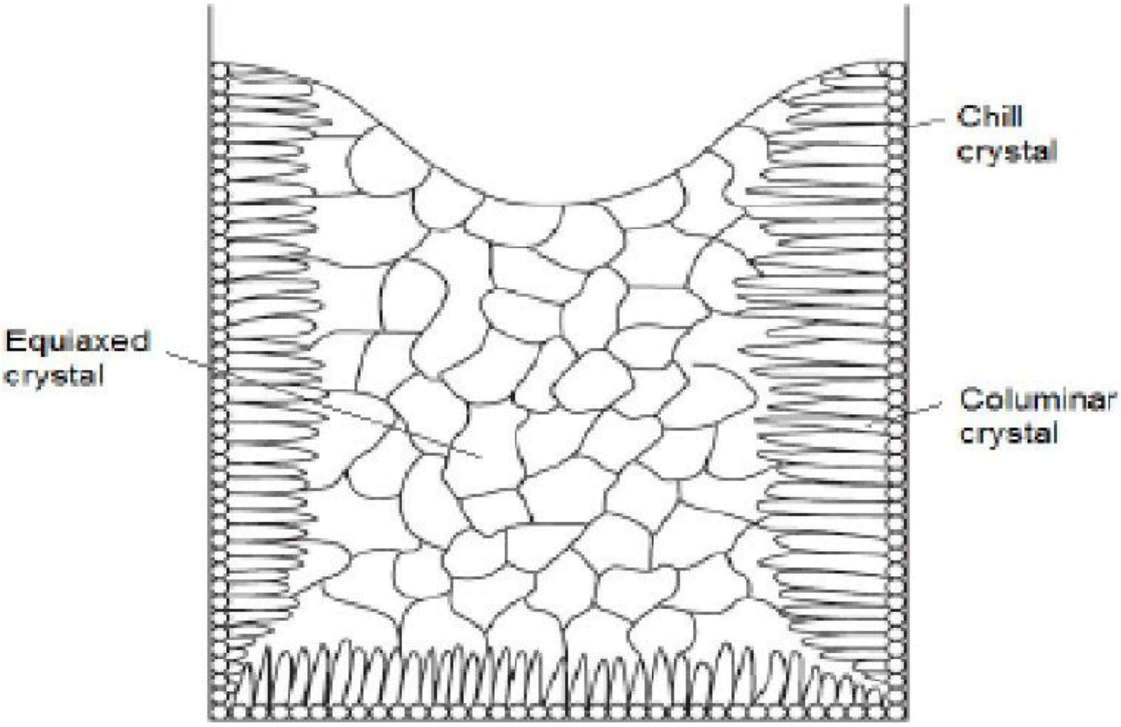
Competitive growth of the grains in the chill zone results in only those grains with favorable orientations developing into columnar grains.

3- Equiaxed crystals.

In the center of the mould the cooling rate is the slowest. While growth of the columnar crystals is taking place, small crystals can start to grow in the central region the final result is a central region of medium-sized almost spherical crystals called equiaxed crystals.

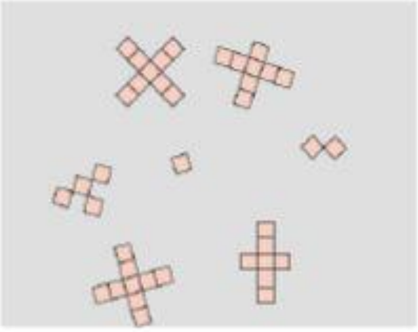


(d) additional nucleation creates the equiaxed zone.

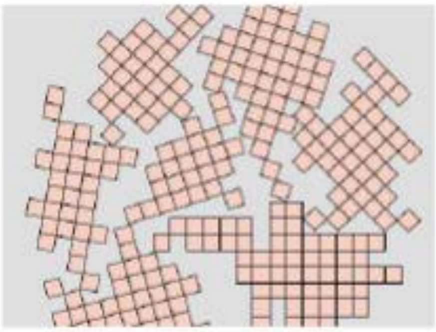


7- solidification : castings defects

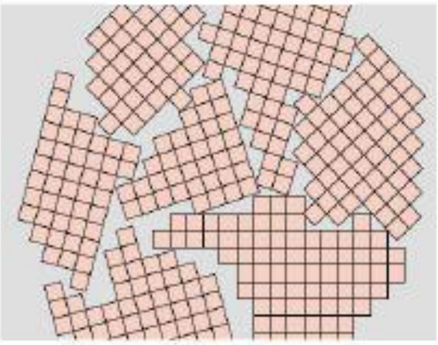
When the temperature of a molten pure metal falls to its freezing point, crystallization will begin. The nucleus of each crystal will be a single unit cell of the appropriate crystal lattice .For example, in the case of a metal with a body-centered cubic lattice, nine atom will come together to form a single unit, and this will grow as further atoms join the lattice structure “ The tiny crystal will reach visible size, and form what is called a “ dendrite.



(a) Small crystallite nuclei.



(b) Growth of the crystallites; the obstruction of some grains that are adjacent to one another is also shown.



(c) Upon completion of solidification, grains having irregular shapes have formed.

(d) The grain structure as it would appear under the microscope; dark lines are the grain boundaries.

Casting defects (macro-defects)

The preceding section discussed defects on an atomic scale that arise from solidification other defects that may result from solidification are large enough to be visible to the naked eye. These are known as macro defects.

The most common macro defects are:

1- Shrinkage.

a. Shrinkage cavities

b. Primary pipe

c. Secondary pipe

2- Porosity.

3-Segregation of impurities .3

1- Shrinkage.

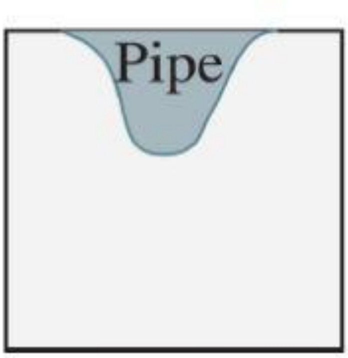
Solid metals occupy less space than they do as liquids and shrinkage takes place during solidification as a result of this decrease in volume.

a. Shrinkage cavities

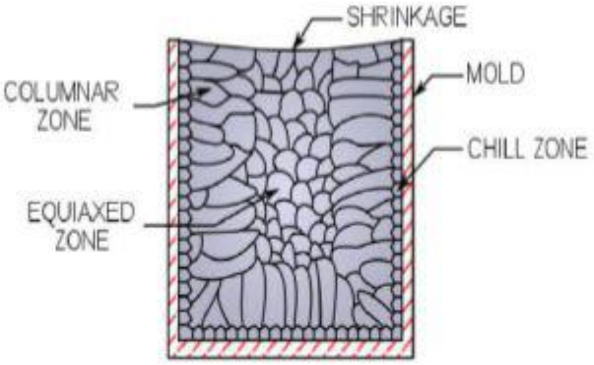
If the mould is of a design such that isolated pockets of liquid remain when the outside surface of the casting is solid, shrinkage cavities will form.

b. Primary pipe

The metal which is adjacent to the mold surface solidifies almost immediately, and as it does so it shrinks. This causes the level of the remaining metal to fall slightly. And as further solidification takes place the process is repeated, the level of the remaining liquid falling still further this sequence of events continues to be repeated until the metal is completely solid and a conical cavity or “primary pipe” remains in the top portion of the ingot.



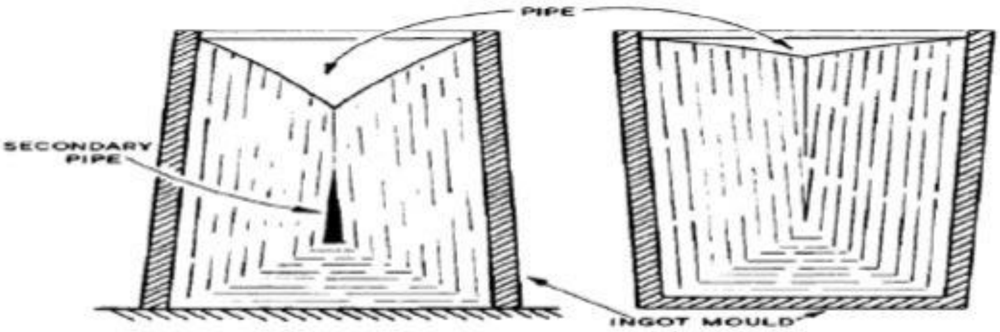
Primary pipe.



Primary pipe and different types of crystals.

c. Secondary pipe

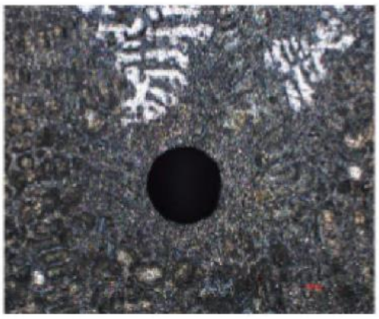
Would be formed due to the shrinkage of trapped molten metal when it solidifies.



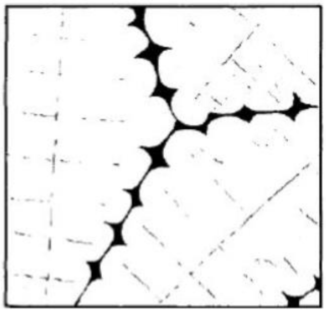
The influence of the shape of the mould on the extent of piping in a steel ingot.

2-Porosity.

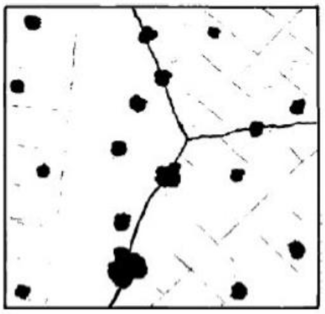
blowholes occur whenever gases are trapped in the casting. They are usually more numerous and smaller than shrinkage cavities and may be distinguished by their rounded form.



Microscopic image of gas hole casting defect



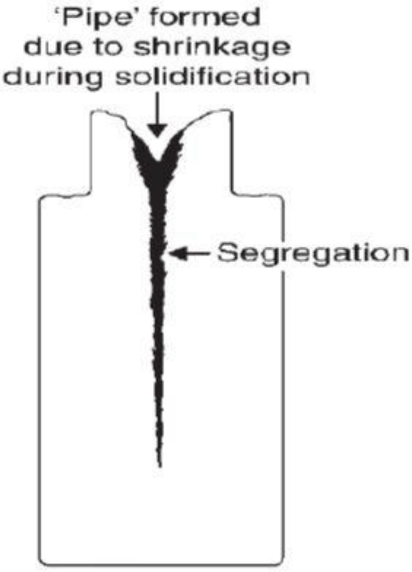
Shrinkage cavities in cast metals tend to follow the shape of the dendritic arms and occur at the crystal boundries.



Porosity in cast metals is usually of rounded shape and occurs at almost any point in the structure.

Segregation of impurities.

There is a tendency for dissolved impurities to remain in that portion of the metal which solidifies last. As the columnar crystals begins to grow inwards they will push in front of them some of the impurities which were dissolved in the molten metal In this way there is a tendency for much of the impurities in the original melt to become concentrated in the central pipe If a vertical section of an ingot is polished and etched, these impurities show as V-shaped markings in the area of the pipe as shown in figure below:



The segregation of impurities in the central 'pipe' of an ingot.

8- mechanical properties :hardness (Brinell, Rockwell, Vickers)

Hardness:

the hardness of a materials is a measure of the resistance of a material to abrasion or indentation, and for metals, the property is a measure of their resistance to permanent or plastic deformation.

there are three main methods for testing hardness:

1. Brinell hardness test.
2. Rockwell hardness test.
3. Vickers hardness test.

1. Brinell hardness test.

the Brinell hardness tester usually consists of a hand-operated vertical hydraulic press, designed to force a ball indenter into the test specimen.

Standard procedure requires that the test be made with a ball of 10 mm diameter.

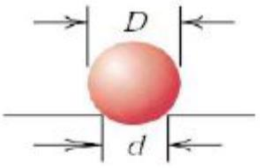
for different materials, the ratio P/D^2 has been standardised in order to obtain accurate and comparable results:

No.	Material	Approximate HB range	P/D^2 ratio used	Load duration (sec)
1.	Steel and cast iron	Over 100	30	10
2.	Copper, copper alloys and aluminum alloys	30-200	10	30
3.	Aluminum	15-100	5	30
4.	Tin, lead and their alloys	3-20	1	30

The Brinell hardness number (HB) is the ratio of the load in kg to the impressed area in mm^2 :

$$HB = \frac{load\ (kg)}{impressed\ area\ (mm^2)}$$

$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$$



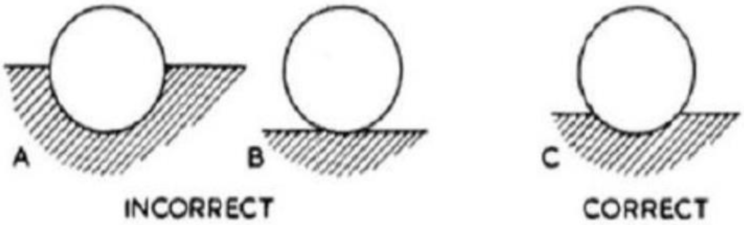
Calculation is usually unnecessary because tables are available for converting the observed diameter of impression to the Brinell hardness number.

Types of indenter:

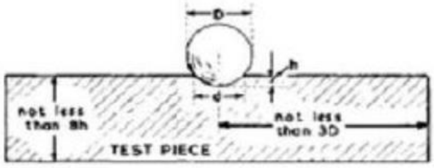
No.	Range of Brinell hardness	Type of indenter
1.	Up to 500 HB	10 mm hardened steel ball
2.	Up to 650 HB	10 mm tungsten carbide ball

Rockwell hardness HRC = (0.2 –e) ×500

.Where **e** is the permanent depth of penetration in mm



The influence of depth of impression on the accuracy of a Brinell determination.



The relationships between ball diameter, depth of impression and dimensions of the test piece in the Brinell-type test.

2. Rockwell hardness test.

this hardness test uses a direct reading instrument based on the principle of differential depth measurement.

The test is carried out by slowly raising the specimen against the indenter until a fixed miner load has been applied. This is indicated on the dial gauge.

Then the major load is applied through a loaded lever system. After the dial pointer comes to rest, the major load is removed and with the minor load still acting, the Rockwell hardness number is read on the dial guage.

$$\text{Rockwell hardness HRC} = (0.2 - e) \times 500$$

.Where **e** is the permanent depth of penetration in mm

There are two Rockwell machines:

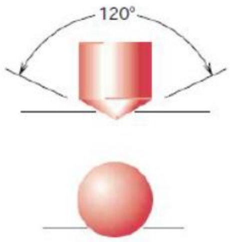
1. The normal tester for relatively thick sections.

2. The superficial tester for thin sections.

Type of tester	Major load (kg)	Minor load (kg)
Normal tester	60, 100, 150	10
Superficial tester	15, 30, 45	3

Types of indenter:

Type of indenter	Size of indenter
Hard steel ball	$\frac{1''}{16}, \frac{1''}{8}, \frac{1''}{4}, \frac{1''}{2}$, *ball diameter.*
Conical diamond indenter	Angle of cone is 120°.



The most common Rockwell scales	Load (kg)	Indenter	Tester type	Material tested
HRB	100	$\frac{1''}{16}$ hard steel ball.	Normal tester	Medium hard material.
HRC	150	Conical diamond 120°	Normal tester	Hardened steels.

3. Vickers hardness test.

in this test, the instrument uses a square-based diamond-pyramid indenter with an included angle of 136° between opposite faces.

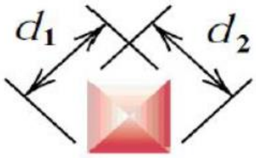
The load range is usually between 1 and 120 kg.

The Vickers hardness tester operates on the same basic principle as the Brinell tester, the numbers being expressed in terms of load and area of the impression.

$$HV = \frac{load\ (kg)}{impressed\ area\ (mm^2)}$$

$$HV = \frac{1.854\ P}{d^2}$$

As a result of the indenter's shape, the impression on the surface of the specimen will be a square.



The length of the diagonal of the square is measured through a microscope fitted with an ocular micrometer that contains movable knife edges.

Tables are usually available to convert the measured diagonal to Vickers hardness number (HV).

As a result of the wide range of applied loads, the Vickers tester is applicable to measuring the hardness of very thin sheets as well as heavy sections.

9. Tensile test, stress-strain diagram

2. Tensile test:

The tensile test is popular since the properties obtained can be applied to design different components. The tensile test measures the following properties:

a. Modulus of elasticity.

b. Yield strength.

c. Tensile strength.

d. Estimate the ductility of the material by calculating:

  (1) Elongation%, or

  (2) Reduction in area%.

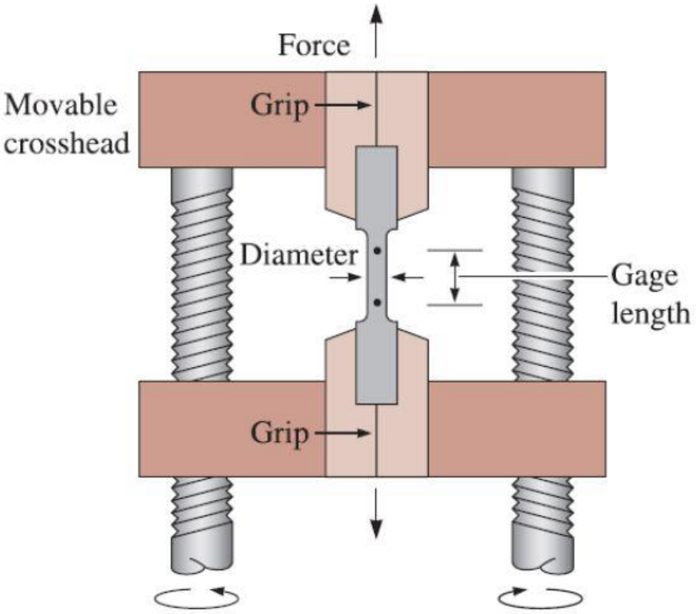


Figure 29-1 A unidirectional force is applied to a specimen in the tensile test by means of the moveable crosshead. The crosshead movement can be performed using screws or a hydraulic mechanism.

Tensile test results:

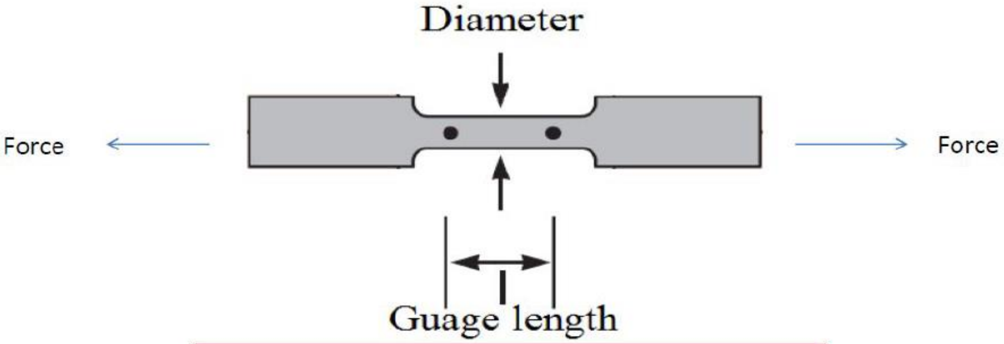


Figure 29.2 The tensile test specimen.

No.	Force (N)	Extension Δ l (mm)
1		
2		
3		

Engineering Stress and Strain: The results of a single test apply to all sizes and cross-sections of specimens for a given material if we convert the force to stress and the distance between gauge marks to strain. Engineering stress and engineering strain are defined by the following equations:

$$\text{Engineering stress} = \frac{Force\ (N)}{Original\ cross\ sectional\ area\ (mm^2)}$$

$$\text{Engineering strain} = \frac{Extension\ (mm)}{Guage\ length\ (mm)}$$

		Calculated	
Load (N)	Δ l (mm)	Stress (N/mm^2)	Strain (mm/mm)
0	0.000	0	0
4450	0.025	35.5	0.0005
13350	0.075	106.5	0.0015
22240	0.125	177.5	0.0025
31150	0.175	248.6	0.0035
33360	0.75	266.2	0.0150
35140	2.0	280.4	0.0400
35580 (max. load)	3.0	284	0.0600
35360	4.0	282.2	0.0800
33800 (fracture)	5.125	269.8	0.1025

Table 29.1 The results of a tensile test of a 12.6 mm diameter aluminum alloy test bar, initial length (l_o) = 50 mm.

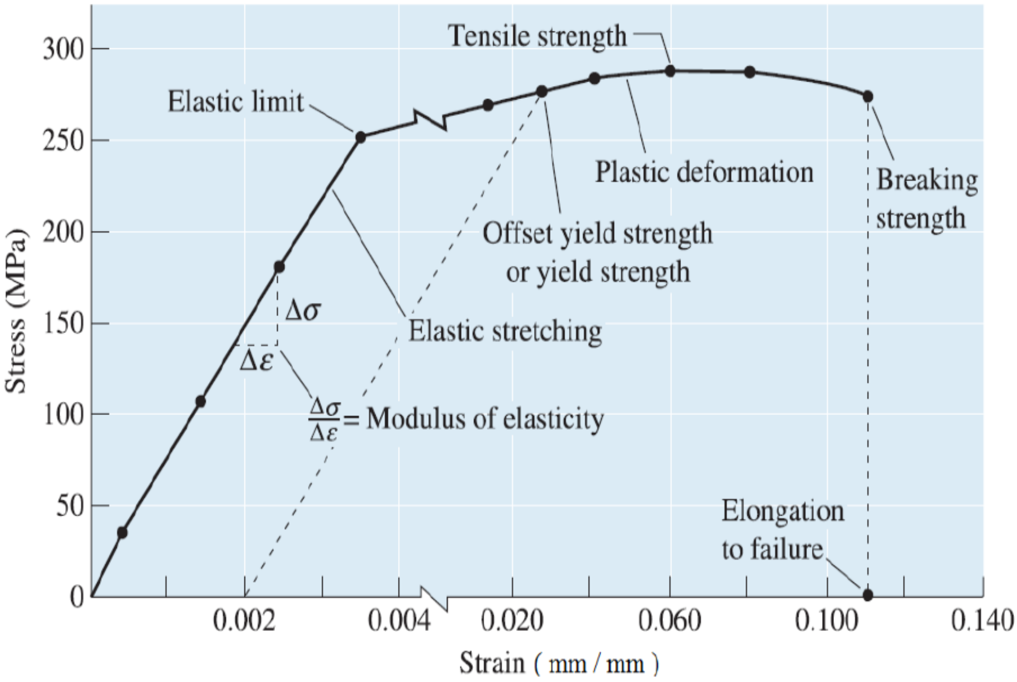


Figure 29.3 The stress-strain curve for an aluminum alloy from Table 29.1

$$\boxed{Modulus\ of\ elasticity = \frac{\Delta\sigma}{\Delta\varepsilon}}$$

$$\boxed{Yield\ strength = \frac{yield\ load}{Ao}}$$

$$\boxed{Tensile\ strength = \frac{max.load}{Ao}}$$

$$\boxed{Elongation\ \% = \frac{\Delta l}{lo}}$$

$$\boxed{Reduction\ in\ area\ \% = \frac{\Delta A}{Ao}}$$

$\boxed{\sigma\ = stress\ (N/mm2)}$

$\boxed{\varepsilon\ = strain\ (mm/mm)}$

$\boxed{A_o = original\ cross\ sectional\ area\ (mm2\ )}$

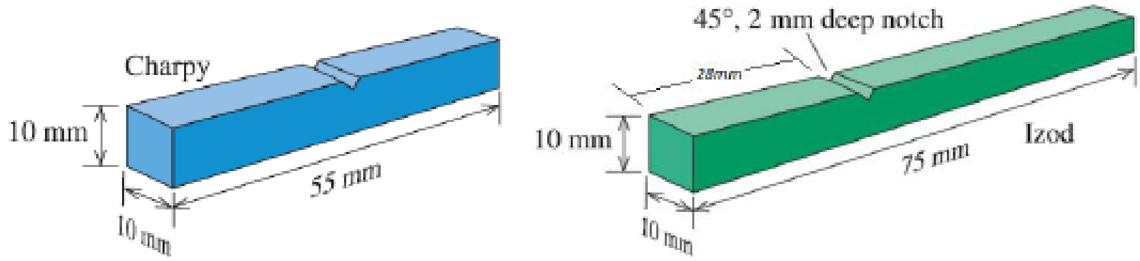
$\boxed{l_o = guage\ length\ (mm)}$

Impact test

Impact: is the ability to withstand crack nucleation and growth under impact (shock) loading.

Generally, notch-type specimens are used for impact tests. Two types of specimens are used, the Charpy and the Izod.

The Charpy specimen is placed in the vise so that it is a simple beam supported at the ends. The Izod specimen is placed in the vise so that one end is free and therefore a cantilever beam.



Charpy Impact test specimen

Izod Impact test specimen

Figure (10.1) Impact test specimens dimensions

Impact test

Toughness: Is the ability of a material to absorb energy and plastically deform without fracturing.

The ordinary impact machine has a swinging pendulum of fixed weight which is raised to a standard height depending upon the type of specimen tested.

At that height, with reference to the vise, the pendulum has a definite amount of potential energy. When the pendulum is released, this energy is converted to kinetic energy until it strikes the specimen.

Impact test

The Charpy specimen will be hit behind the V-notch.

Striking energy= $300\ J$
$= 300\ N.m$

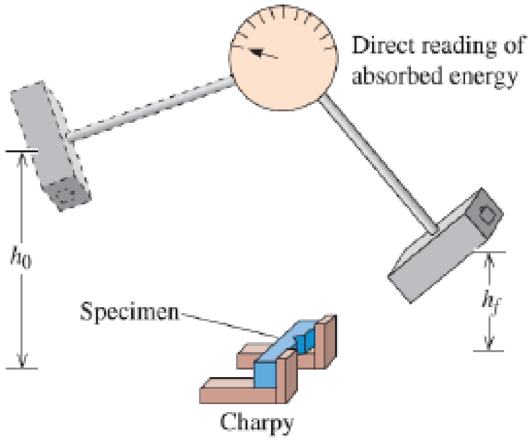


Figure (10.2) Charpy impact test arrangement

Impact test

while the Izod specimen, placed with the V-notch facing the pendulum, will be hit above the V-notch.

Striking energy= $167\ J$
$= 167\ N.m$

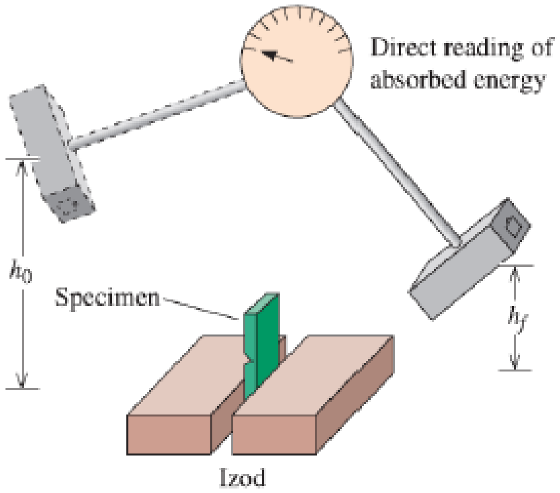
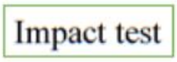
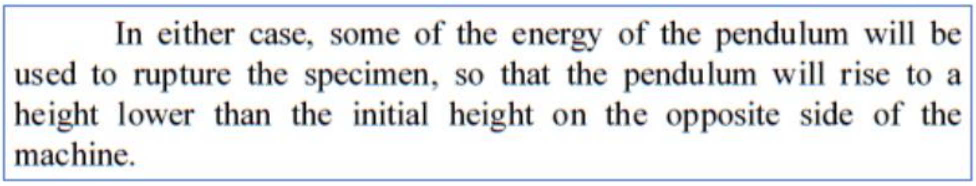


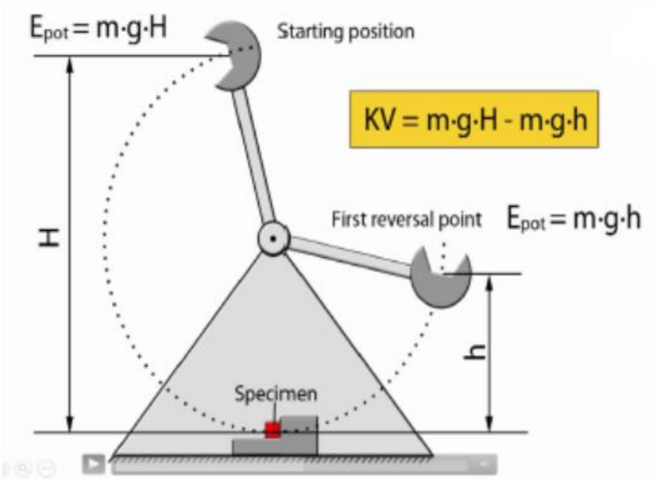
Figure (10.3) Izod impact test arrangement



Impact test



In either case, some of the energy of the pendulum will be used to rupture the specimen, so that the pendulum will rise to a height lower than the initial height on the opposite side of the machine.



Impact test

In either case, some of the energy of the pendulum will be used to rupture the specimen, so that the pendulum will rise to a height lower than that the initial height on the side of the machine.

The weight of the pendulum times the difference in heights will indicate the energy absorbed by the specimen. Impact strength of the metal can be calculated as follows:

$$R = \frac{E}{A} \text{ (Kg.m/cm}^2\text{)}$$

Where:

R= Impact strength of the metal ($Kg.m/cm^2$)
E = Energy used to rupture the specimen (Kg.m)
A = Breaking cross-sectional area (cm^2)

$E = wh_o – wh_f$

$$E = w\,(h_o - h_f)$$
$$E = w\,(\cos\alpha - \cos\beta)$$

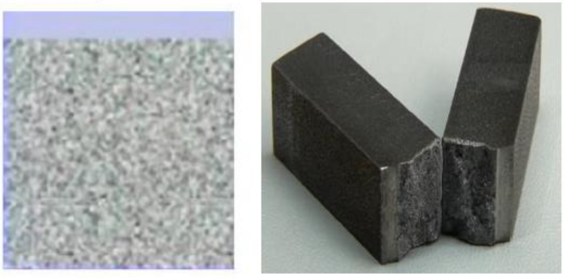
Where:

W = pendulum mass (25.81 Kg)

l = pendulum length (0.75 m)

α= angle of pendulum before impact (141.5°)

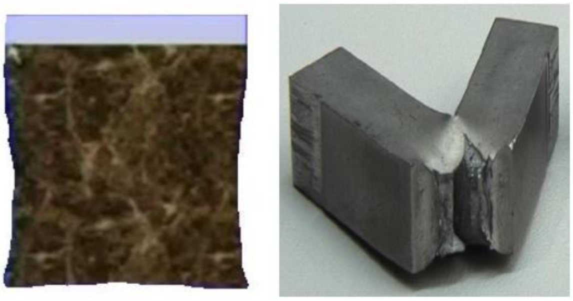
β = angle of pendulum after impact (degree)



Impact test

Cleavage or granular fracture: little notch root contraction

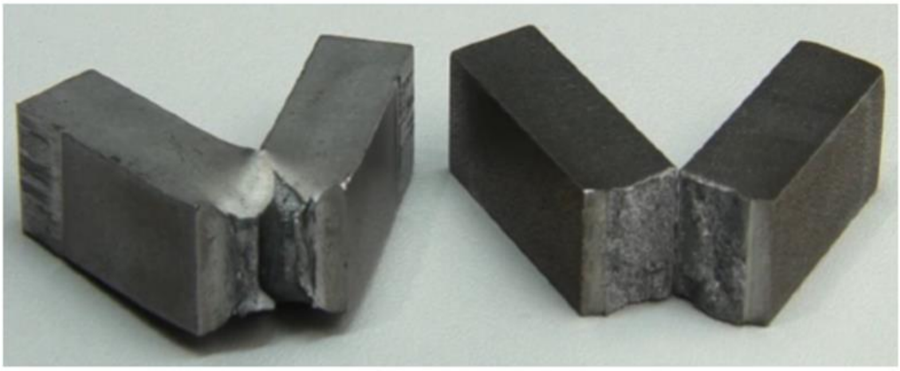
Figure(10.5 A) Appearance of fractured surface.



Impact test

Fibrous or shear fracture: large notch root contraction

Figure(10.5 B) Appearance of fractured surface.



Figure(10.5 C) Appearance of fractured surface.

Impact test

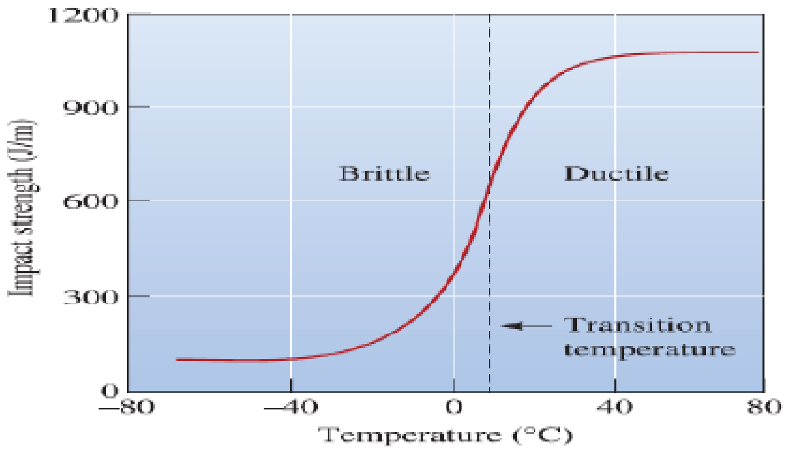


Figure (10.4): Results from a series of Izod impact tests for a tough nylon thermoplastic polymer.

The transition temperature of the polymers used in booster rocket and other factors led to the Challenger disaster.

Impact test

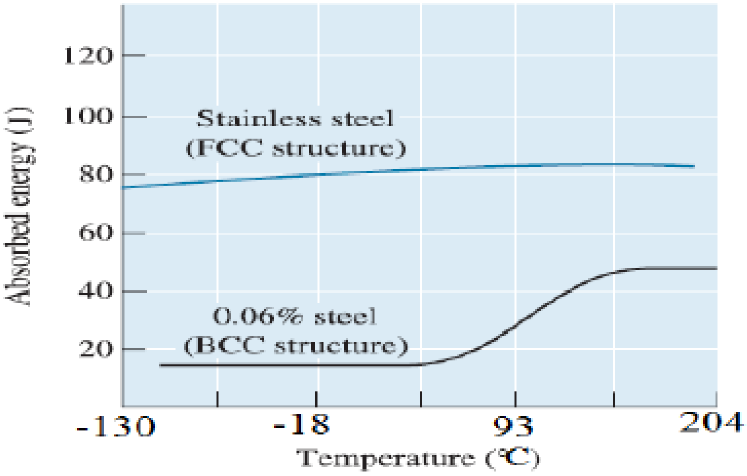


Figure (10.7) The Charpy V-notch properties for a BCC carbon steel and an FCC stainless steel. The FCC crystal structure typically leads to higher absorbed energies and no transition temperature.

The effect of this transition in steel may have contributed to the failure of the Titanic.

11. Creep test

Creep: can be defined as the deformation of a material with passage of time when the material is subjected to a constant stress.

For metals, other than the very soft metals like lead, creep effects are negligible at ordinary temperatures but become significant at high temperatures.

Because creep tests with metals are usually performed at high temperatures a thermostatically controlled heater surrounds the test piece.

The temperature of the test piece is generally measured by a thermocouple.

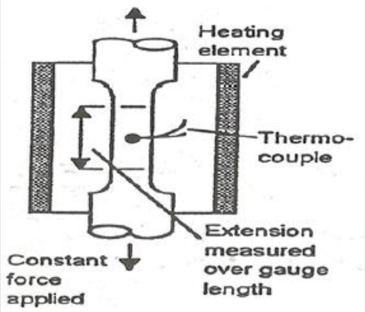


Figure 11.1 Creep test

11. Creep test

The figure below shows the general form of results from a creep test.

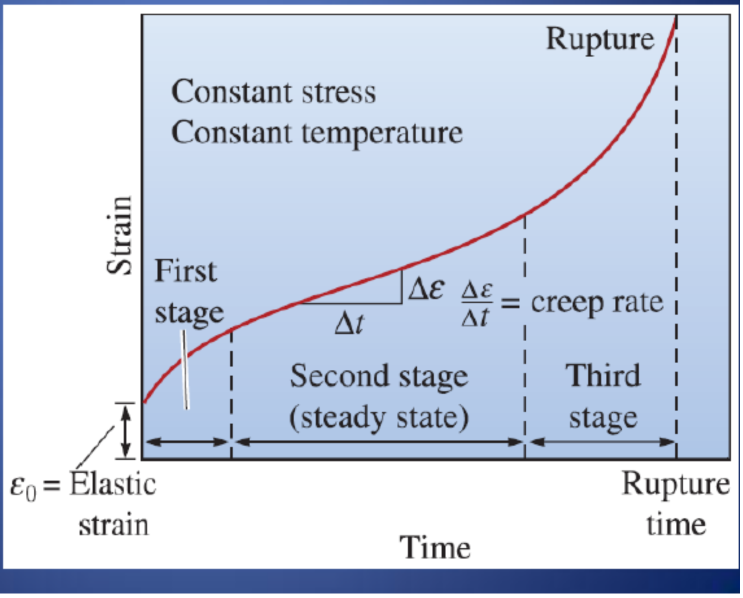


Figure 11.2: A typical creep curve showing the strain produced as a function of time for a constant stress and temperature.

11. Creep test

The creep test curve generally has three parts:

1. First stage:

during the first stage the strain is changing but the rate at which it is changing with time decreases ($\frac{d\epsilon}{dt}\downarrow$).

2. Second stage:

during the second stage the strain increases steadily with time at constant rate ($\frac{d\epsilon}{dt} = constant$).

3. Third stage:

during the third stage the rate at which the strain is changing increases and eventually causes failure ($\frac{d\epsilon}{dt}\uparrow$).

11. Creep test

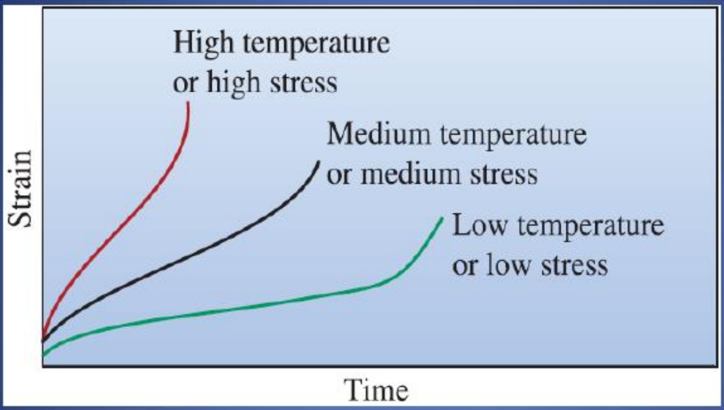
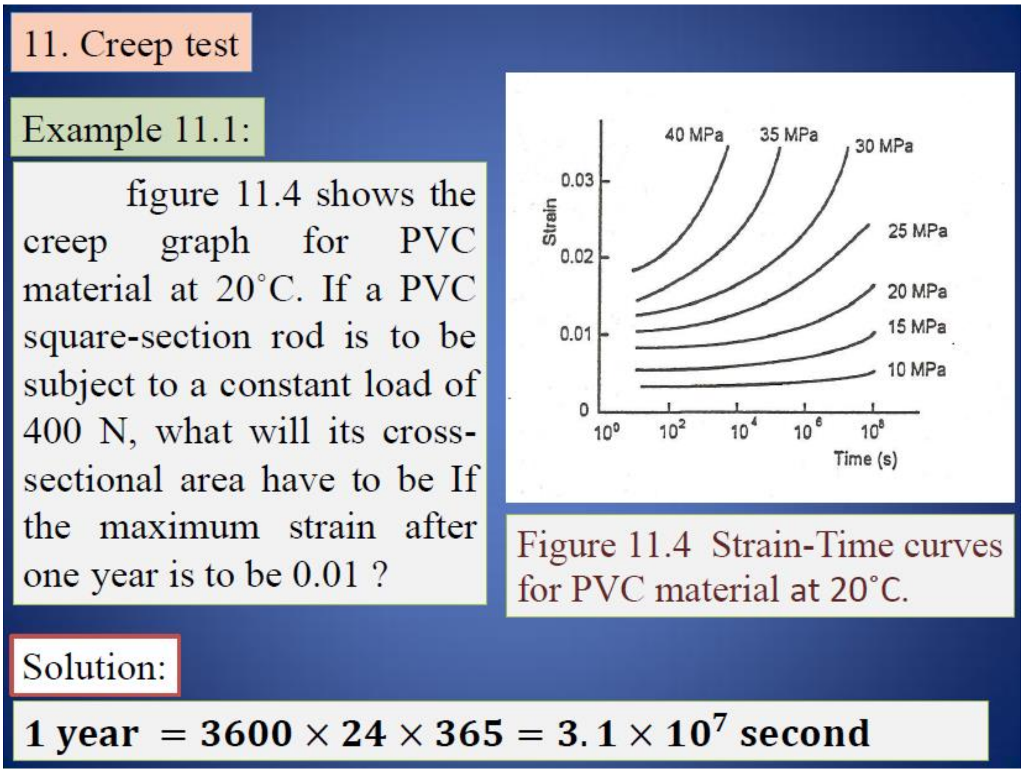


Figure 11.3 The effect of temperature or applied stress on the creep curve.



11. Creep test

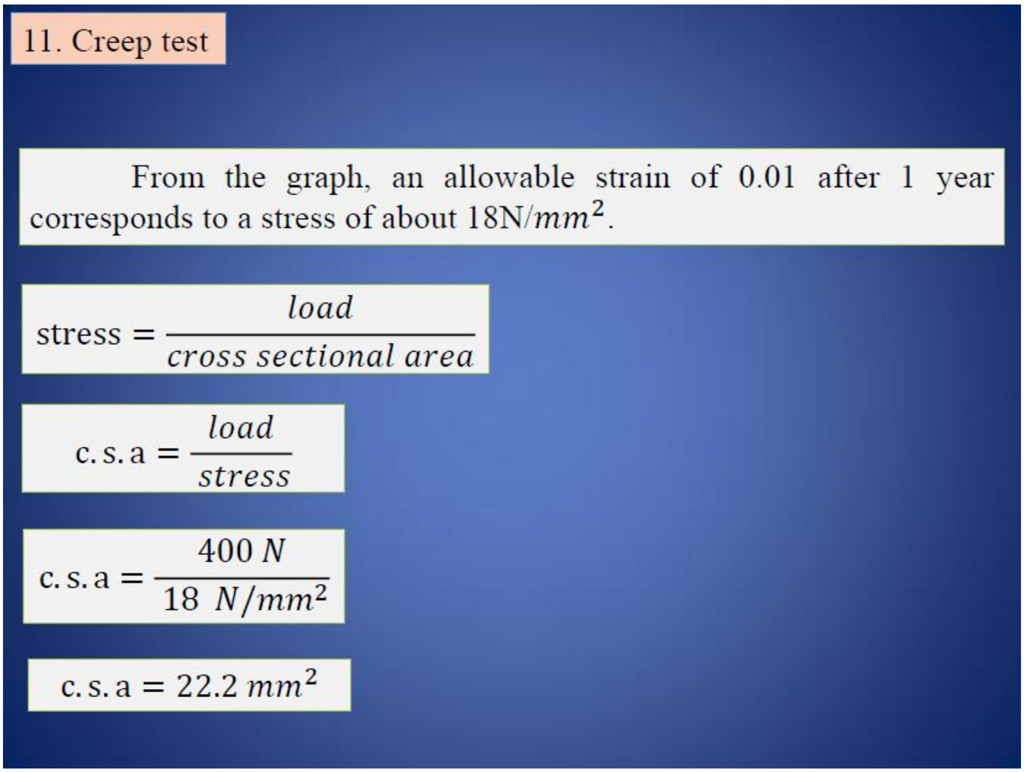
Example 11.1:

figure 11.4 shows the creep graph for PVC material at 20°C. If a PVC square-section rod is to be subject to a constant load of 400 N, what will its cross-sectional area have to be If the maximum strain after one year is to be 0.01 ?

Figure 11.4 Strain-Time curves for PVC material at 20°C.

Solution:

$$\mathbf{1\ year\ = 3600 \times 24 \times 365 = 3.1 \times 10^{7}\ second}$$



11. Creep test

From the graph, an allowable strain of 0.01 after 1 year corresponds to a stress of about 18N/mm^2.

$$\text{stress} = \frac{load}{cross\ sectional\ area}$$

$$\text{c.s.a} = \frac{load}{stress}$$

$$\text{c.s.a} = \frac{400\ N}{18\ N/mm^2}$$

$$\text{c.s.a} = 22.2\ mm^2$$

12. Fatigue test

Fatigue test

The fatigue test can tell us how long a part may survive or the maximum allowable loads that can be applied without causing failure.

Fatigue tests can be carried out in a number of ways, the way used being the one needed to simulate the type of stress changes that will occur to the material of the component when in service.

The following types are examples of fatigue testing machine:

1. Bending stress machines:

which bend a test piece of the material alternatively one way and then the other, as shown in figure 12.1.

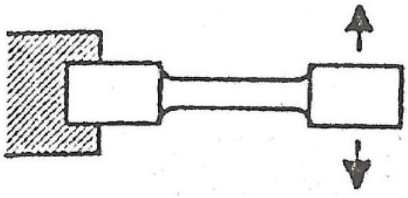


Figure 12.1

2. Torsional stress machines:

which twist the test piece alternatively one way and then the other, as shown in figure 12.2.

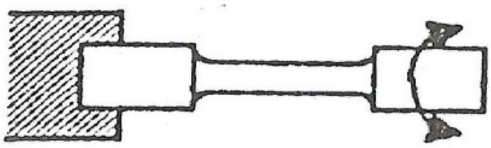


Figure 12.2

3. Alternating tension and compression machines:

which produces alternating tension and compression by direct stressing, as shown in figure 12.3.

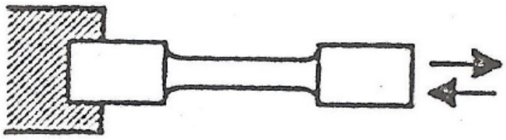


Figure 12.3

Types of alternating stresses:

1. About zero stress.

the tests can be carried out with stresses which alternate about zero stress, as shown in figure 12.4. The stress varies between $+\sigma$ and $-\sigma$, tensile stress being denoted by a positive sign and compressive stress by a negative sign.

The mean stress (σ_m) is zero.

(σ_a) is the stress amplitude.

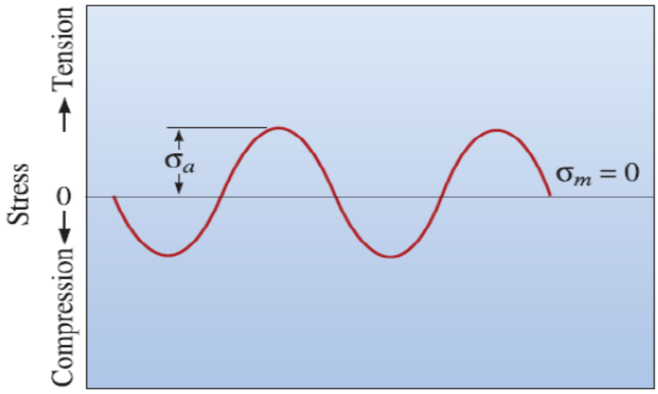


Figure 12.4

2. From zero to some maximum stress.

Apply a repeated stress which varies from zero to some maximum stress, as shown in figure 12.5. The mean stress is half the stress range.

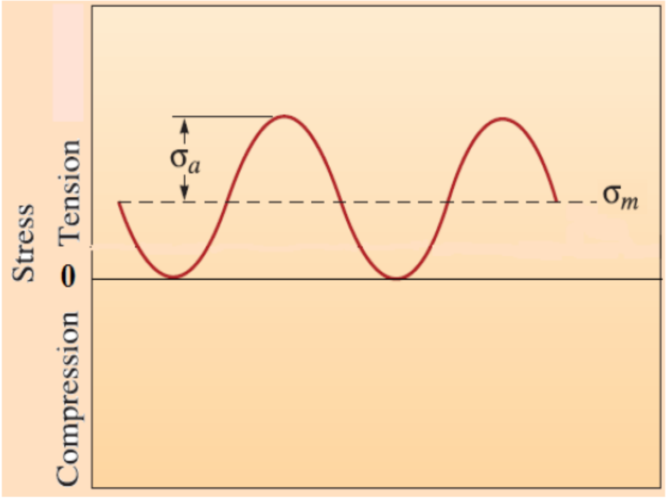


Figure 12.5

3. About some stress value.

Apply a stress which varies about some stress value and does not necessarily reach zero at all, as shown in figure 12.6.

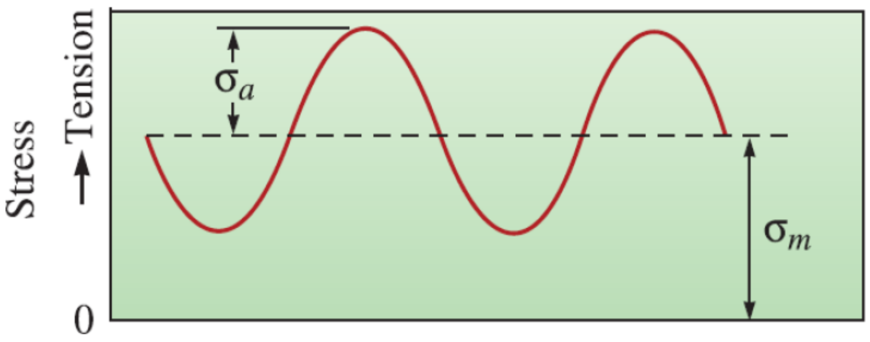


Figure 12.6

Definitions

The following are standard definitions used to describe the variables:

$$\text{Stress range} = \text{maximum stress} - \text{minimum stress}$$

$$\text{Stress amplitude} = \left(\frac{\text{maximum stress} - \text{minimum stress}}{2}\right)$$

$$\text{Mean Stress} = \left(\frac{\text{maximum stress} + \text{minimum stress}}{2}\right)$$

$$\text{Load ratio} = \frac{\text{maximum stress}}{\text{minimum stress}}$$

S-N graph:

during the fatigue tests, the machine is kept running with a particular stress range, alternating the stress until the piece fails. The number of cycles of stressing up to failure is recorded.

The test is repeated for different stress amplitudes. Such tests enable S-N graphs to be plotted. The vertical axis is the stress amplitude and the horizontal axis is the number of cycles N to failure.

Fatigue limit:

is the stress amplitude at a particular number of cycles which will result in failure.

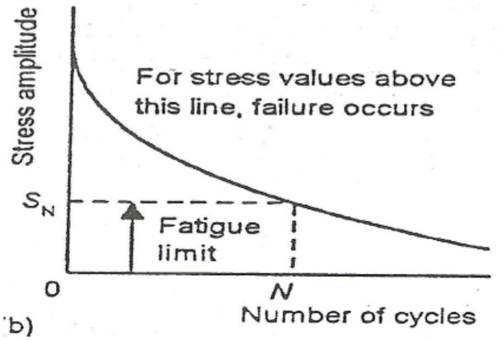


Figure 12.7 S-N curve for an aluminum alloy..

Endurance limit:

for which the material will endure an infinite number of stress cycles with smaller stress amplitude.

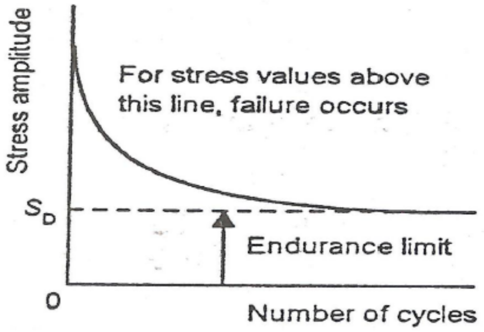


Figure 12.8 S-N curve for a steel.

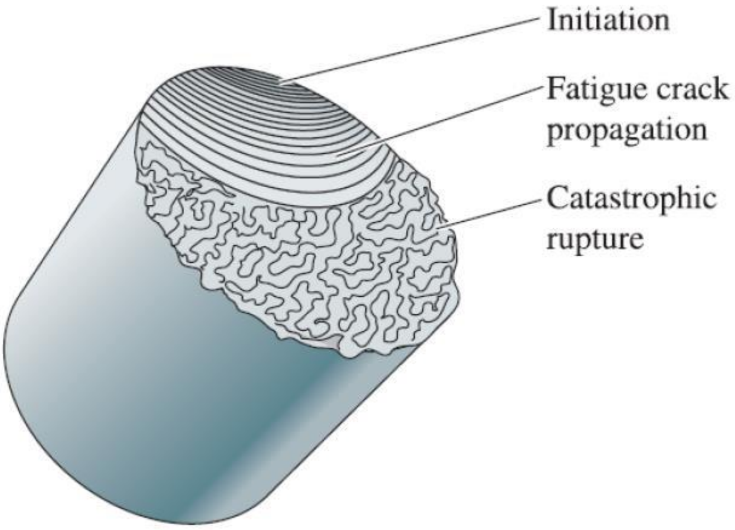


Figure 12.9 Schematic representation of a fatigue fracture surface in a steel shaft, showing the initiation region, the propagation of the fatigue crack (with beach markings), and catastrophic rupture when the crack length exceeds a critical value at the applied stress.

Example 12.1:

An 8.0 mm diameter cylindrical rod fabricated from a red brass alloy (Figure 12.10) is subjected to reversed tension-compression load cycling along its axis. If the maximum tensile and compressive loads are 7500 N and 7500 N , respectively, determine its fatigue life.

Solution:

$$A = \frac{\pi}{4} d^2$$

$$A = \frac{\pi}{4} 8^2$$

$$A = 50.26\ mm^2$$

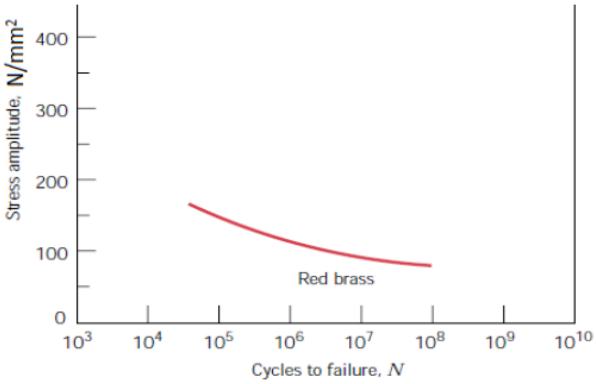


Figure 12.10 S-N curve for red brass.

$\sigma_{max} = \frac{P_{max}}{A}$ $\sigma_{max} = \frac{7500\ N}{50.26\ mm^2}$ $\sigma_{max} = 149.2\ N/mm^2$

$\sigma_{min} = \frac{P_{min}}{A}$ $\sigma_{min} = \frac{-7500\ N}{50.26\ mm^2}$ $\sigma_{min} = -149.2\ N/mm^2$

$$\text{Stress amplitude} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\text{Stress amplitude} = \frac{149.2 - (-149.2)}{2}$$

Stress amplitude =149.2 N/mm2

Then from S-N curve (figure 12.10), we can find the fatigue life corresponding to stress amplitude (149.2 N/mm2) which equal: The fatigue life= 10^5 *cycles*.

13. Cooling curves for metals and alloys

Cooling curves for metals and alloys:

When pure water is cooled to 0°C it changes from liquid to solid, i.e. ice is formed.

Figure 13.1 shows the type of graph produced if the temperature of water is plotted against time during a temperature change from above 0°C to below 0°C.

Down to 0°C the water only exists in the liquid state.

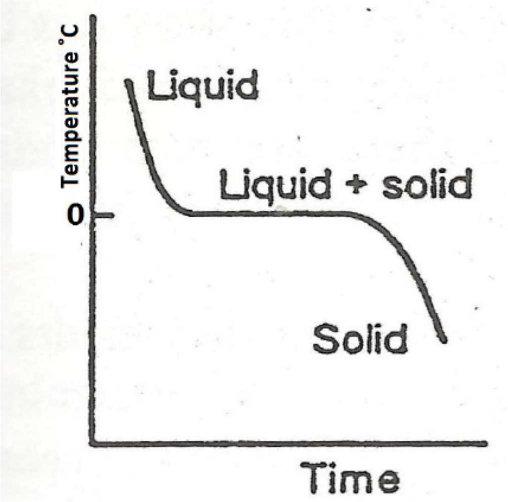


Figure 13.1 Cooling curves for water during solidification.

At 0°C solidification starts to occur and while solidification is occurring the temperature remains constant, latent heat being extracted during this time.

All pure substances show the same type of behaviour as water when they change state.

Figure 13.2 shows the cooling curve for copper, the transition from liquid copper to solid copper taking place at 1084°C.

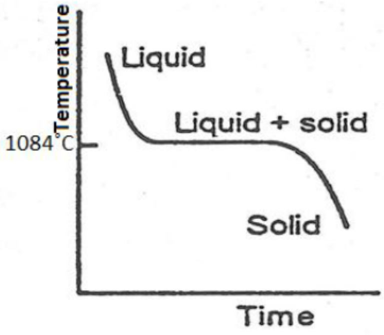


Figure 13.2 Cooling curves for pure copper during solidification.

The cooling curve for an alloy do not show a constant temperature occurring during the change of state. Figure 13.3 shows cooling curve for 70% Cu- 30%Ni alloy.

With alloys, the temperature is not constant during solidification. The temperature range over which this solidification occurs depends on the relative proportions of the elements in the alloy.

For the alloy with 70% copper and 30% nickel, the transition between liquid and solid starts at 1240°C and is completed at 1160°C when all the alloy is solid.

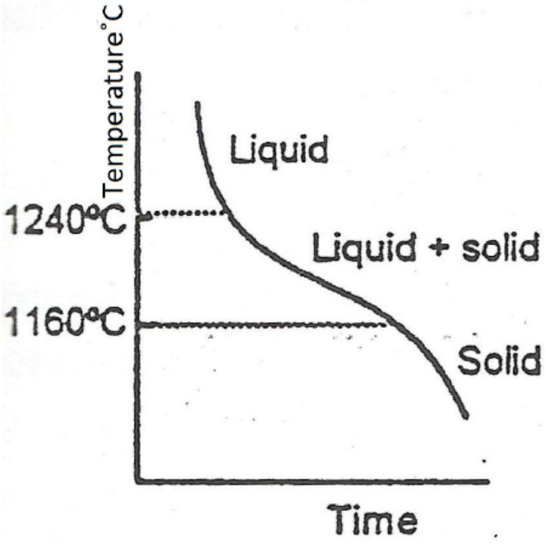


Figure 13.3 Cooling curve for 70%Cu-30% Ni alloy.

For the alloy with 90% copper and 10% nickel, the transition between liquid and solid starts at 1140˚C and is completed at 1100˚C when all the alloy is solid as shown in figure 13.4.

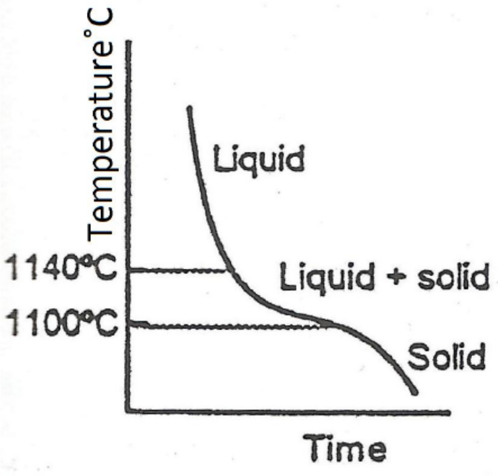


Figure 13.4 Cooling curve for 90%Cu-10% Ni alloy.

14. Construction of thermal equilibrium diagram

If the cooling curves are obtained for the entire range of copper-nickel alloys, a composite diagram can be produced which shows the effect of the relative proportions of the constituents on the temperatures at which solidification starts and that at which it is complete.

Types of thermal equilibrium diagram:

1. Thermal equilibrium diagram of two metals completely soluble in solid state.

2. Thermal equilibrium diagram of two metals completely insoluble in solid state.

3. Thermal equilibrium diagram of two metals partially soluble in solid state.

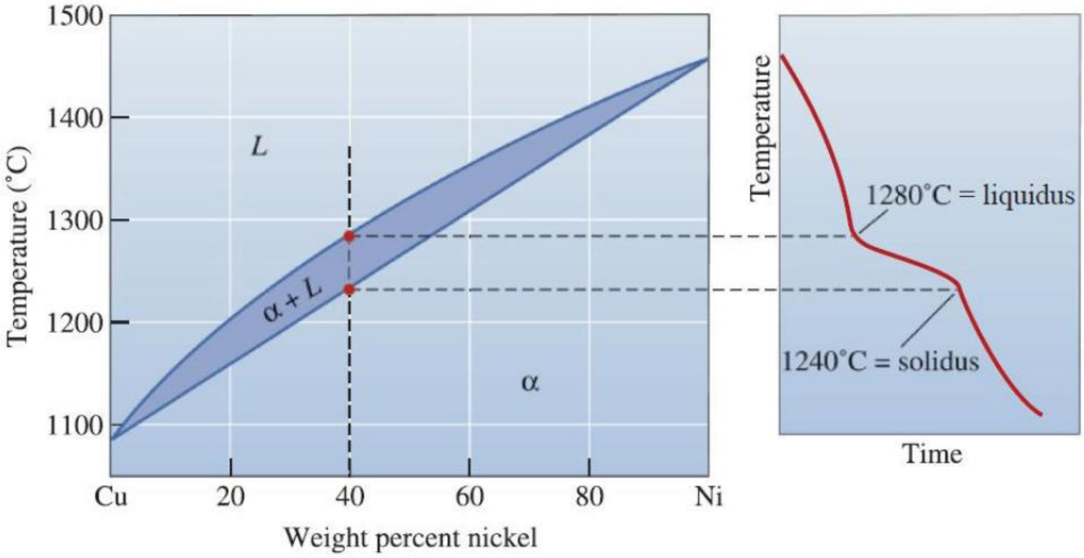


Figure 13.5 Thermal equilibrium diagram for Cu-Ni alloys, with cooling curve for Cu-40%Ni alloy.

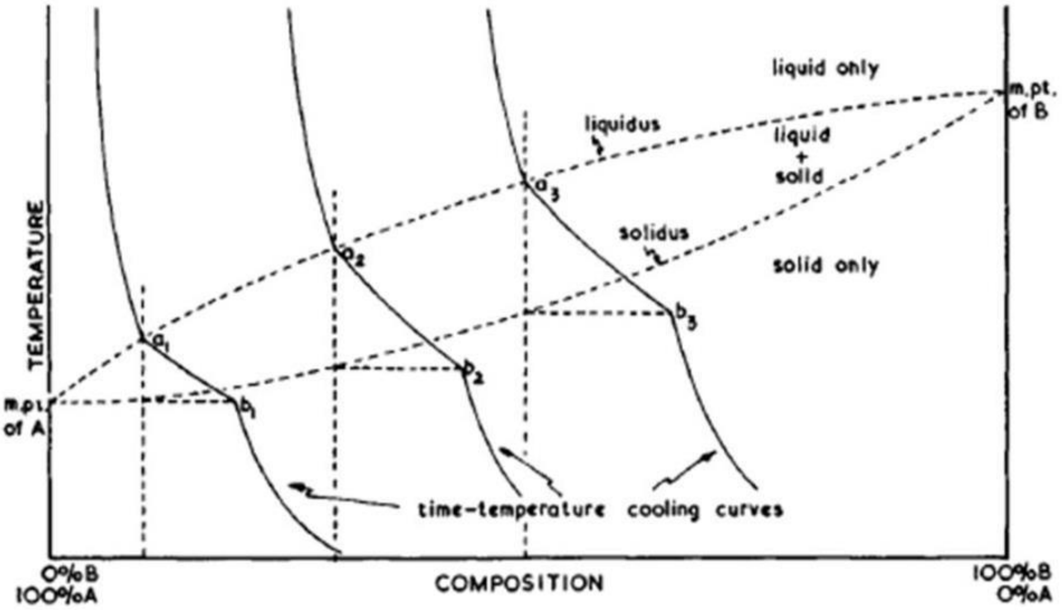


Figure 13.6 The construction of a simple equilibrium diagram of the solid solution type using cooling curves of a series of alloys.

15. Thermal equilibrium diagram for two metals completely soluble in each other in solid state.

Solid solution:

When small amounts of elements are added, a solid material known as a solid solution may form. A solid solution contains two or more types of atoms or ions that are dispersed uniformly throughout the material.

The impurity or solute atoms may occupy regular lattice sites in the crystal or interstitial sites.

By controlling the amount of these point defects via the composition, the mechanical and other properties of solid solutions can be manipulated.

If we were to mix any amounts of liquid copper and liquid nickel, only one liquid phase would be produced. This liquid alloy has the same composition and properties everywhere (Figure 15-1) because nickel and copper have unlimited liquid solubility.

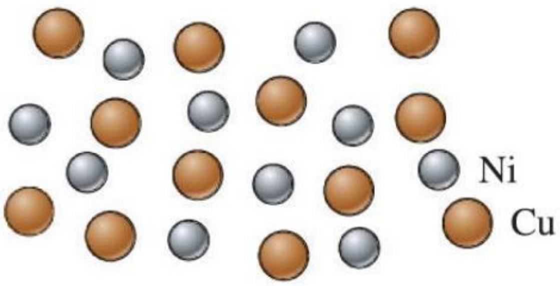


Figure 15.1 Liquid copper and liquid nickel are completely soluble in each other.

If the liquid copper-nickel alloy solidifies and cools to room temperature while maintaining thermal equilibrium, only one solid phase is produced.

After solidification, the copper and nickel atoms do not separate but, instead, are randomly located within the FCC crystal structure.

Within the solid phase, the structure, properties, and composition are uniform (figure 15.2).

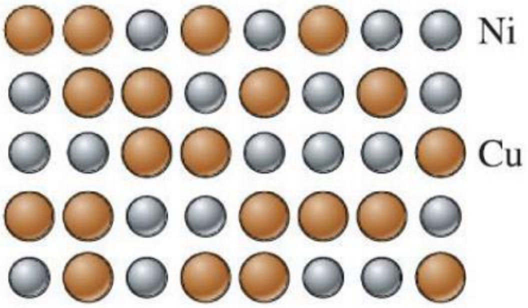


Figure15.2 Solid copper-nickel alloys display complete solid solubility with copper and nickel atoms occupying random lattice sites.

Mixture: contains more than one type of phase, and the characteristics of each phase are retained when the mixture is formed.

Solid solution: the components of a solid solution completely dissolve in one another and do not retain their individual characteristics.

Example 15.1

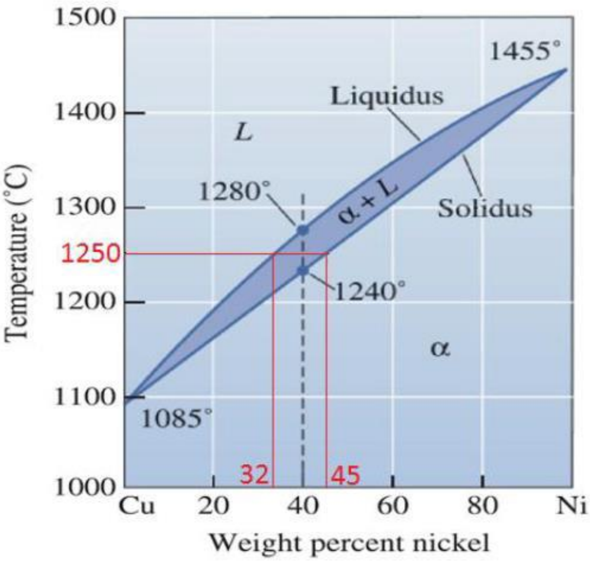
Figure 15.3 shows the phase diagram of copper-nickel alloys, determine the amounts of solid and liquid present in 60% copper – 40% nickel alloy at a temperature of 1250°C.

Solution:

Applying the lever rule:

$$\text{the fraction of solid } = \frac{40-32}{45-32}$$

$$\text{the fraction of solid } = 0.62$$



$$\text{the fraction of liquid } = \frac{45-40}{45-32}$$

Figure15.3 Cu-Ni phase diagram

$$\text{the fraction of liquid } = 0.38$$

Example 15.2

Figure 15.4 shows the phase diagram of NiO-MgO (ceramic) refractory material. Select a composition that can be used at 2200°C without melting, but can be melted and cast at 2600°C.

Solution:

For a liquidus below 2600°C there must be less than about 65% MgO.

For a solidus above 2200°C there must be at least about 37% MgO.

Thus a composition of between 37% and 65% MgO could be used.

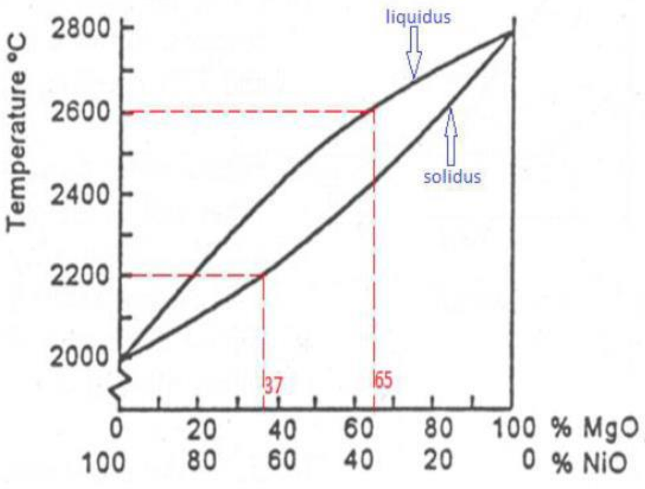
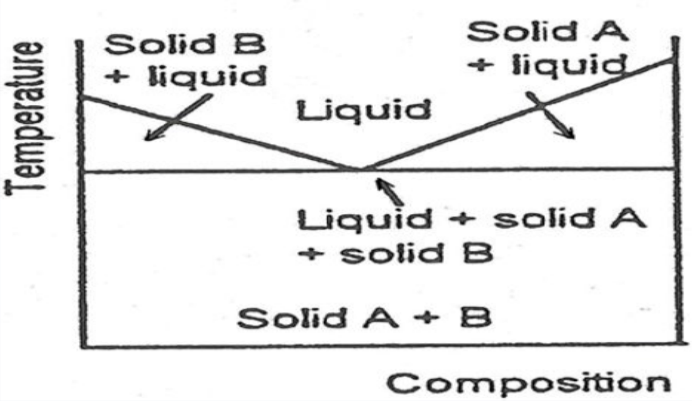


Figure15.4

16. Two metals completely insoluble in each other in solid state.

Figure (16.1) shows the type of phase diagram produced when the two alloy components A and B are completely soluble in each other in the liquid state but completely insoluble in each other in the solid state.



Each of the two components in the solid state retains its independent identity.

Figure (16.1) phase diagram for two metals completely insoluble in each other in the solid state.

16. Two metals completely insoluble in each other in solid state.

At one particular composition, called the eutectic composition, the temperature at which solidification occurs is a minimum.

At this temperature, called the eutectic temperature, the liquid changes to the solid state without any change in temperature, as shown in figure (16.2).

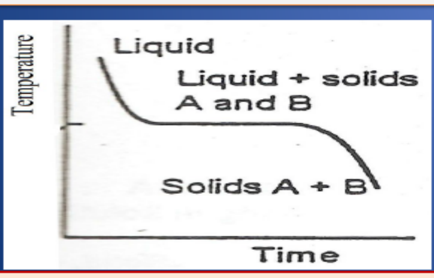


Figure (16.2) Cooling curve for eutectic composition.

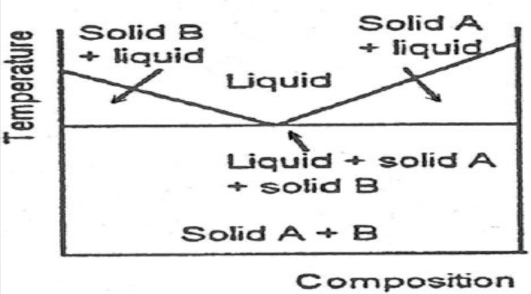


Figure (16.1) phase diagram for two metals completely insoluble in each other in the solid state.

16. Two metals completely insoluble in each other in solid state.

The resulting structure, known as the eutectic structure, is generally a laminar structure with layers of metal A alternating with layers of metal B.

The properties of the eutectic can be summarised as:

1. Solidification takes place at a single and lowest temperature.
2. The eutectic structure is a laminar and mixture of the two solid phases.
3. The eutectic composition is a constant for that range of alloys.

16. Two metals completely insoluble in each other in solid state.

Consider the sequence of events and the resulting structure when different composition alloys are cooled from the liquid as shown in figure (16.3).

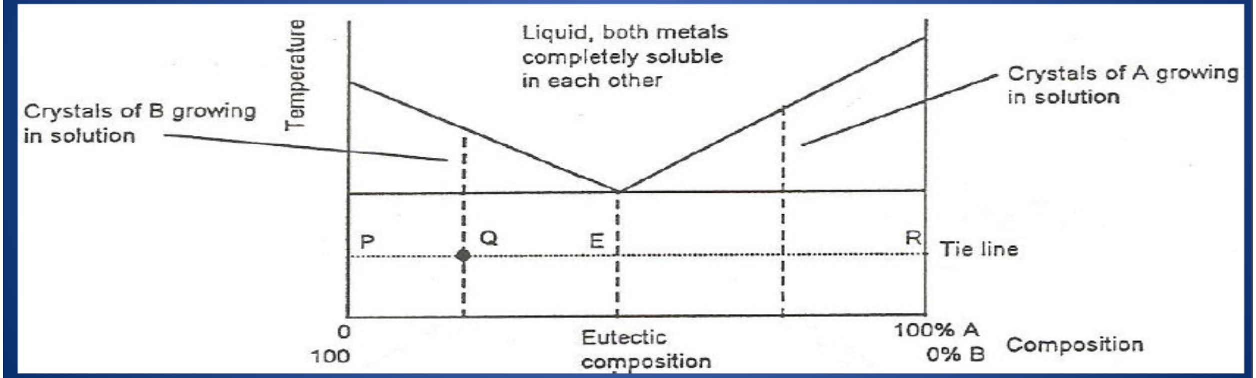


Figure (16.3) Phase diagram for two metals completely insoluble in solid state.

16. Two metals completely insoluble in each other in solid state.

For composition prior to the eutectic composition, when the liquid alloy is cooled to the liquidus temperature, crystals of metal B start to grow.

This means that as metal B is withdrawn from liquid, the composition of the liquid must change to a lower concentration of B and a higher concentration of A.

This continues until the concentration in the liquid reach that of the eutectic composition. When this happens, solidification of the liquid gives the eutectic structure.

16. Two metals completely insoluble in each other in solid state.

The resulting alloy has thus crystals of B embedded in a structure having the composition and structure of the eutectic. Figure (16.4) shows the cooling curve for hypoeutectic composition.

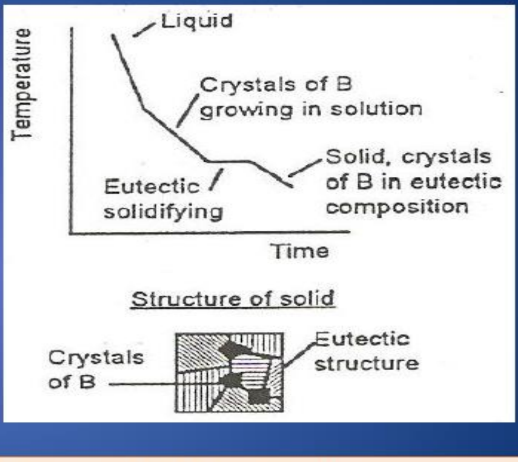


Figure (16.4) Cooling curve for hypoeutectic alloy.

16. Two metals completely insoluble in each other in solid state.

For the eutectic composition, the transition from liquid to solid results in the eutectic structure. Figure (16.5) shows the cooling curve for eutectic composition.

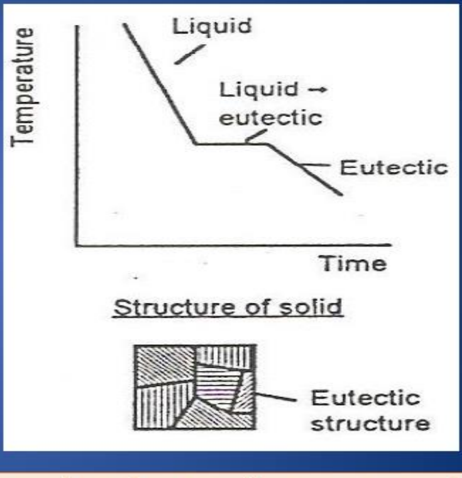


Figure (16.5) Cooling curve for eutectic composition.

16. Two metals completely insoluble in each other in solid state.

For composition after the eutectic composition, when the liquid alloy is cooled to the liquidus temperature, crystals of metal A start to grow.

This means that as metal A is withdrawn from liquid, the composition of the liquid must change to a lower concentration of A and a higher concentration of B.

This continues until the concentration in the liquid reach that of the eutectic composition. When this happens, solidification of the liquid gives the eutectic structure.

16. Two metals completely insoluble in each other in solid state.

The resulting alloy has thus crystals of A embedded in a structure having the composition and structure of the eutectic. Figure (16.6) shows the cooling curve for hypereutectic composition.

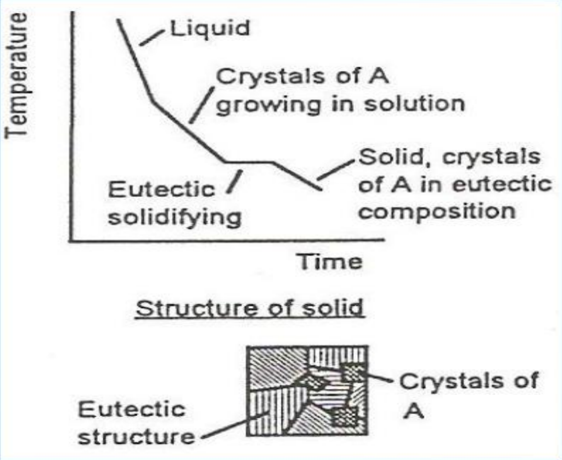


Figure (16.6) Cooling curve for hypereutectic composition.

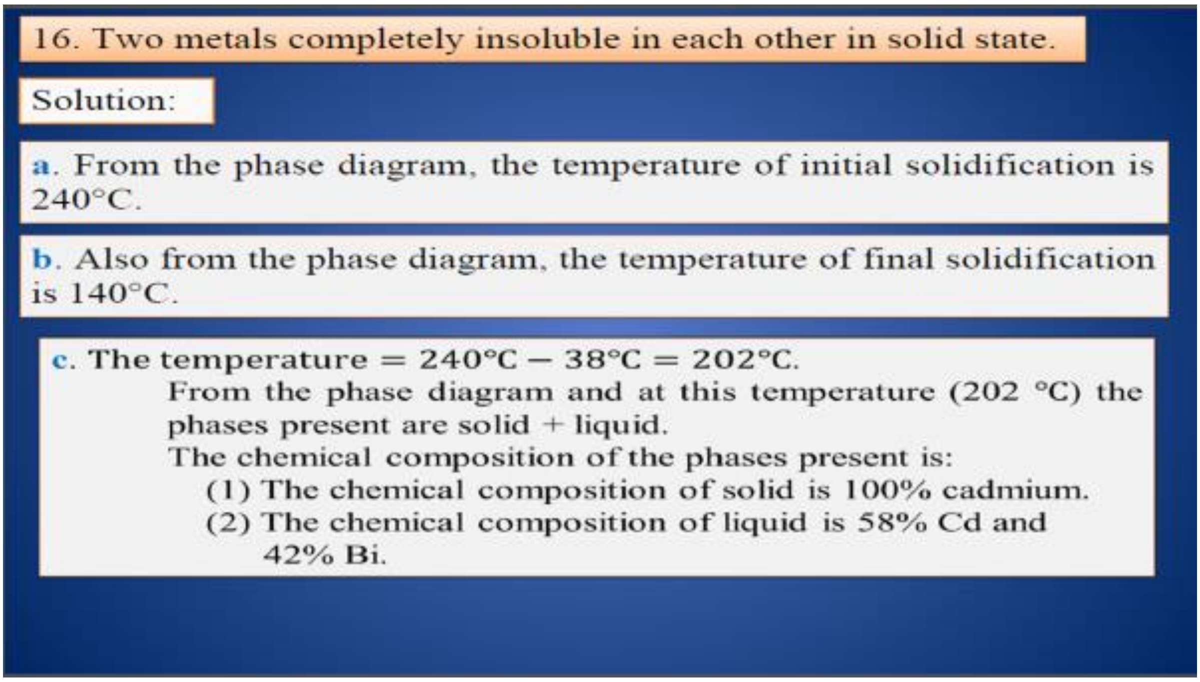
16. Two metals completely insoluble in each other in solid state.

Example 16.1

Bismuth (melting point 271°C) and cadmium (melting point 321° C) are assumed to be completely soluble in the liquid state and completely insoluble in the solid state. They form a eutectic at 140°C containing 40% cadmium.

1. Draw the equilibrium diagram to scale on a piece of graph paper labeling all points, lines, and areas.

2. For an alloy containing 70% cadmium:
   a. Give the temperature of initial solidification.
   b. Give the temperature of final solidification.
   c. Give the chemical composition and relative amounts of the phases present at a temperature of 38°C below (a).
   e. Draw the cooling curve for this alloy.



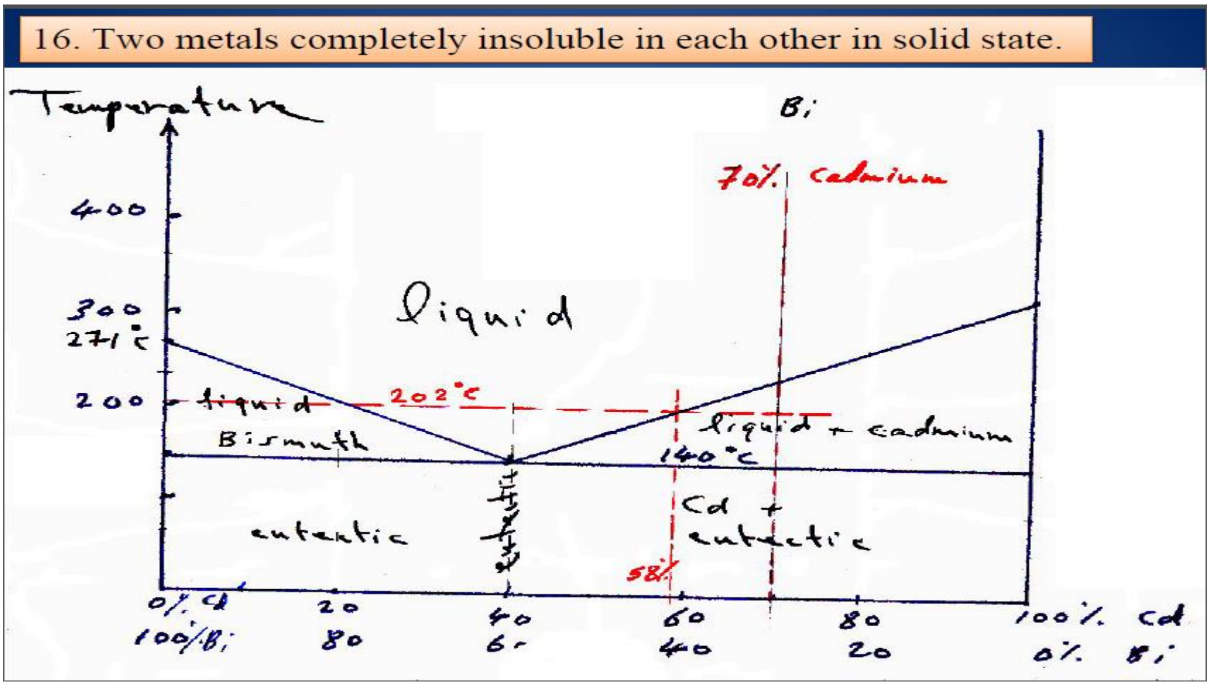
16. Two metals completely insoluble in each other in solid state.

Solution:

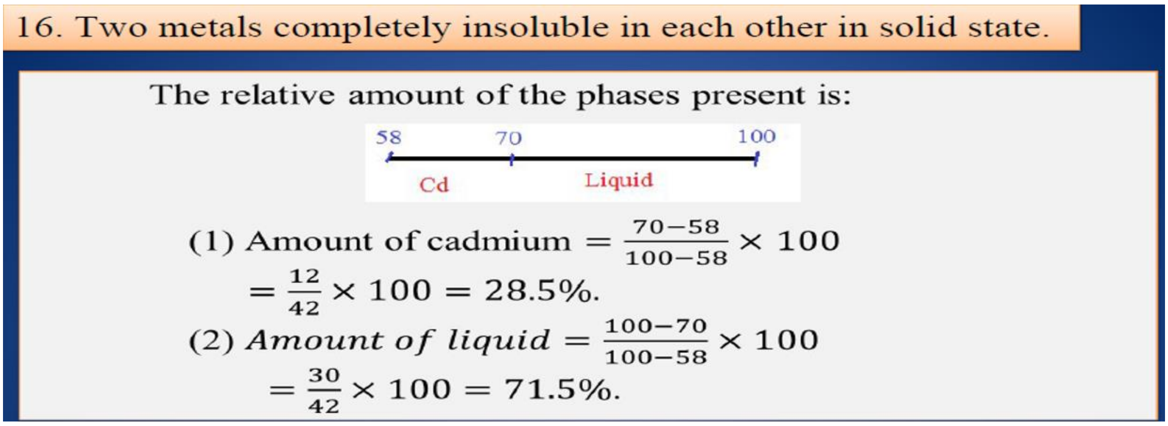
a. From the phase diagram, the temperature of initial solidification is 240°C.

b. Also from the phase diagram, the temperature of final solidification is 140°C.

c. The temperature = 240°C − 38°C = 202°C.
From the phase diagram and at this temperature (202 °C) the phases present are solid + liquid.
The chemical composition of the phases present is:
(1) The chemical composition of solid is 100% cadmium.
(2) The chemical composition of liquid is 58% Cd and 42% Bi.



16. Two metals completely insoluble in each other in solid state.

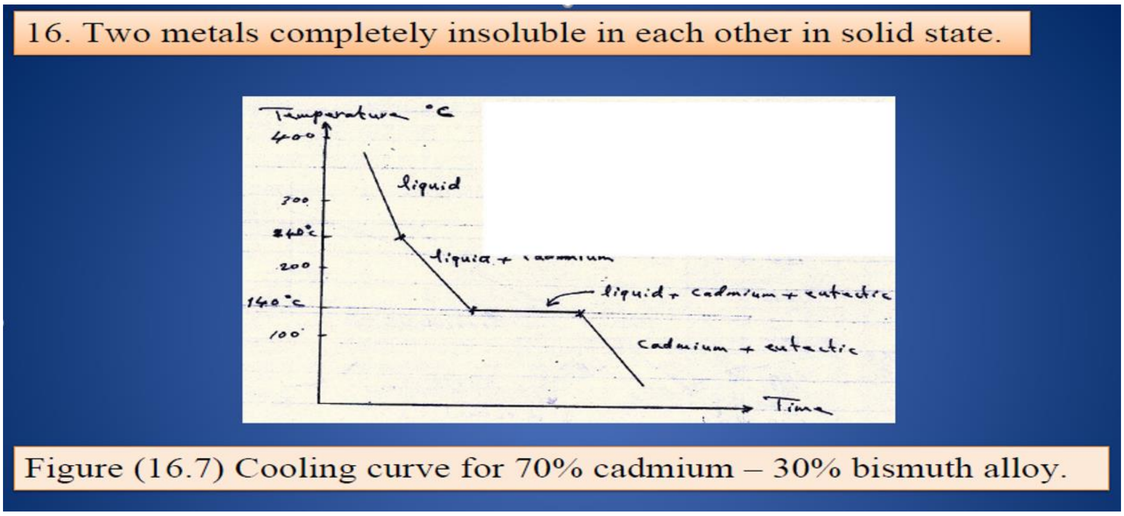


16. Two metals completely insoluble in each other in solid state.

The relative amount of the phases present is:

$$(1)\ \text{Amount of cadmium} = \frac{70-58}{100-58} \times 100 = \frac{12}{42} \times 100 = 28.5\%.$$

$$(2)\ \textit{Amount of liquid} = \frac{100-70}{100-58} \times 100 = \frac{30}{42} \times 100 = 71.5\%.$$



16. Two metals completely insoluble in each other in solid state.

Figure (16.7) Cooling curve for 70% cadmium – 30% bismuth alloy.

Phase diagram for two metals partially soluble in each other in solid state: few systems show complete solubility or complete insolubility in the solid state, in most cases one metal will dissolve in the other for only a limited range of concentrations, i.e., there is limited solubility.

Lead-tin alloys are of this type, figure (17.1) showing the phase diagram.

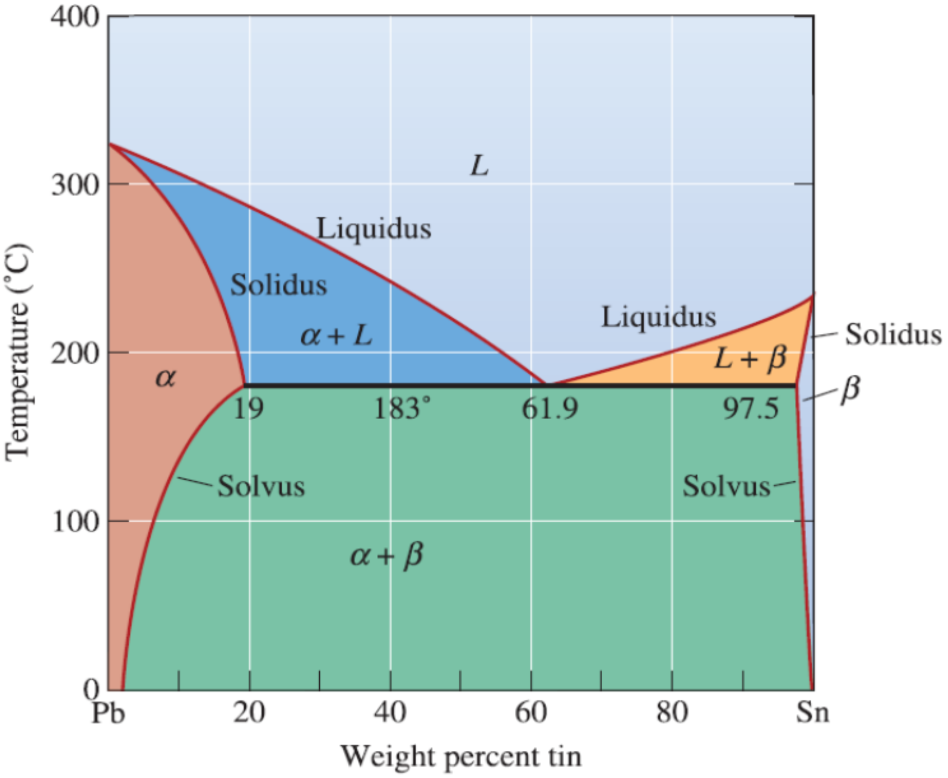


Figure 17-1 The lead–tin equilibrium phase diagram.

Solid-Solution Alloys: alloys that contain 0 to 2% Sn behave exactly like the copper-nickel alloys; a single-phase solid solution forms during solidification (Figure 17.2).

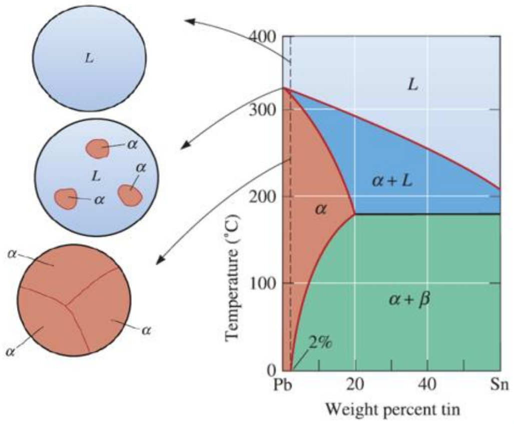


Figure 17.2 Solidification and microstructure of a Pb-2% Sn alloy.

Alloys That Exceed the Solubility Limit: Alloys containing between 2% and 19% Sn also solidify to produce a single solid solution ; however, as the alloy continues to cool, a solid-state reaction occurs, permitting a second solid phase (β) to precipitate from the original phase (Figure 17.3).

On this phase diagram, the is a solid solution of tin in lead; however, the solubility of tin in the solid solution is limited. At 0°C, only 2% Sn can dissolve in .

As the temperature increases, more tin dissolves into the lead until, at 183°C, the solubility of tin in lead has increased to 19% Sn. This is the maximum solubility of tin in lead. The solubility of tin in solid lead at any temperature is given by the solvus curve. Any alloy containing between 2% and 19% Sn cools past the solvus, the solubility limit is exceeded, and a small amount of (β) forms.

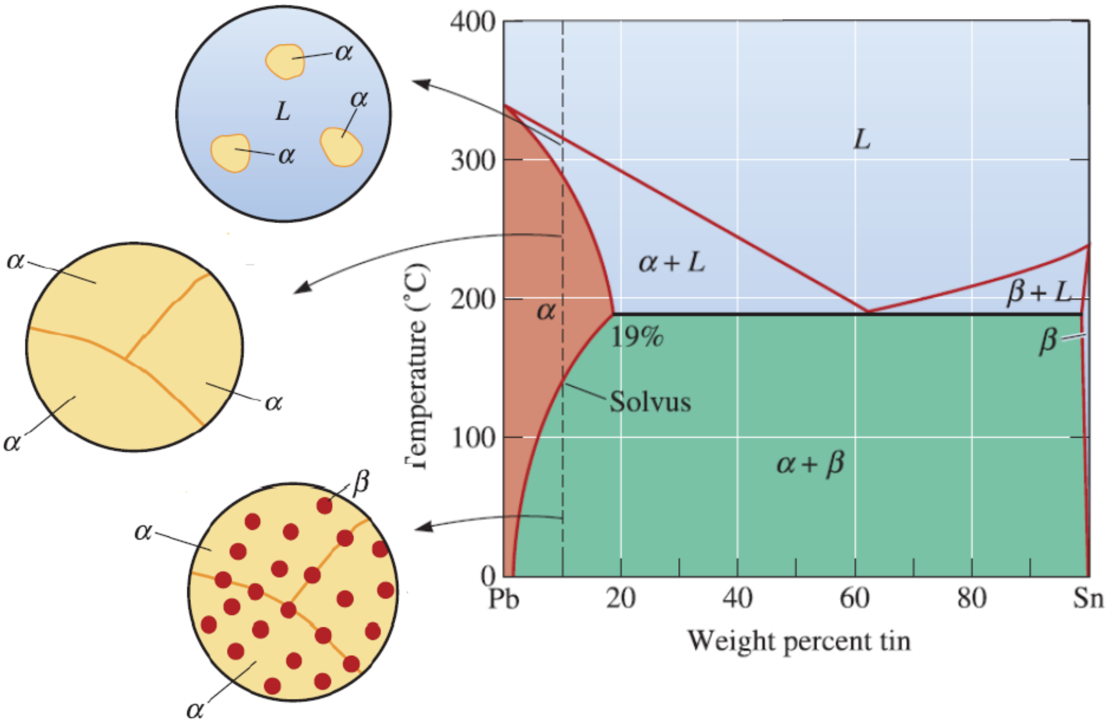


Figure 17.3 Solidification, precipitation, and microstructure of a Pb-10% Sn alloy.

Example 17.1

Determine the amount of α in comparison with β that forms if a 90% lead- 10% tin alloy is cooled to 0°C.

Solution:

The fraction of the solid which is α is:

$$\text{solid } \alpha = \frac{100-10}{100-2} = 0.918$$

The fraction of the solid which is β is:

$$\text{solid } \beta = \frac{10-2}{100-2} = 0.082$$

Alloys between 19.2% and 61.9% tin: the eutectic composition is 61.9% tin - 38.1% lead. When an alloy with between 19.2% and 61.9% tin is cooled from the liquid, the behaviour is similar to that which occurs with two metals which are insoluble in the solid state.

The result is a solid structure with crystals of α solid solution crystals in the eutectic structure.

Figure (17.4) shows the solidification for one of these alloys.

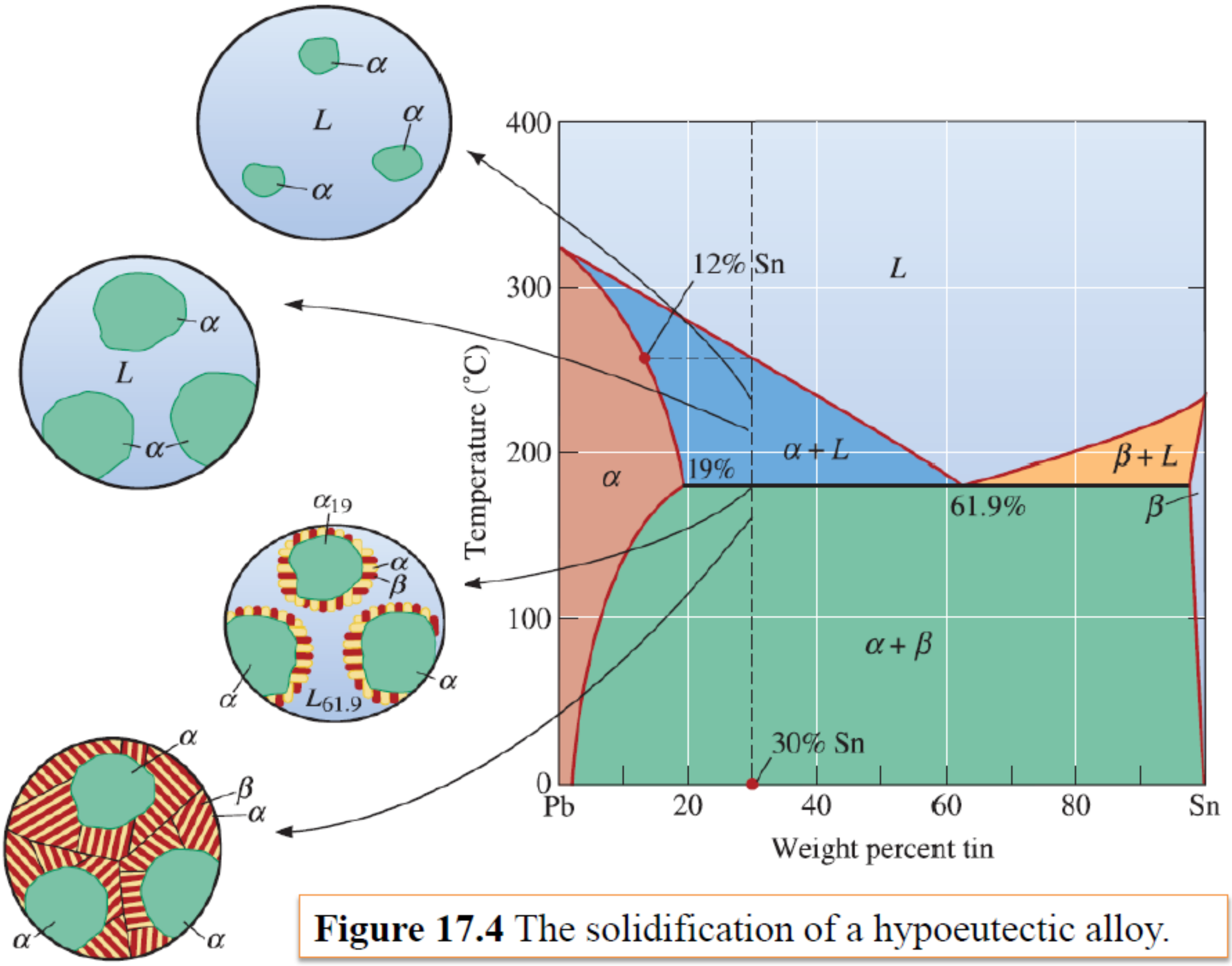


Figure 17.4 The solidification of a hypoeutectic alloy.

Figure (17.5) shows the cooling curve for one of these alloys.

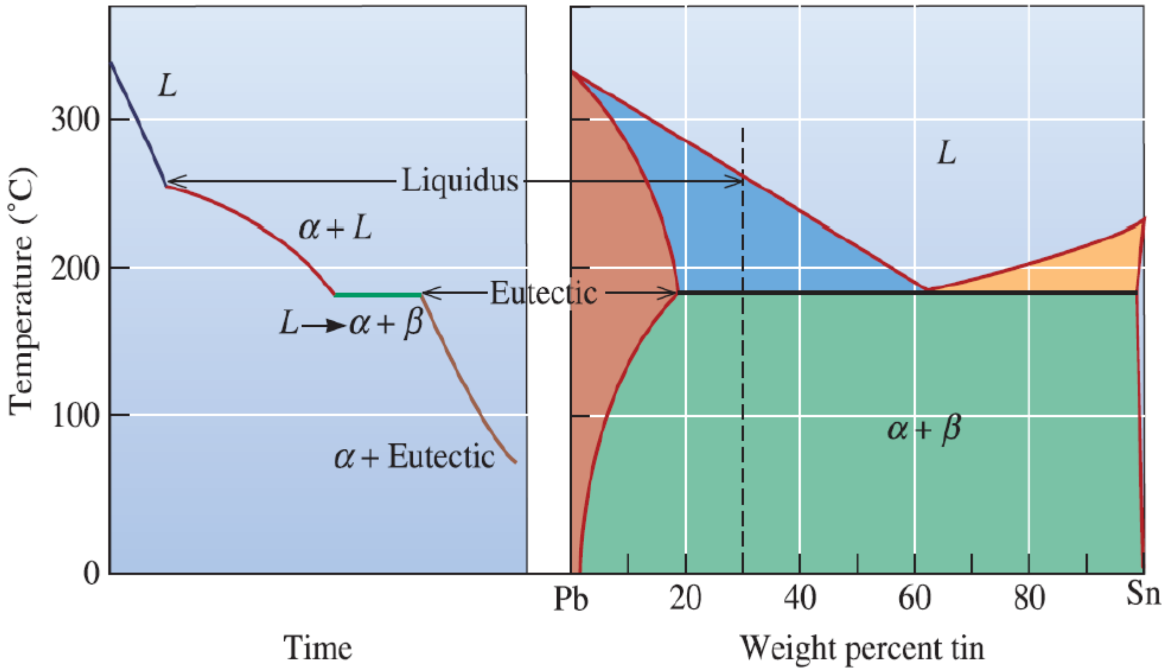


Figure 17.5 The cooling curve for a hypoeutectic Pb-30% Sn alloy.

Example 17.2

Determine the composition of α and β at:

(a) 0°C.

(b) 170°C.

Solution:

(a) The ends of the tie line for 0°C are at 2% and 100% tin, thus:
The α phase is 2% tin – 98% lead &
The β phase 100% tin.

(b) The ends of the tie line for 170°C are at 15% and 98% tin, thus:
The α phase is 15% tin – 85% lead &
The β phase is 98% tin – 2% lead.

Example 17.3

Determine the amounts of α and β phase that forms if the 30% tin – 70% lead alloy is cooled to 0°C.

Solution:

Using the lever rule with the tie line drawn at 0°C, the amount which is:

$$\alpha = \frac{100-30}{100-2}$$

$$\alpha = 71.4\%$$

$$\beta = \frac{30-2}{100-2}$$

$$\beta = 28.6\%$$

Eutectic Alloys

The alloy containing 61.9% Sn has the eutectic composition (Figure 17.6). The word eutectic comes from the Greek word eutectos that means easily fused.

Indeed, in a binary system showing one eutectic reaction, an alloy with a eutectic composition has the lowest melting temperature. This is the composition for which there is no freezing range (i.e., solidification of this alloy occurs at one temperature, 183°C in the Pb-Sn system).

Above 183°C, the alloy is all liquid and, therefore, must contain 61.9% Sn. After the liquid cools to 183°C, the eutectic reaction begins:

$$L_{61.9\%Sn} \rightarrow \alpha_{19.2\%Sn} + \beta_{97.5\%Sn}$$

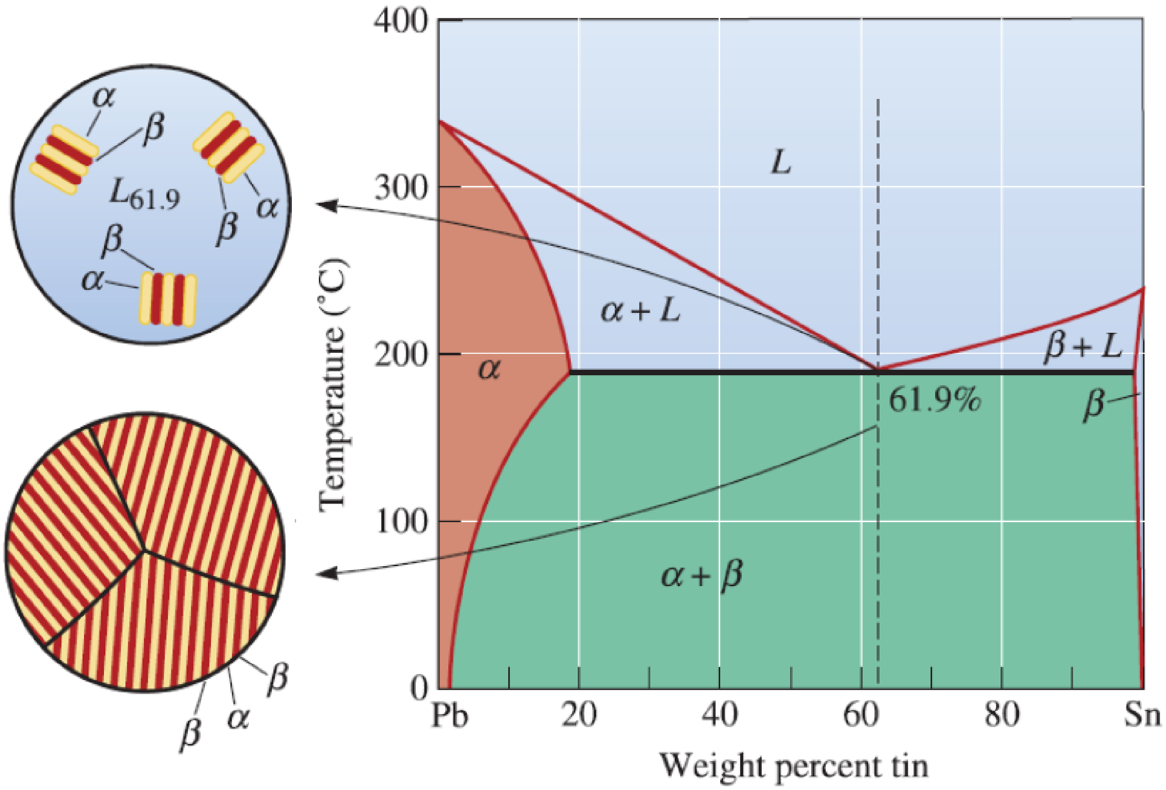


Figure 17.6 Solidification and microstructure of the eutectic alloy Pb-61.9% Sn.

Two solid solutions α and β are formed during the eutectic reaction. The compositions of the two solid solutions are given by the ends of the eutectic line.

Since solidification occurs completely at 183°C, the cooling curve **(Figure 17.7)** is similar to that of a pure metal.

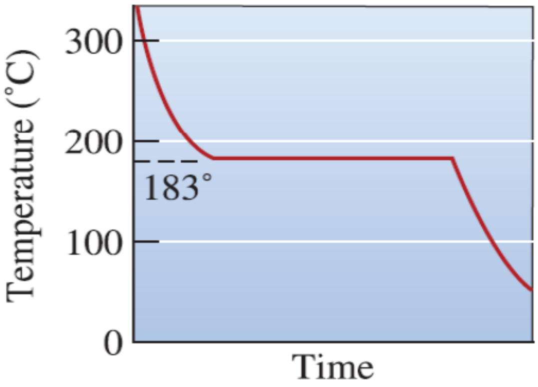


Figure 17.7 The cooling curve for an eutectic alloy

Example 17.3

(a) Determine the mass and composition of α *and* β in 200 g of a lead-tin alloy of eutectic composition immediately after the eutectic reaction has been completed. **(b)** Calculate the masses of lead and tin in α *and* β. **(c)** Calculate the masses of tin and lead in the alloy.

Solution: **(a)**

$$\alpha = \frac{(97.5 - 61.9)}{(97.5 - 19.2)} \times 200\,grams$$

$\alpha = 90.9\ grams$ (mass)

$\alpha\ 19.2\%\ Sn$ (composition)

$$\beta = \frac{(61.9 - 19.2)}{(97.5 - 19.2)} \times 200\,grams$$

$\beta = 109.1\ grams$ (mass)

$\beta\ 97.5\%\ Sn$ (composition)

(b)

in α phase the masses of tin and lead can be calculated as follows:

$Sn = 0.192 \times 90.9\ grams$ $\qquad Sn = 17.5\ grams$

$Pb = (90.9 - 17.5)\ grams$ $\qquad Pb = 73.4\ grams$

in β phase the masses of tin and lead can be calculated as follows:

$Sn = 0.975 \times 109.1\ grams$ $\qquad Sn = 106.4\ grams$

$Pb = (109.1 - 106.4)\ grams$ $\qquad Pb = 2.7\ grams$

(c)

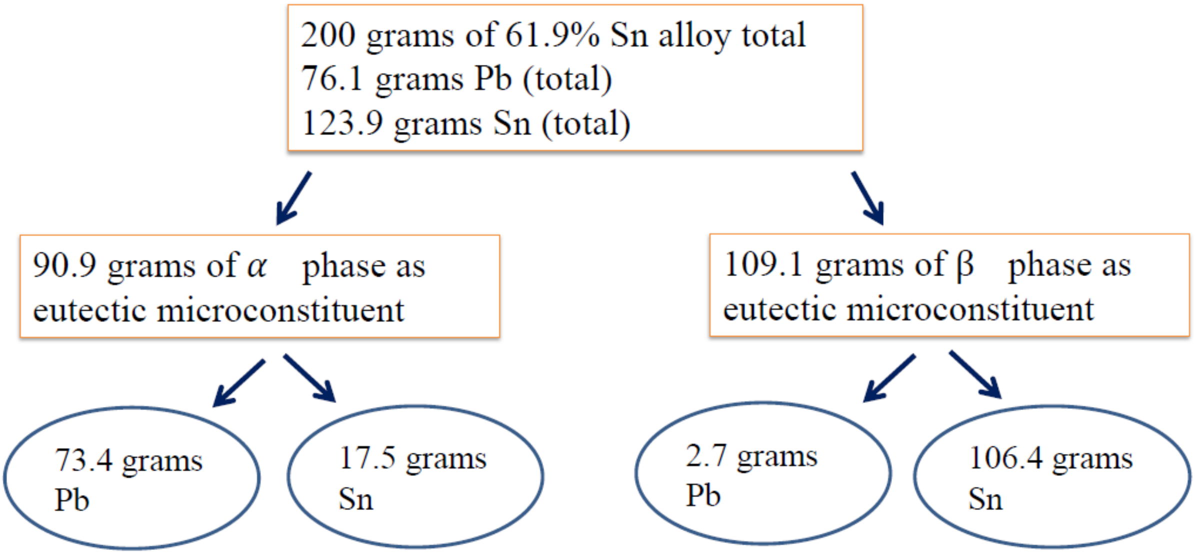
$Pb = mass\ of\ Pb\ in\ \alpha + mass\ of\ Pb\ in\ \beta$

$Pb = 73.4\ grams + 2.7\ grams$ $\qquad Pb = 76.1\ grams$

$Sn = mass\ of\ Sn\ in\ \alpha + mass\ of\ Sn\ in\ \beta$

$Sn = 17.5\ grams + 106.4\ grams$

$Pb = 123.9\ grams$



18. Iron-making

1. Iron production

Smelting:- Smelting of iron ore takes place in the blast-furnace as shown in figure below. A modern blast-furnace is something like 60 m high and 7.5 m in diameter at the base, and may produce from 2000 to 10,000 tons of iron per day.

Table : *Materials involved with a daily output of 2000 tonnes of pig iron*

Charge	*Amount, tonnes*
Ore, say 50% iron	4 000
Limestone **CaCO3**	800
Coke	1 800
Air	8 000
Total	14 600
Products	
Pig iron	2 000
Slag	1 600
Dust	200
Furnace gas	10 800
Total	14 600

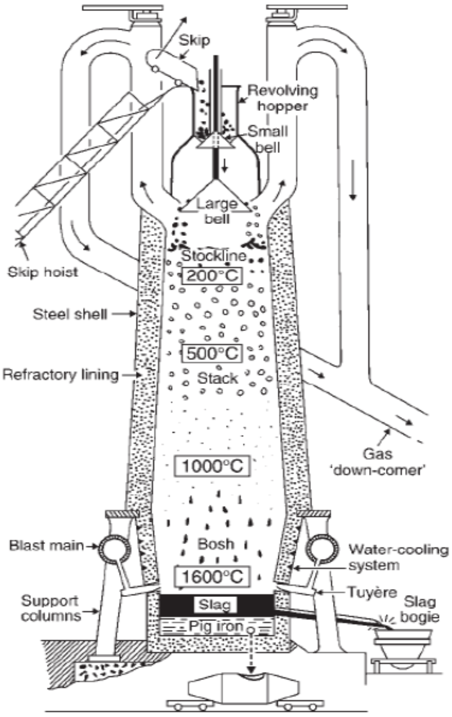


Figure *A modern blast-furnace.*

Steel-making.

Steel-making:

the bulk of steel is made either by one of the basic oxygen processes developed since 1952 or in the electric-arc furnace.

1. Basic oxygen steel-making (BOS):

The process of steel-making is mainly one involving oxidation of impurities present in the original charge, so that they form a slag which floats on the surface of the molten steel or are lost as fume. The impurities, mainly carbon, phosphorus, sulphur, silicon and manganese.

Steel-making.

The basic oxygen converter uses no additional fuel. The pig iron impurities (carbon, silicon, manganese, sulphur and phosphorous) serve as fuel.

Oxidizing stage

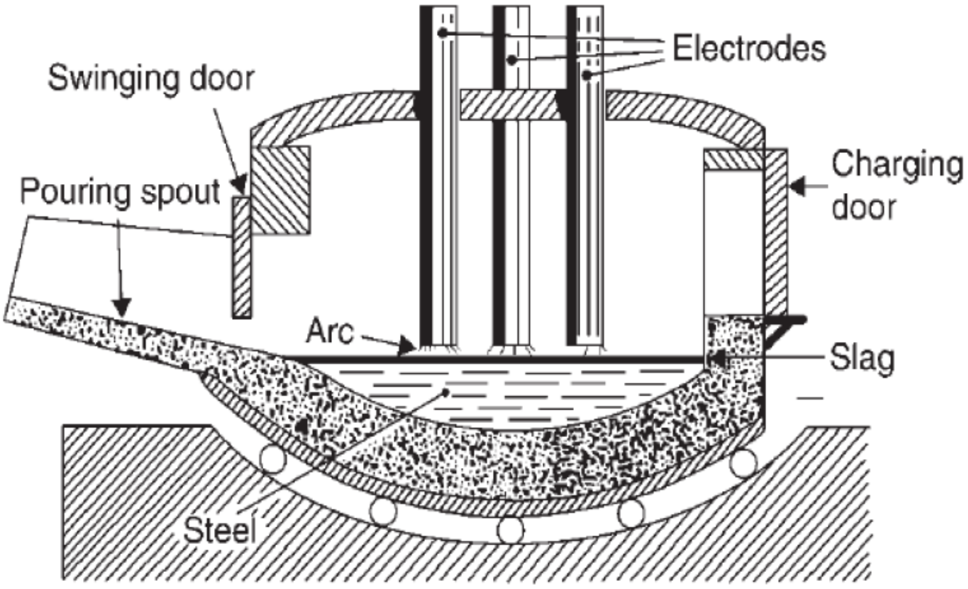
At this stage the heat, produced causes oxidizing phosphorous, sulphur, silicon and manganese. The oxides are absorbed into the slag. By the end of the stage the slag is removed.

2. Electric-arc steel-making:

Electric-arc steel-making is now the only alternative process to BOS. the chemical conditions within the electric-arc furnace can be varied at will to favour successive removal of the various impurities present in the charge.

Sulphur, which was virtually impossible to eliminate in either the Bessemer or openhearth processes, can be effectively reduced to extremely low limits in the electric-arc process.

Steel-making.



Steel-making.

Hence the main advantages of the arc process are:

(1) Removal of sulphur is reliable.

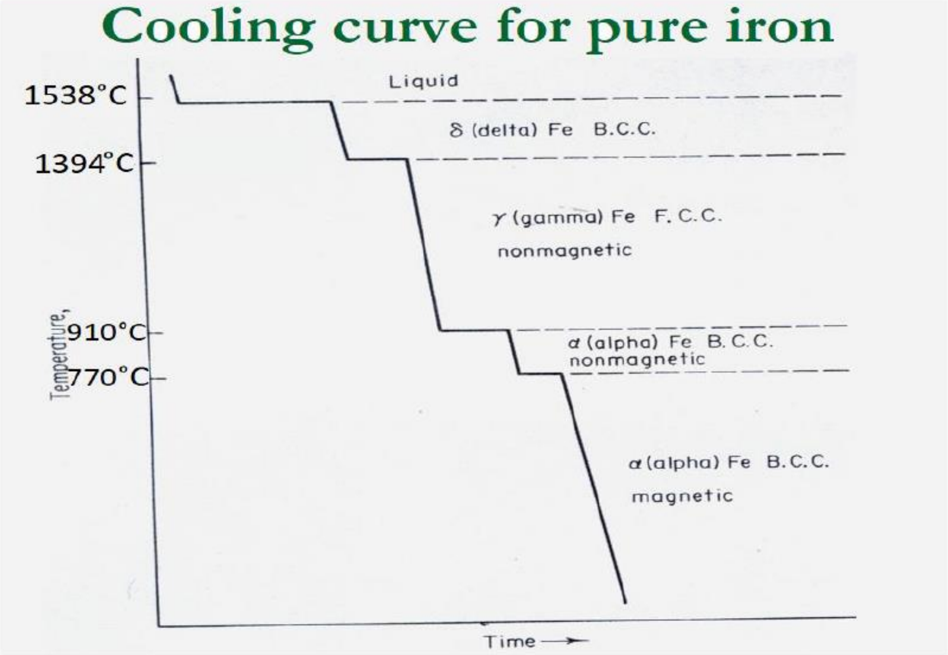
(2) Conditions are chemically 'clean' and contamination of the charge is impossible.

(3) Temperature can be accurately controlled.

(4) Carbon content can be adjusted between fine limits.

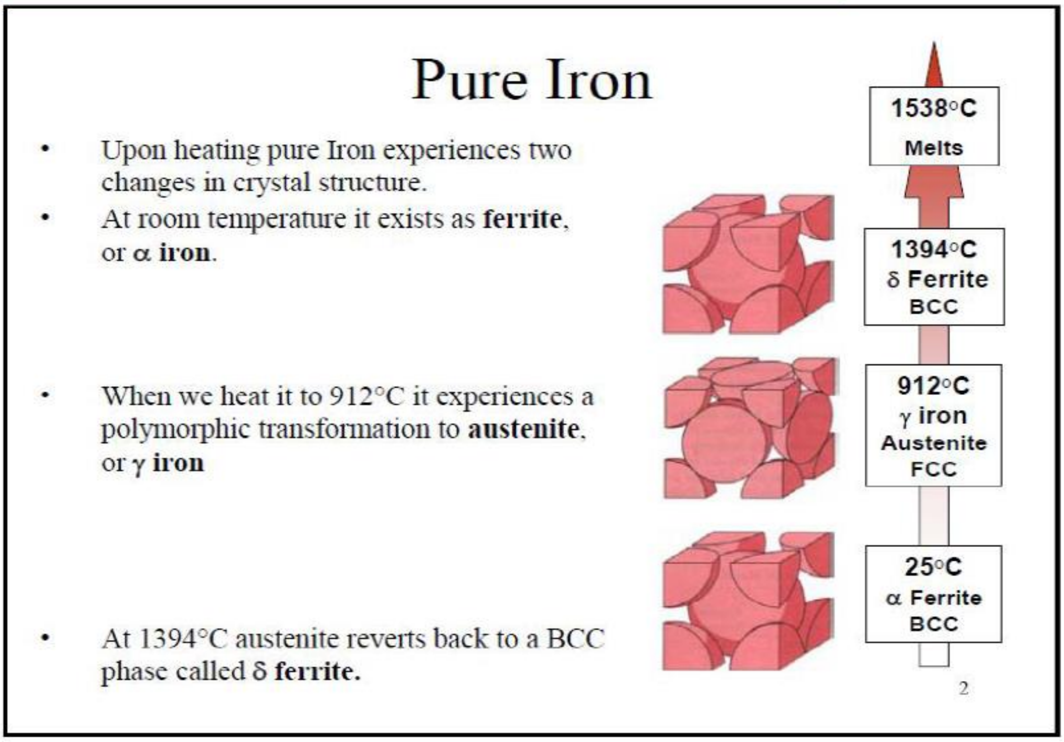
(5) The addition of alloying elements can be made with precision.

Thermal equilibrium diagram for Iron-iron carbide.



Cooling curve for pure iron

Thermal equilibrium diagram for Iron-iron carbide.



Pure Iron

- Upon heating pure Iron experiences two changes in crystal structure.
- At room temperature it exists as **ferrite**, or α **iron**.
- When we heat it to 912°C it experiences a polymorphic transformation to **austenite**, or γ **iron**
- At 1394°C austenite reverts back to a BCC phase called δ **ferrite.**

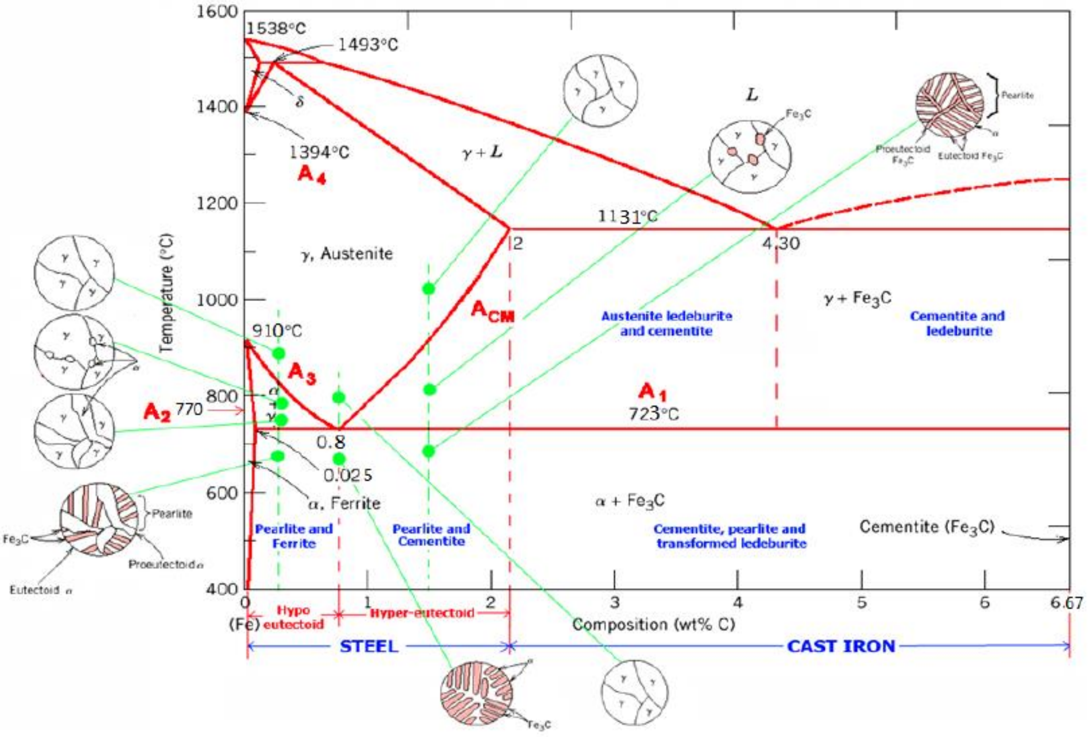
1538°C
Melts

1394°C
δ Ferrite
BCC

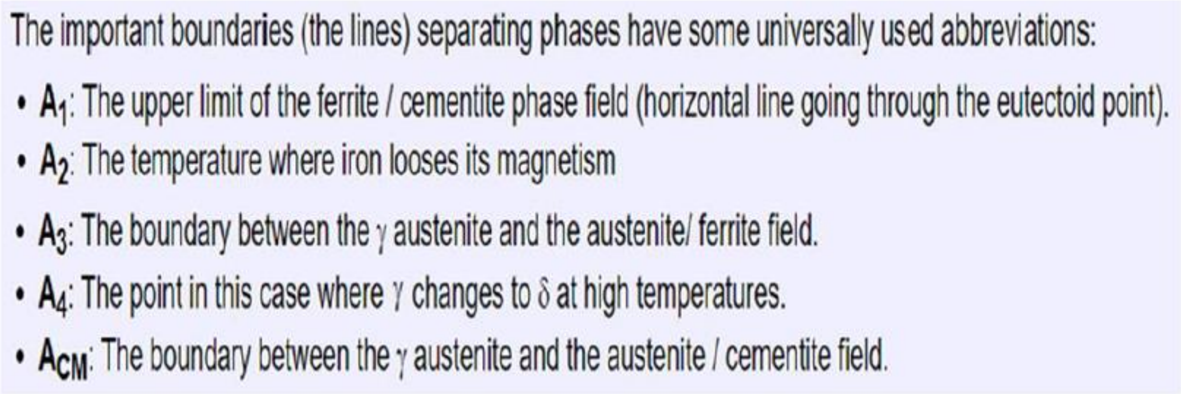
912°C
γ iron
Austenite
FCC

25°C
α Ferrite
BCC

Thermal equilibrium diagram for Iron-iron carbide.



Thermal equilibrium diagram for Iron-iron carbide.


The important boundaries (the lines) separating phases have some universally used abbreviations:

- A_1: The upper limit of the ferrite / cementite phase field (horizontal line going through the eutectoid point).
- A_2: The temperature where iron looses its magnetism
- A_3: The boundary between the γ austenite and the austenite/ ferrite field.
- A_4: The point in this case where γ changes to δ at high temperatures.
- A_{CM}: The boundary between the γ austenite and the austenite / cementite field.

Thermal equilibrium diagram for Iron-iron carbide.

Example (1)

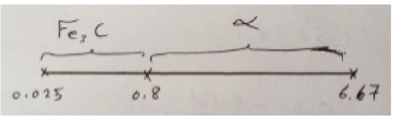
Determine the percentage of alpha ferrite and cementite present just below 723 °C in slowly cooled.

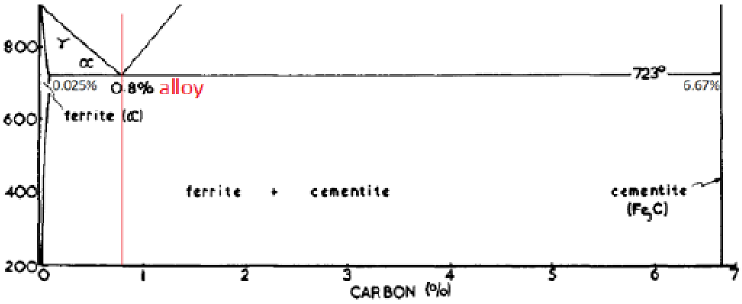
(a) 0.8% carbon steel.

(b) 2.0% carbon steel.

Solution:

(a) 0.8%C





$$\alpha = \frac{6.67 - 0.8}{6.67 - 0.025} \times 100$$

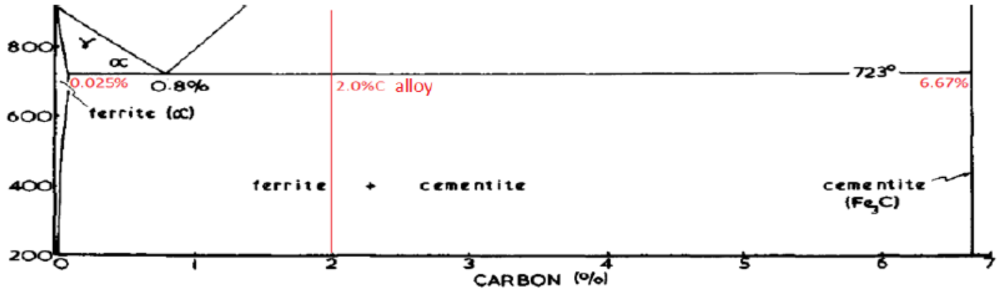
$$\alpha = 88.3\%$$

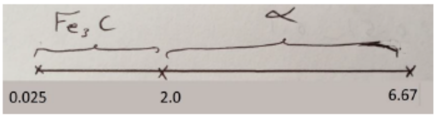
$$Fe_3C = \frac{0.8 - 0.025}{6.67 - 0.025} \times 100$$

$$Fe_3C = 11.7\%$$

Thermal equilibrium diagram for Iron-iron carbide.

(b) 2.0%C





$$\alpha = \frac{6.67-2}{6.67-0.025}\times 100$$

$\alpha = 70.2\%$

$$Fe_3C = \frac{2-0.025}{6.67-0.025}\times 100$$

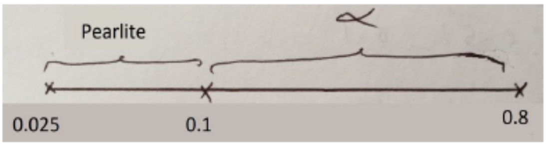
$Fe_3C = 29.8\%$

Thermal equilibrium diagram for Iron-iron carbide.

Example (2)

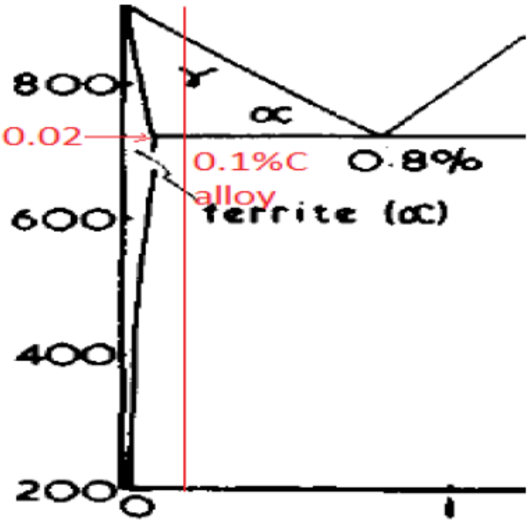
A carbon steel contains 0.1% carbon. What will be the percentage of pearlite present at just below 723 °C if it is slowly cooled from the austenite state?

Solution:



$$\text{pearlite\%} = \frac{0.1-0.025}{0.8-0.025}\times 100$$

$\text{pearlite} = 10.3\%$

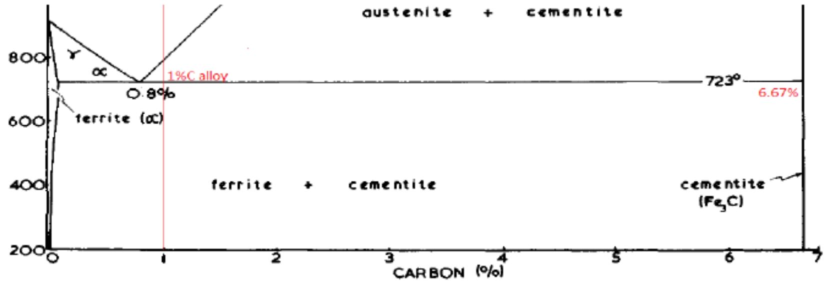


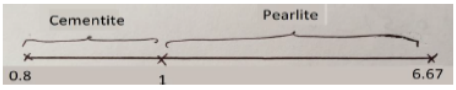
Thermal equilibrium diagram for Iron-iron carbide.

Example (3)

A carbon steel contains 1% carbon. What will be the percentage of pearlite present at just below 723 °C if it is slowly cooled from the austenite state?

Solution:





$$\text{pearlite\%} = \frac{6.67 - 1.0}{6.67 - 0.8} \times 100$$

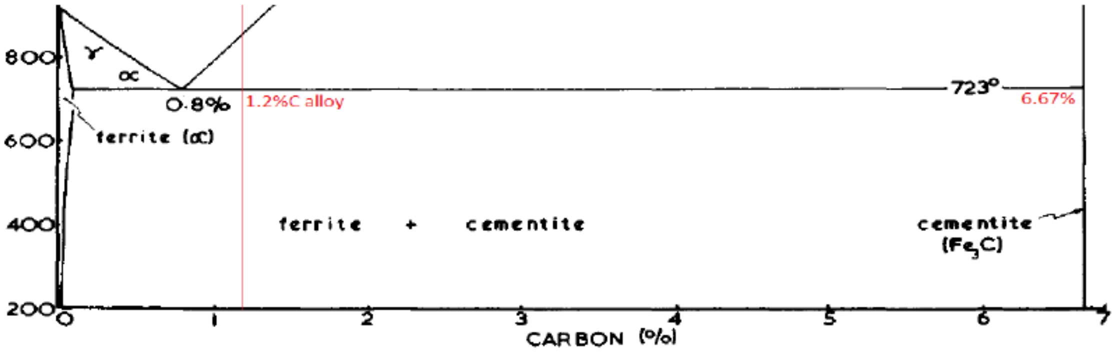
pearlite =96.6%

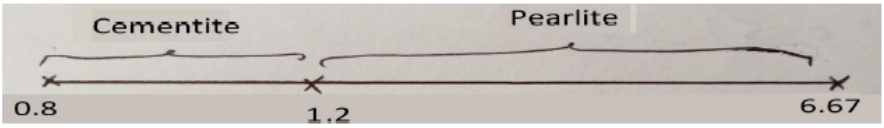
Thermal equilibrium diagram for Iron-iron carbide.

Example (4)

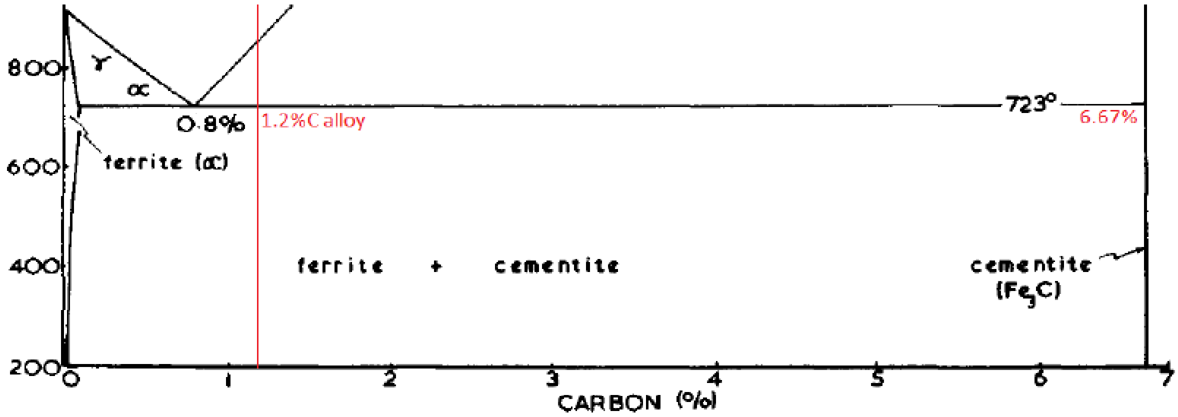
A carbon steel contains 1.2% carbon. What will be the percentage of cementite and pearlite present at just below 723 °C if it is slowly cooled from the austenite state?

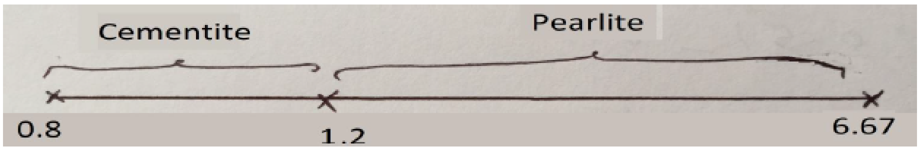
Solution:





Thermal equilibrium diagram for Iron-iron carbide.





$$\text{Cementite}\% = \frac{1.2 - 0.8}{6.67 - 0.8} \times 100$$

$$\text{Cementite} = 6.8\%$$

$$\text{pearlite}\% = \frac{6.67 - 1.2}{6.67 - 0.8} \times 100$$

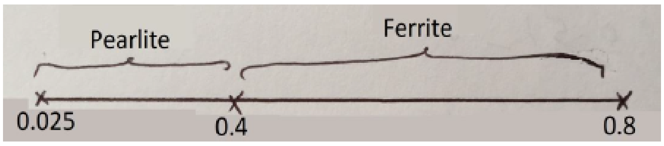
$$\text{pearlite} = 93.2\%$$

Thermal equilibrium diagram for Iron-iron carbide.

Example (5)

A carbon steel contains 0.4% carbon. What will be the percentage of alpha ferrite and pearlite present at just below 723 °C if it is slowly cooled from the austenite state?

Solution:

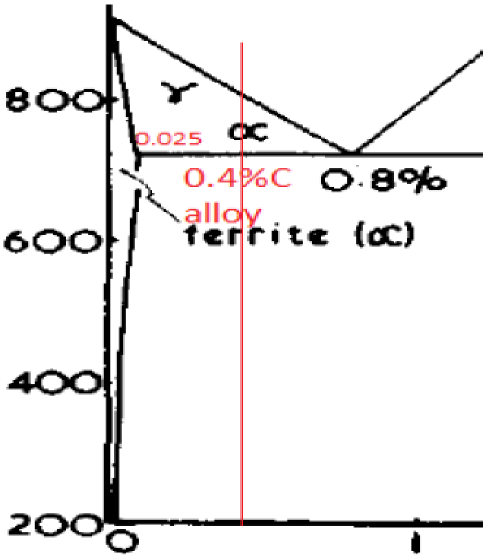


$$\text{alpha ferrite\%} = \frac{0.8 - 0.4}{0.8 - 0.025} \times 100$$

alpha ferrite =51.3%

$$\text{pearlite\%} = \frac{0.4 - 0.025}{0.8 - 0.025} \times 100$$

pearlite =48.7%



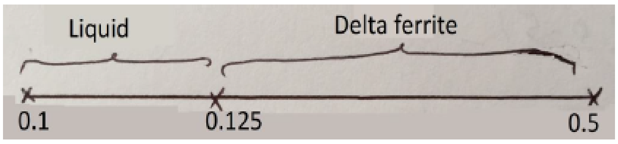
Thermal equilibrium diagram for Iron-iron carbide.

Example (6)

For the peritectic region of the iron-iron carbide phase diagram, determine the composition and relative amounts of each phase just above and just below the peritectic isotherm for 0.125% C alloy.

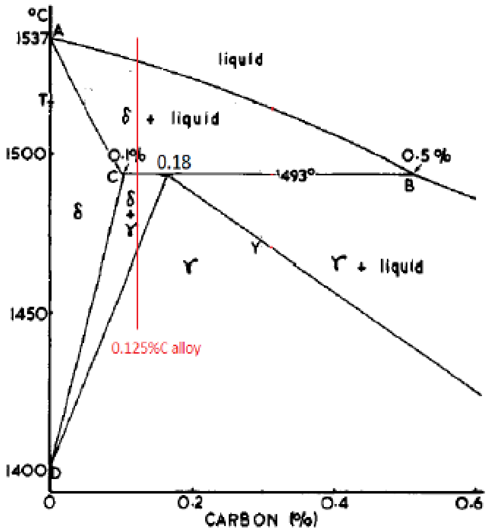
Solution:

(a) Above the peritectic isotherm



δ *composition*: 0.1% C

liquid composition: 0.5 % C



Thermal equilibrium diagram for Iron-iron carbide.

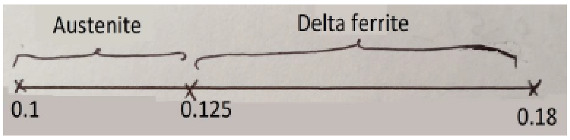
$$\delta\% = \frac{0.5-0.125}{0.5-0.1}\times 100$$

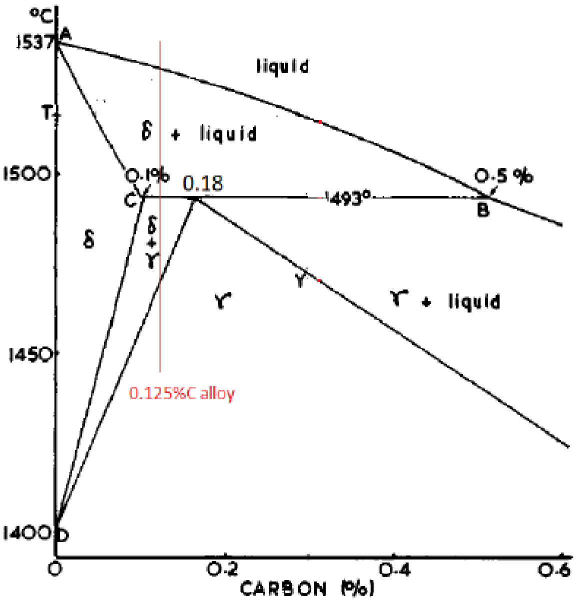
$\delta\%$ =93.7%

$$\text{liquid}\% = \frac{0.125-0.1}{0.5-0.1}\times 100$$

liquid% =6.3%

(b) below the peritectic isotherm

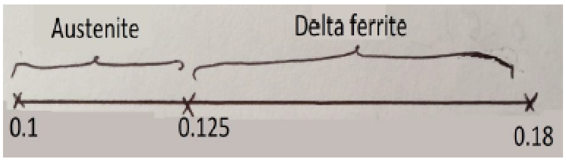


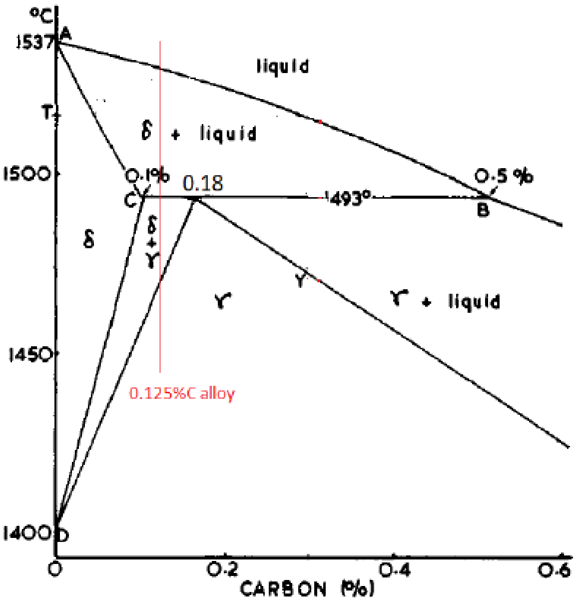


δ *composition*: 0.1% C

γ *composition*: 0.18% C

Thermal equilibrium diagram for Iron-iron carbide.





$$\delta\% = \frac{0.18-0.125}{0.18-0.1}\times 100$$

$\delta\%$ =68.7%

$$\gamma\% = \frac{0.125-0.1}{0.18-0.1}\times 100$$

$\gamma\%$ =31.3%

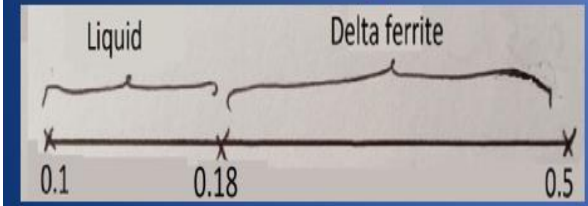
21. Thermal equilibrium diagram for Iron-iron carbide (2).

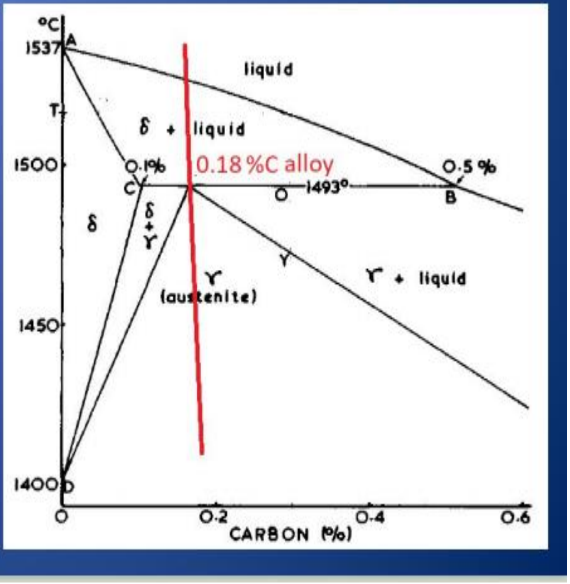
Example (7)

For the peritectic region of the iron-iron carbide phase diagram, determine the composition and relative amounts of each phase just above and just below the peritectic isotherm for 0.18% C alloy.

Solution:

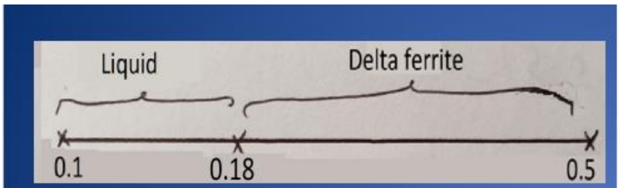
(a) Above the peritectic isotherm

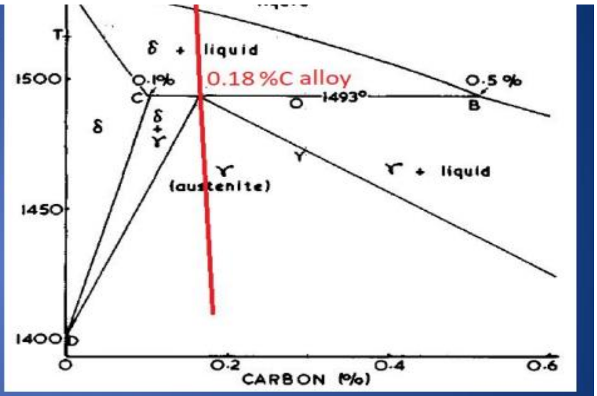




$\delta \; composition: 0.1\% \; C$

$liquid \; composition: 0.5 \; \% \; C$





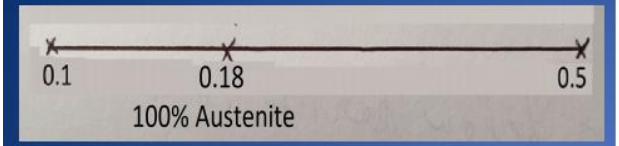
$$\delta\% = \frac{0.5 - 0.18}{0.5 - 0.1} \times 100$$

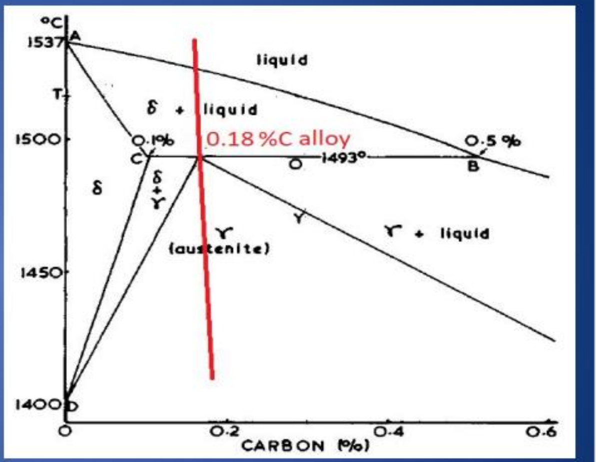
$$\delta\% = 80.0\%$$

$$\text{liquid}\% = \frac{0.18 - 0.1}{0.5 - 0.1} \times 100$$

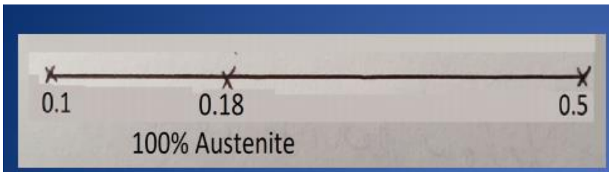
$$\text{liquid}\% = 20.0\%$$

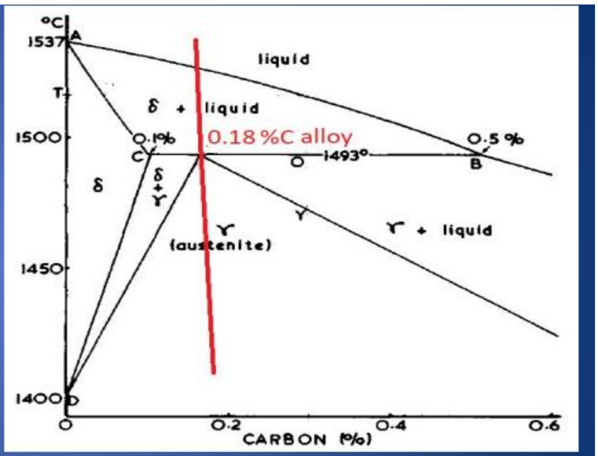
(b) below the peritectic isotherm





For alloy 0.18%C below the peritectic, there is only single phase γ :-



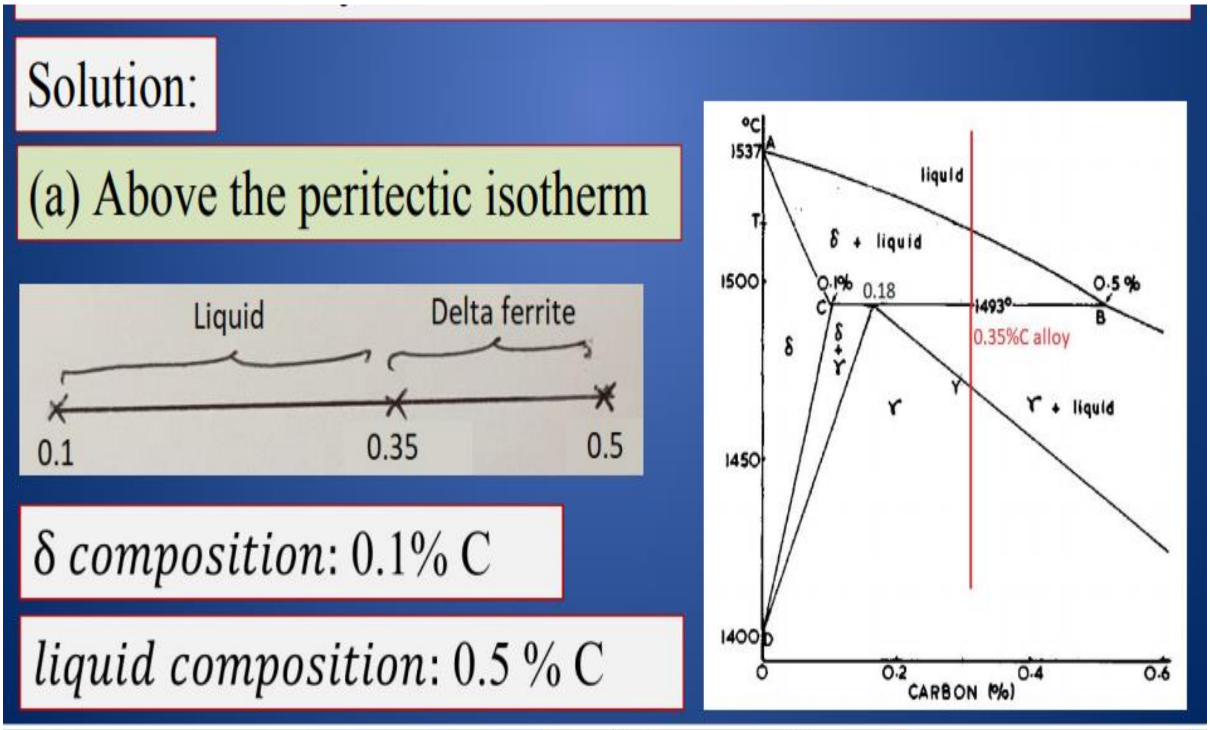


For alloy 0.18%C below the peritectic, there is only single phase γ :-

$\gamma = 100\%$ as the amount of austenite.

Example (8)

For the peritectic region of the iron-iron carbide phase diagram, determine the composition and relative amounts of each phase just above and just below the peritectic isotherm for 0.35% C alloy.

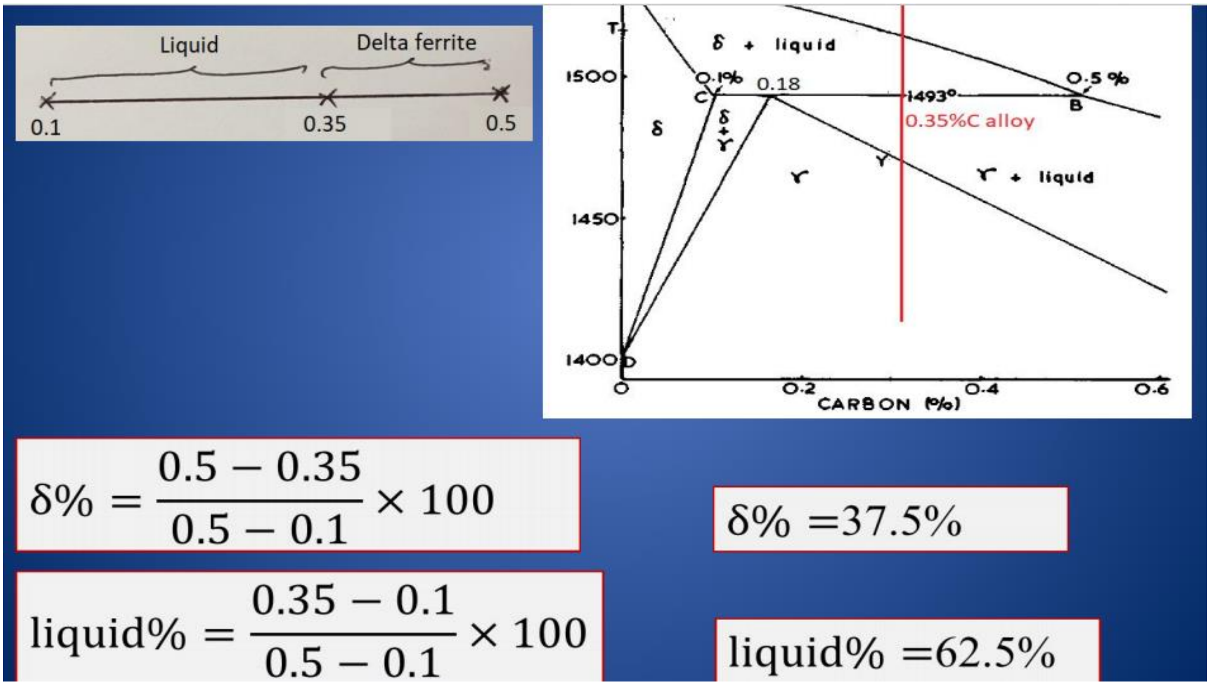


Solution:

(a) Above the peritectic isotherm

δ *composition*: 0.1% C

liquid composition: 0.5 % C

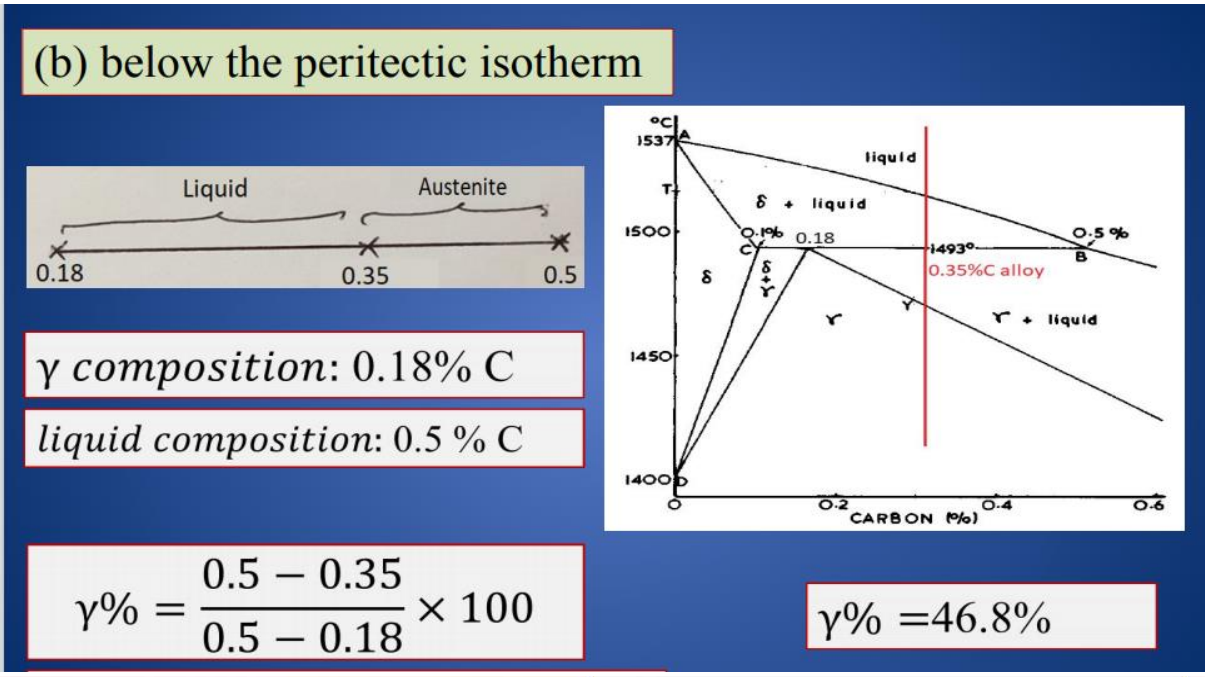


$$\delta\% = \frac{0.5 - 0.35}{0.5 - 0.1} \times 100$$

$\delta\%$ =37.5%

$$\text{liquid}\% = \frac{0.35 - 0.1}{0.5 - 0.1} \times 100$$

liquid% =62.5%



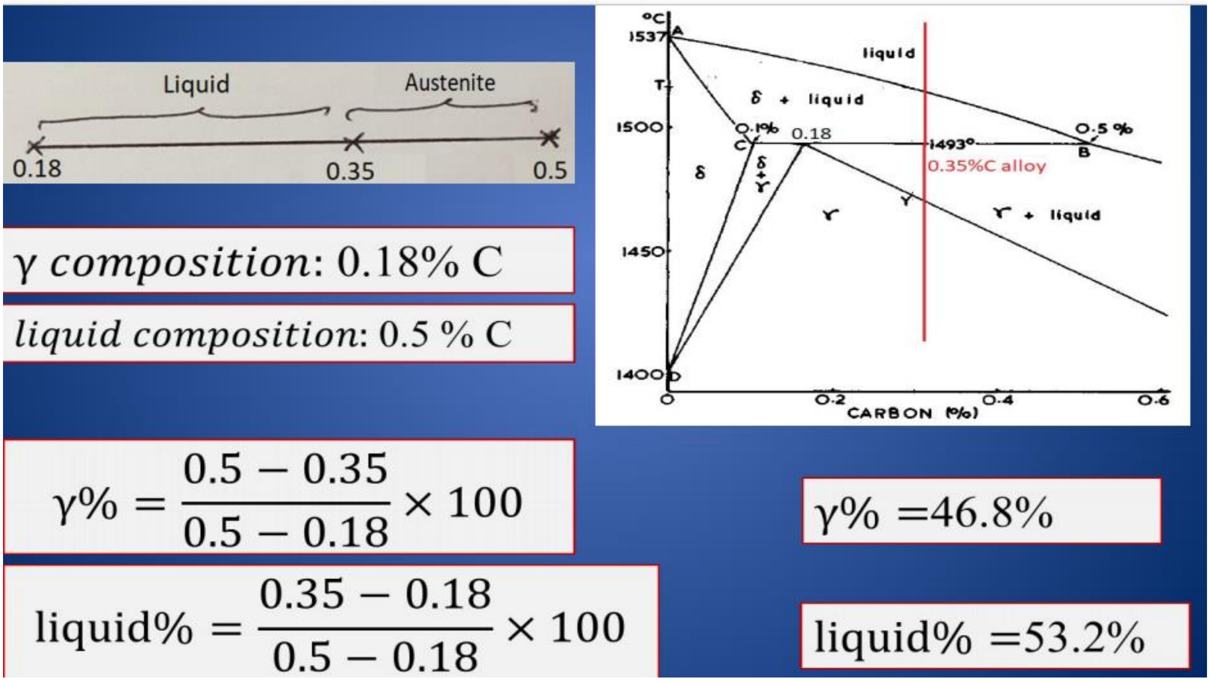
(b) below the peritectic isotherm

γ *composition*: 0.18% C

liquid composition: 0.5 % C

$$\gamma\% = \frac{0.5 - 0.35}{0.5 - 0.18} \times 100$$

$\gamma\%$ =46.8%



γ *composition*: 0.18% C

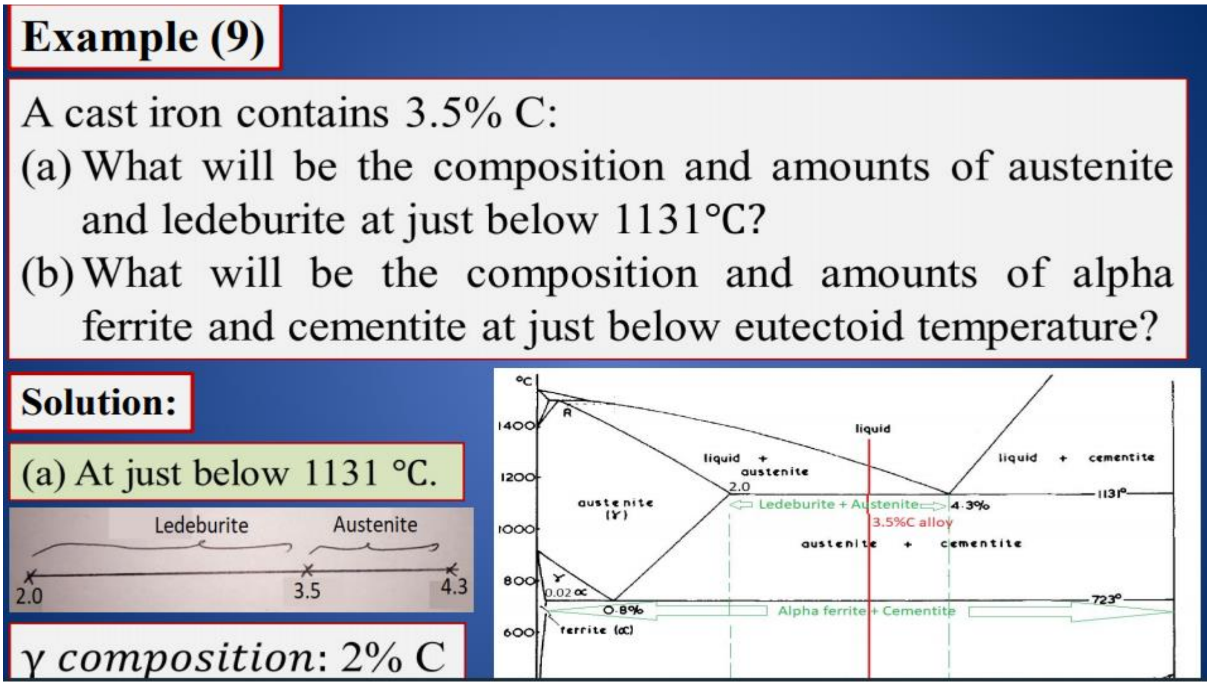
liquid composition: 0.5 % C

$$\gamma\% = \frac{0.5 - 0.35}{0.5 - 0.18} \times 100$$

$\gamma\%$ =46.8%

$$\text{liquid}\% = \frac{0.35 - 0.18}{0.5 - 0.18} \times 100$$

liquid% =53.2%



Example (9)

A cast iron contains 3.5% C:

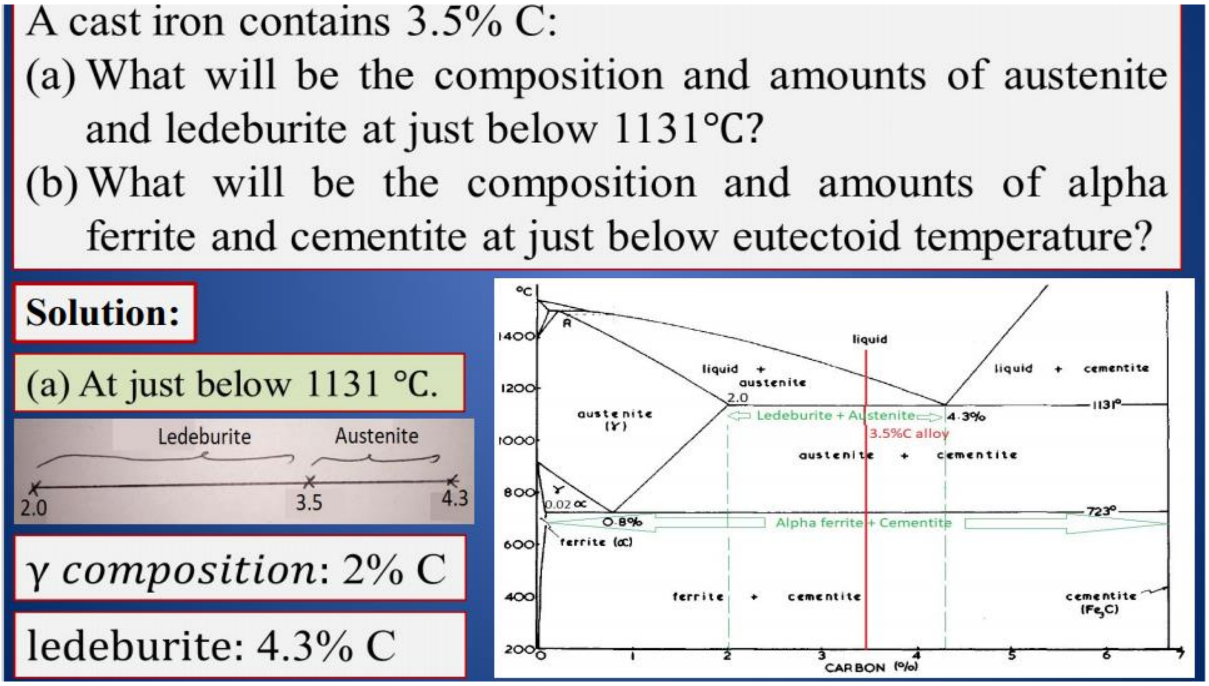
(a) What will be the composition and amounts of austenite and ledeburite at just below 1131°C?

(b) What will be the composition and amounts of alpha ferrite and cementite at just below eutectoid temperature?

Solution:

(a) At just below 1131 °C.

γ *composition*: 2% C



A cast iron contains 3.5% C:

(a) What will be the composition and amounts of austenite and ledeburite at just below 1131°C?

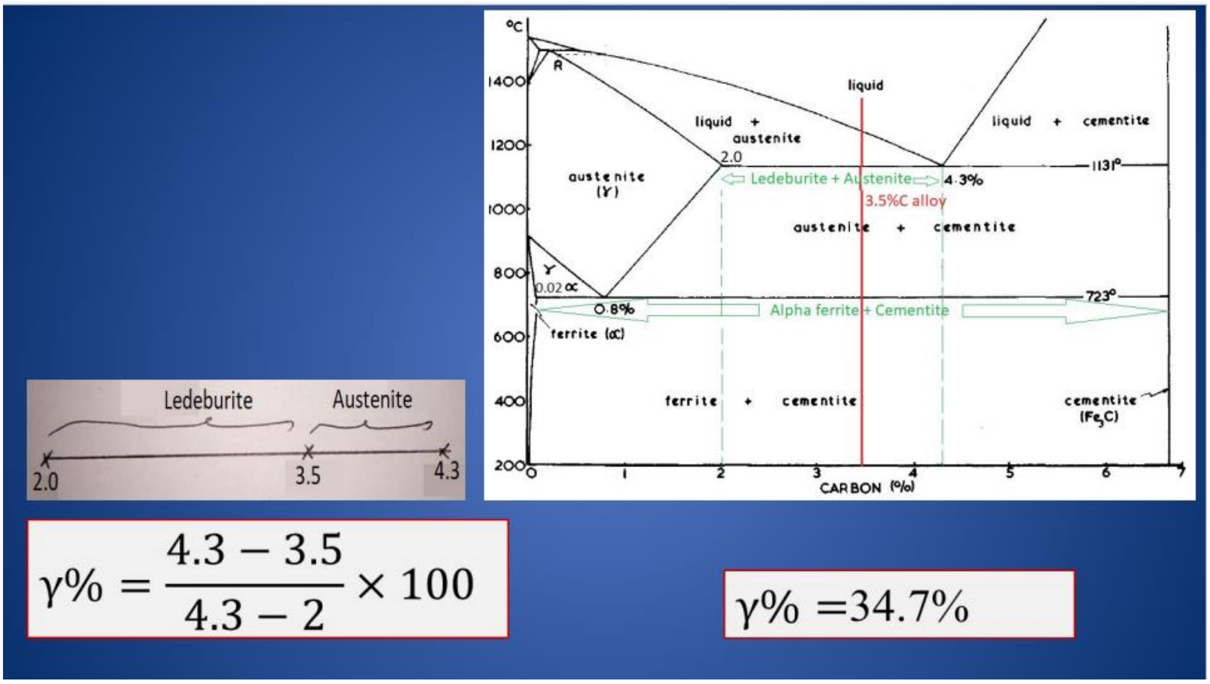
(b) What will be the composition and amounts of alpha ferrite and cementite at just below eutectoid temperature?

Solution:

(a) At just below 1131 °C.

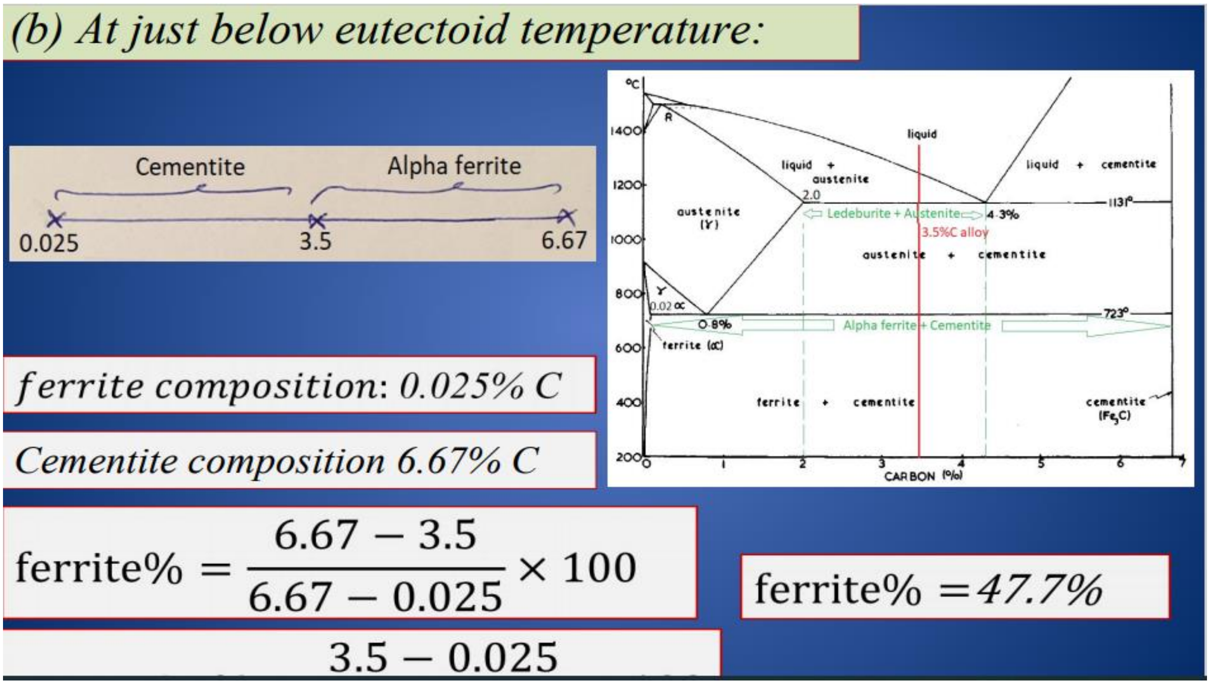
γ *composition*: 2% C

ledeburite: 4.3% C



$$\gamma\% = \frac{4.3 - 3.5}{4.3 - 2} \times 100$$

$\gamma\% = 34.7\%$



(b) *At just below eutectoid temperature:*

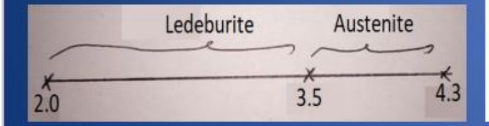
ferrite composition: *0.025% C*

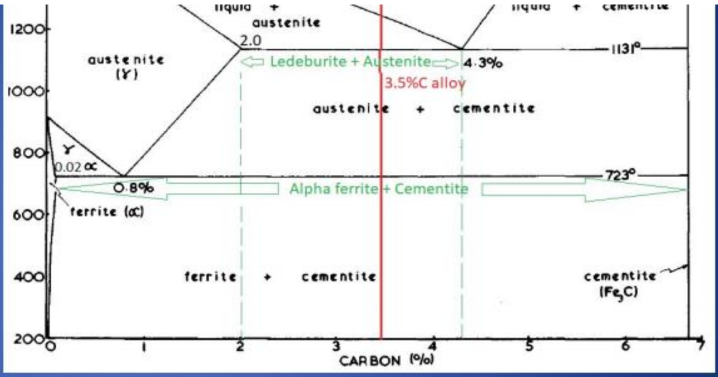
Cementite composition 6.67% C

$$\text{ferrite}\% = \frac{6.67 - 3.5}{6.67 - 0.025} \times 100$$

ferrite% = *47.7%*

$$3.5 - 0.025$$





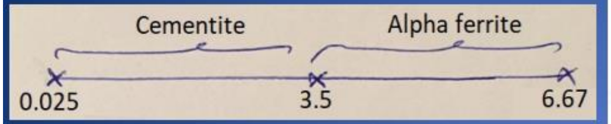
$$\gamma\% = \frac{4.3 - 3.5}{4.3 - 2} \times 100$$

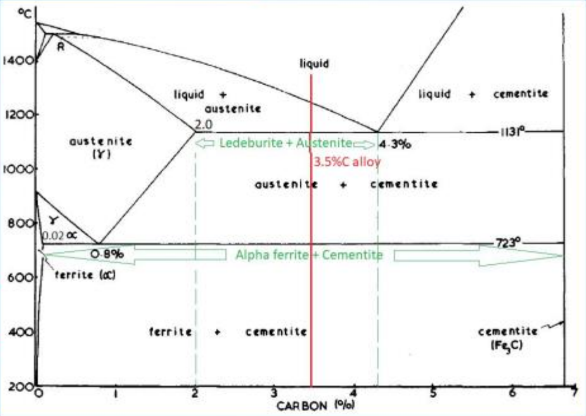
$\gamma\%$ =34.7%

$$ledeburite\% = \frac{3.5 - 2}{4.3 - 2} \times 100$$

$ledeburite\%$ =65.3%

(b) At just below eutectoid temperature:





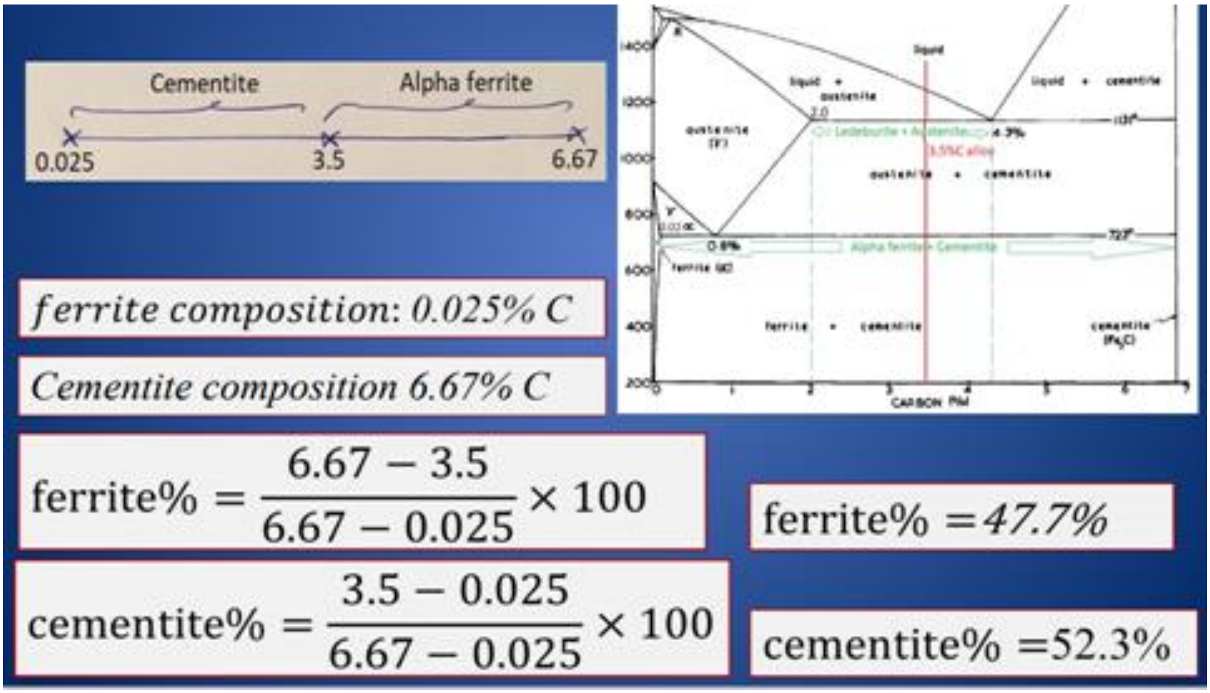
ferrite composition: *0.025% C*

Cementite composition 6.67% C

$$\text{ferrite}\% = \frac{6.67 - 3.5}{6.67 - 0.025} \times 100$$

ferrite% =*47.7%*

$$3.5 - 0.025$$



ferrite composition: 0.025% C

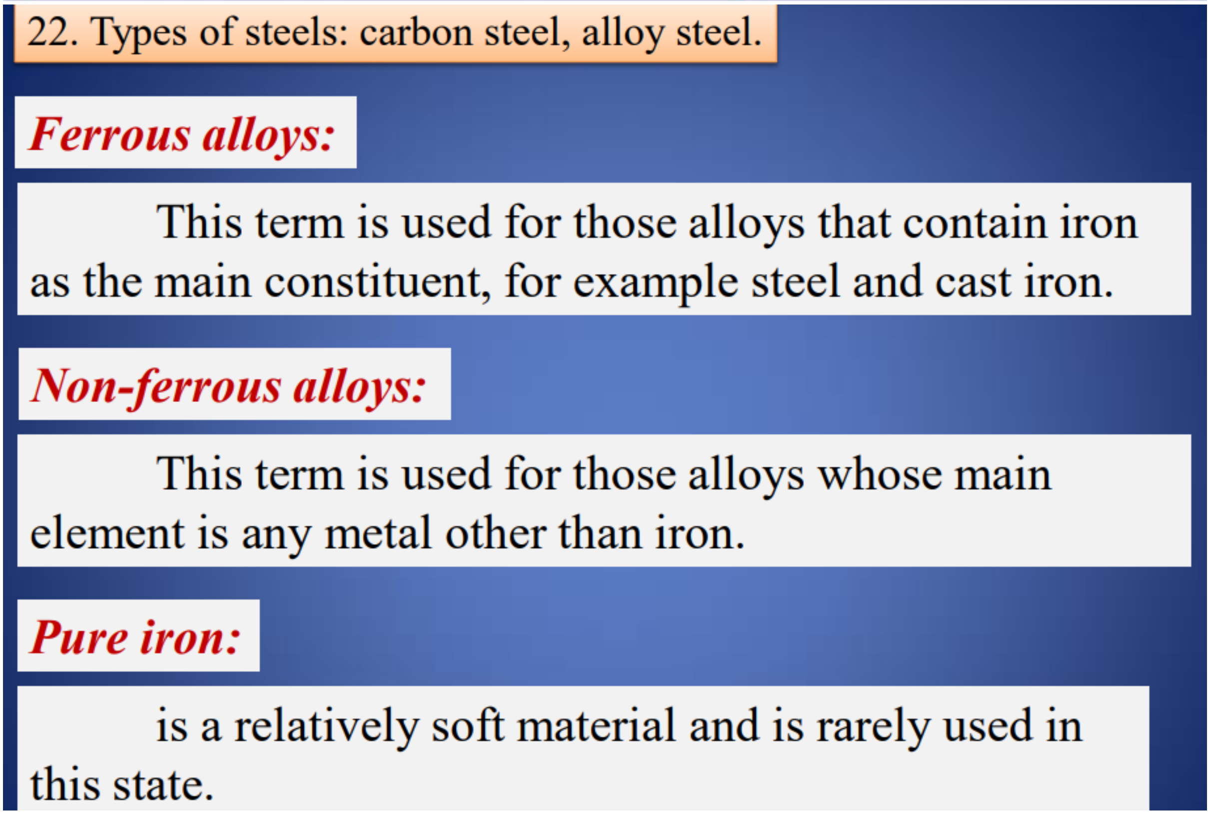
Cementite composition 6.67% C

$$\text{ferrite\%} = \frac{6.67 - 3.5}{6.67 - 0.025} \times 100$$

ferrite% = *47.7%*

$$\text{cementite\%} = \frac{3.5 - 0.025}{6.67 - 0.025} \times 100$$

cementite% =52.3%



22. Types of steels: carbon steel, alloy steel.

Ferrous alloys:

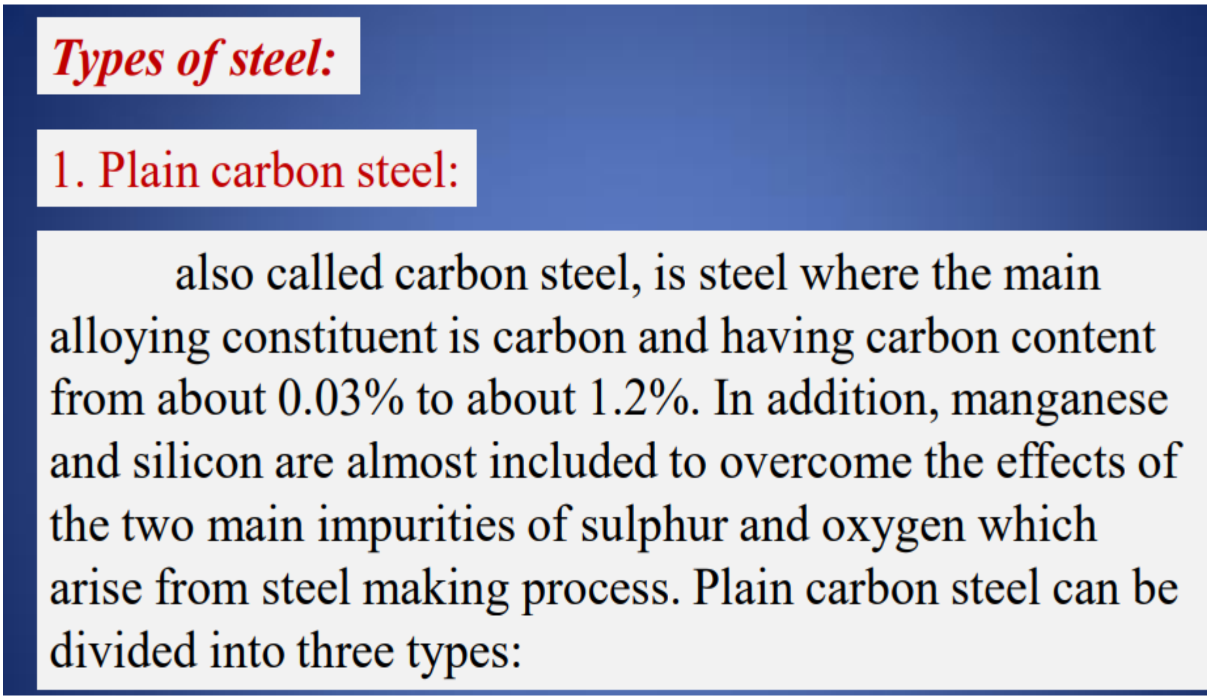
This term is used for those alloys that contain iron as the main constituent, for example steel and cast iron.

Non-ferrous alloys:

This term is used for those alloys whose main element is any metal other than iron.

Pure iron:

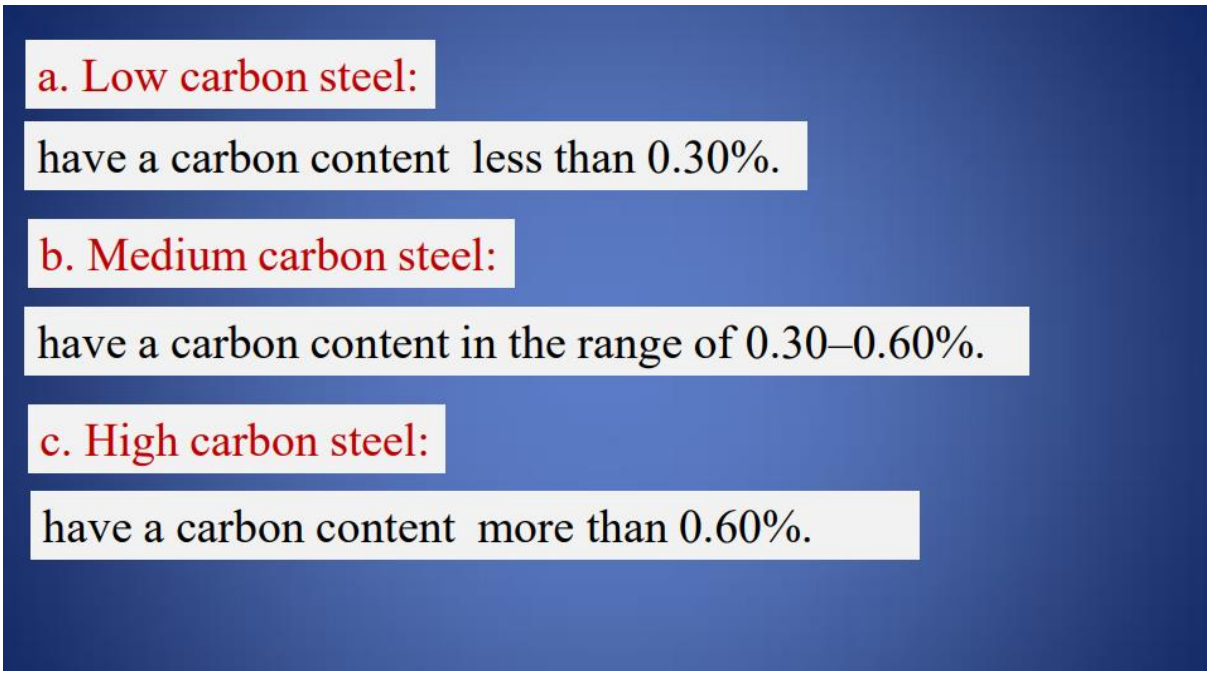
is a relatively soft material and is rarely used in this state.



Types of steel:

1. Plain carbon steel:

also called carbon steel, is steel where the main alloying constituent is carbon and having carbon content from about 0.03% to about 1.2%. In addition, manganese and silicon are almost included to overcome the effects of the two main impurities of sulphur and oxygen which arise from steel making process. Plain carbon steel can be divided into three types:



a. Low carbon steel:

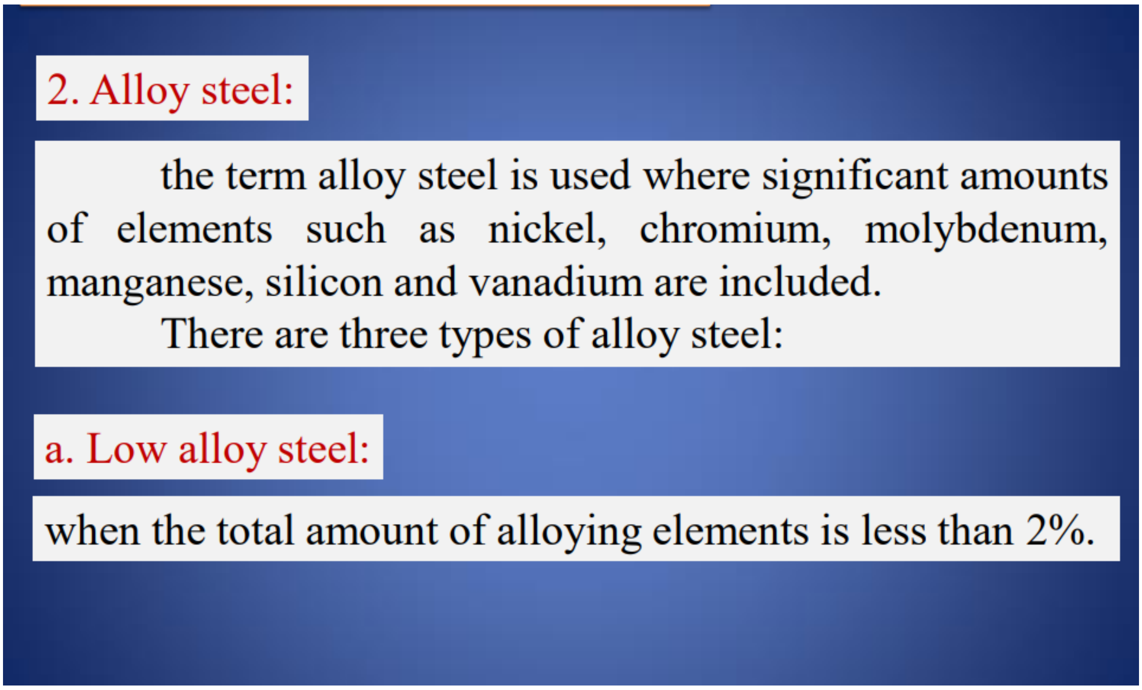
have a carbon content less than 0.30%.

b. Medium carbon steel:

have a carbon content in the range of 0.30–0.60%.

c. High carbon steel:

have a carbon content more than 0.60%.



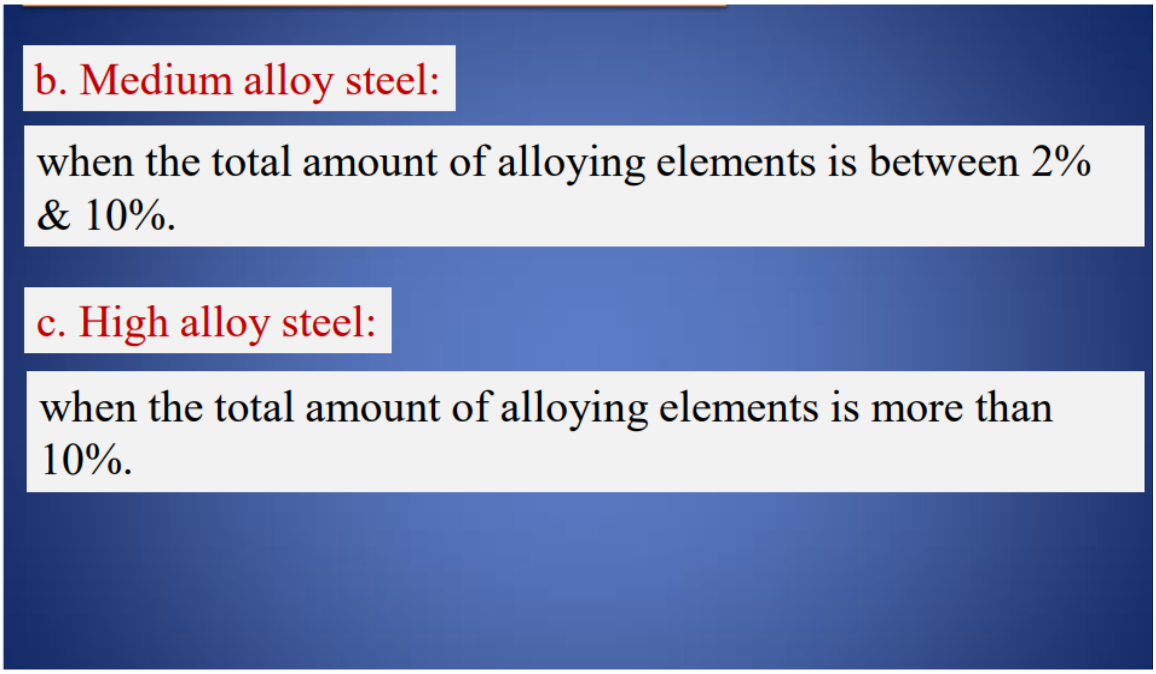
2. Alloy steel:

the term alloy steel is used where significant amounts of elements such as nickel, chromium, molybdenum, manganese, silicon and vanadium are included.

There are three types of alloy steel:

a. Low alloy steel:

when the total amount of alloying elements is less than 2%.



b. Medium alloy steel:

when the total amount of alloying elements is between 2% & 10%.

c. High alloy steel:

when the total amount of alloying elements is more than 10%.

Impurities in steel

1. Manganese:

a. It is soluble in austenite and ferrite and forms a stable carbide, Mn_3C.

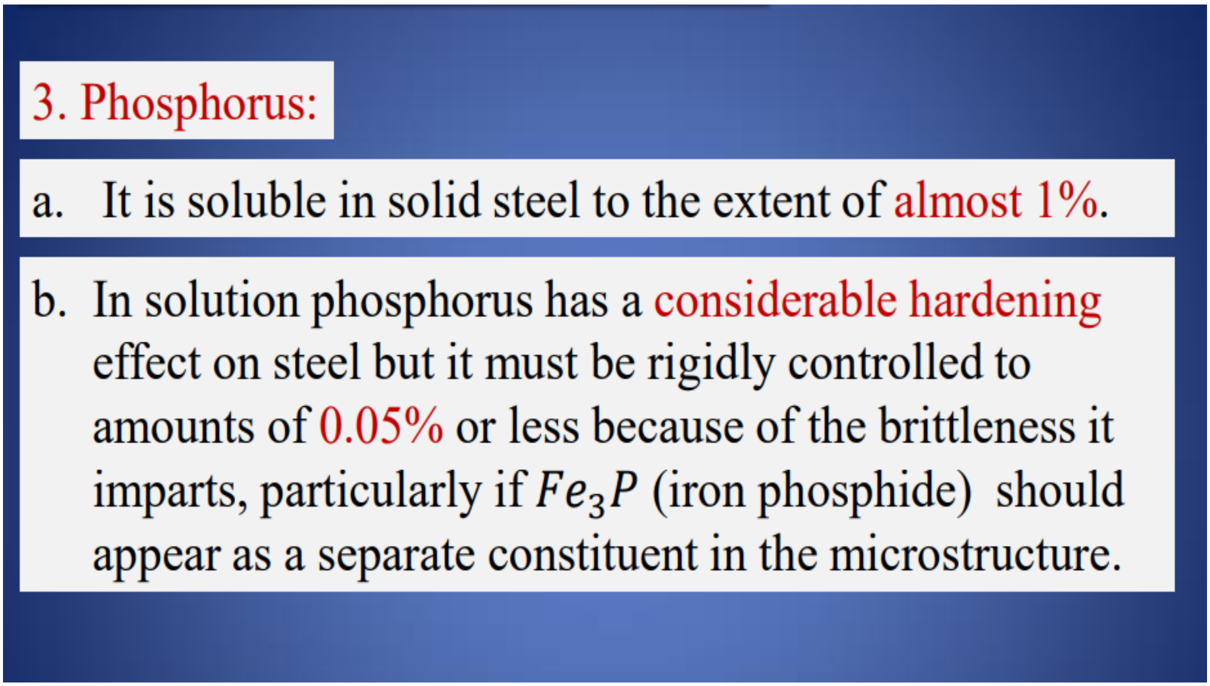
b. Manganese increases the depth of hardening of a steel. It also improves strength and toughness.

c. Manganese should not exceed 0.3% in high-carbon steels because of a tendency to induce quench cracks particularly during water-quenching.

2. Silicon:

a. It imparts fluidity to steels intended for the manufacture of castings in amounts up to 0.3%.

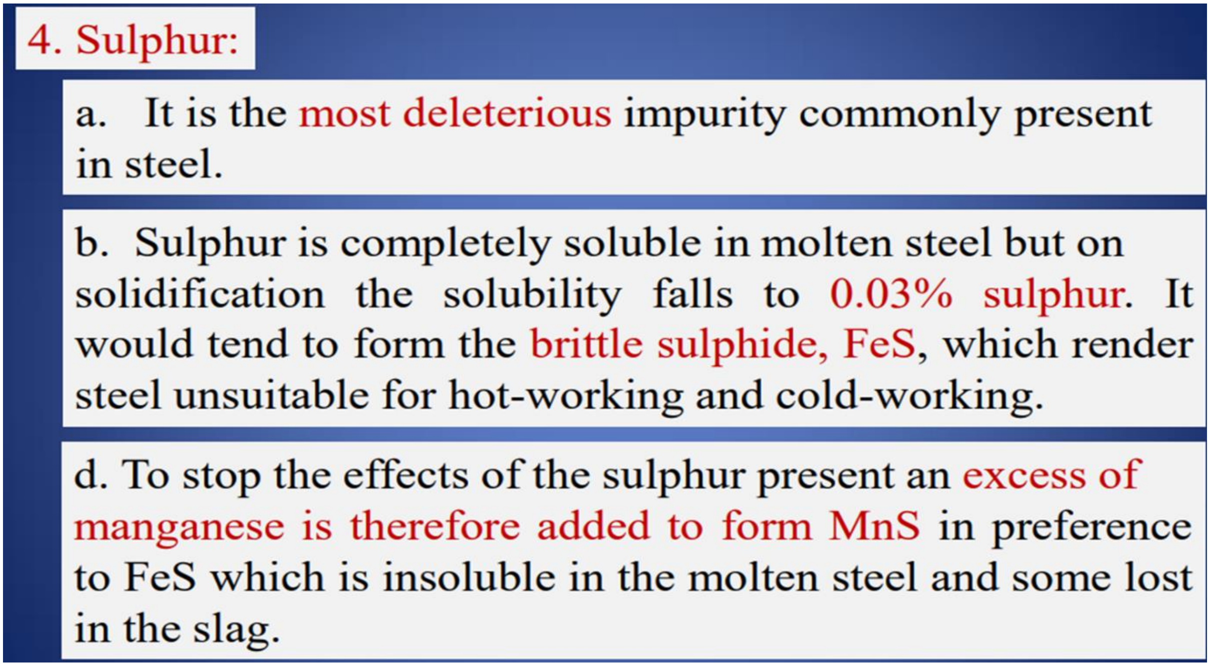
b. In high-carbon steels silicon must be kept low, because of its tendency to render cementite unstable and liable to decompose into graphite and ferrite.



3. Phosphorus:

a. It is soluble in solid steel to the extent of almost 1%.

b. In solution phosphorus has a considerable hardening effect on steel but it must be rigidly controlled to amounts of 0.05% or less because of the brittleness it imparts, particularly if Fe_3P (iron phosphide) should appear as a separate constituent in the microstructure.

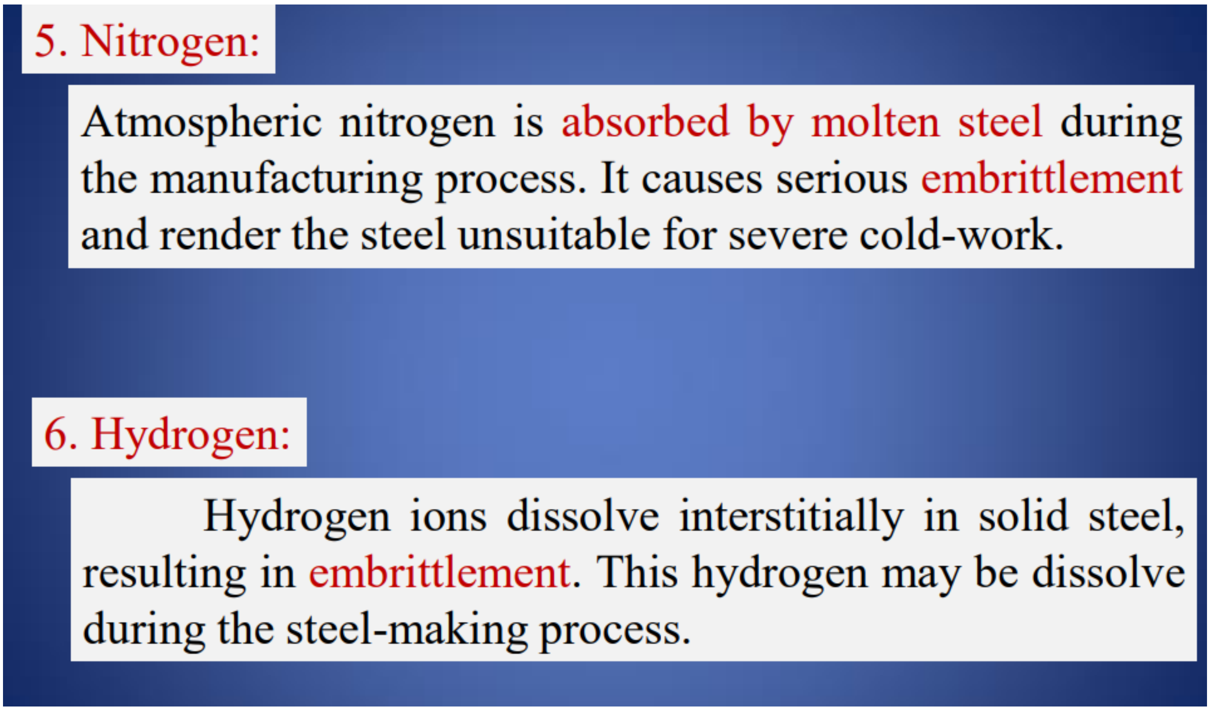


4. Sulphur:

a. It is the most deleterious impurity commonly present in steel.

b. Sulphur is completely soluble in molten steel but on solidification the solubility falls to 0.03% sulphur. It would tend to form the brittle sulphide, FeS, which render steel unsuitable for hot-working and cold-working.

d. To stop the effects of the sulphur present an excess of manganese is therefore added to form MnS in preference to FeS which is insoluble in the molten steel and some lost in the slag.

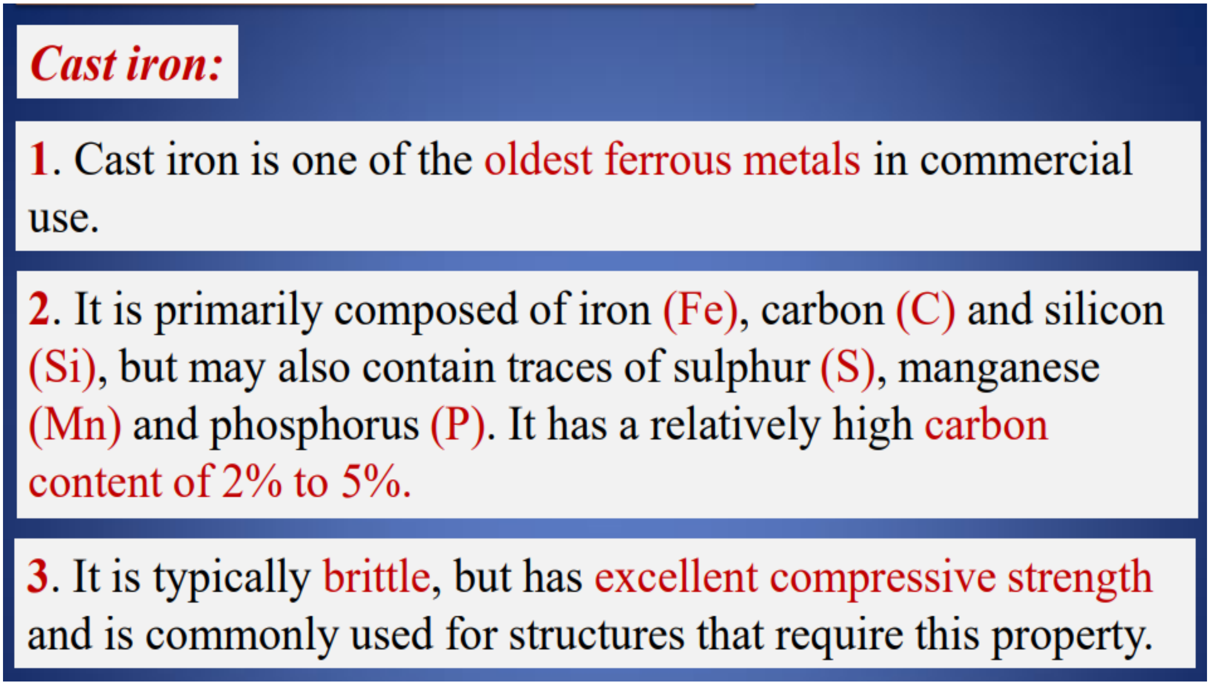


5. Nitrogen:

Atmospheric nitrogen is absorbed by molten steel during the manufacturing process. It causes serious embrittlement and render the steel unsuitable for severe cold-work.

6. Hydrogen:

Hydrogen ions dissolve interstitially in solid steel, resulting in embrittlement. This hydrogen may be dissolve during the steel-making process.

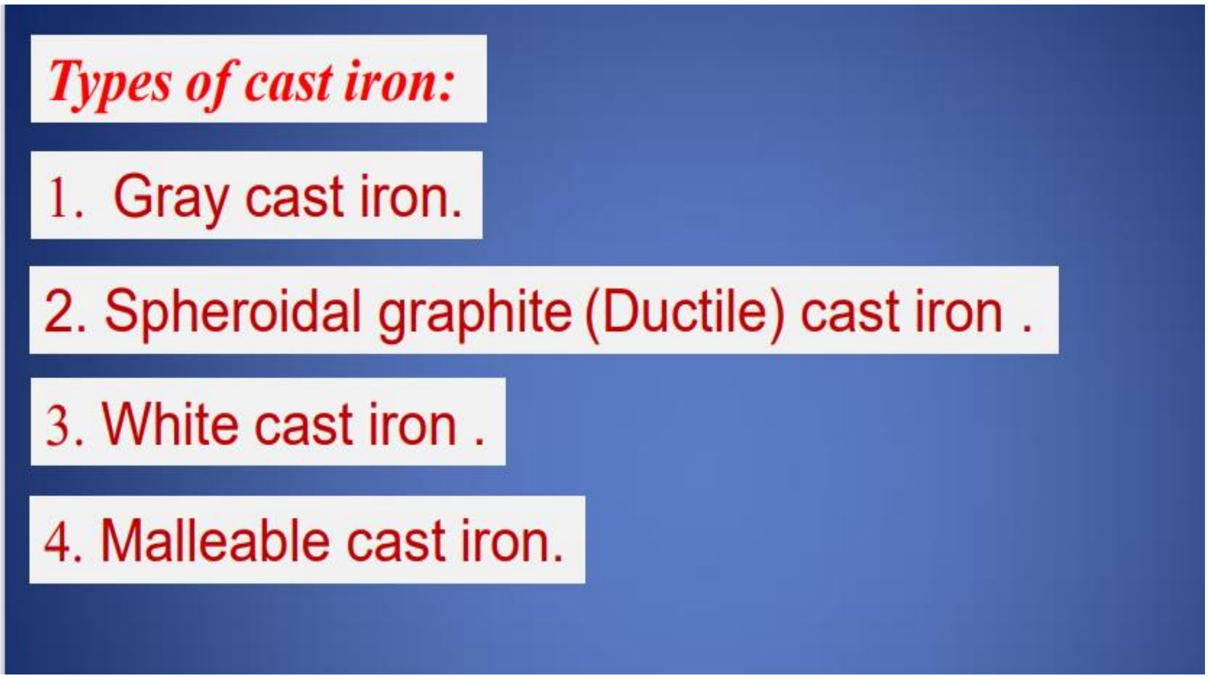


Cast iron:

1. Cast iron is one of the oldest ferrous metals in commercial use.

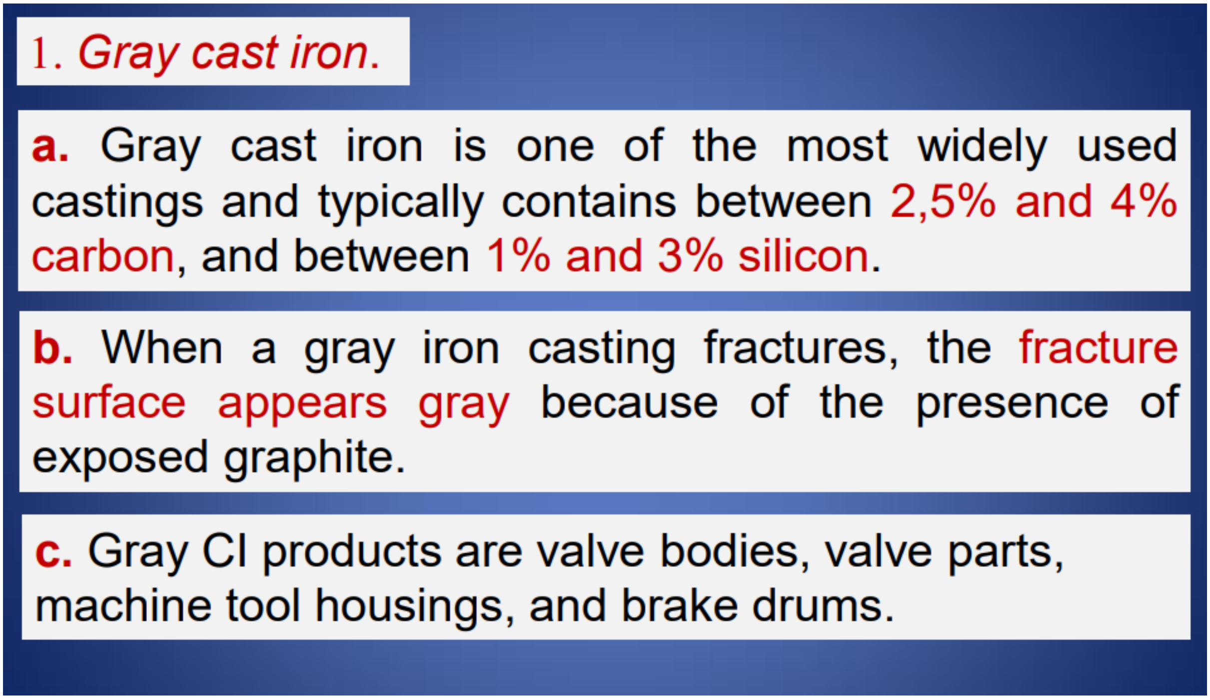
2. It is primarily composed of iron (Fe), carbon (C) and silicon (Si), but may also contain traces of sulphur (S), manganese (Mn) and phosphorus (P). It has a relatively high carbon content of 2% to 5%.

3. It is typically brittle, but has excellent compressive strength and is commonly used for structures that require this property.



Types of cast iron:

1. Gray cast iron.
2. Spheroidal graphite (Ductile) cast iron .
3. White cast iron .
4. Malleable cast iron.



1. *Gray cast iron.*

a. Gray cast iron is one of the most widely used castings and typically contains between 2,5% and 4% carbon, and between 1% and 3% silicon.

b. When a gray iron casting fractures, the fracture surface appears gray because of the presence of exposed graphite.

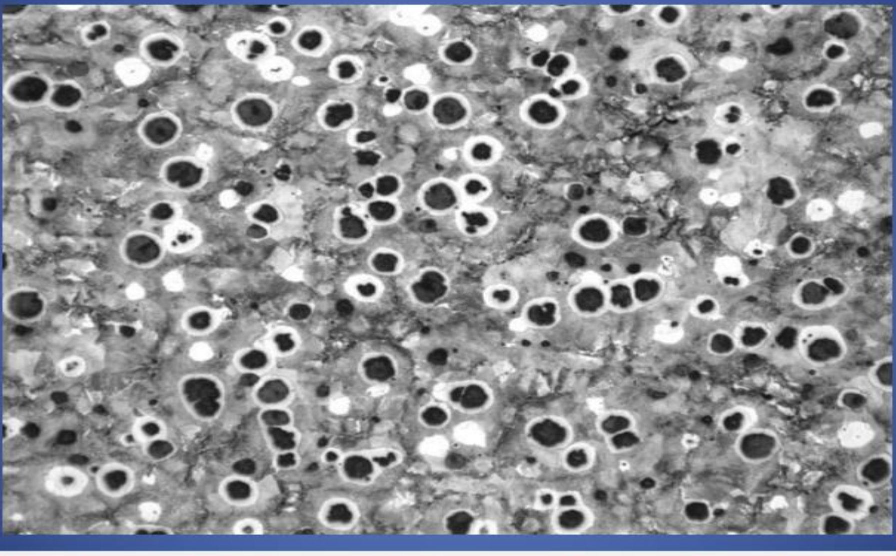
c. Gray CI products are valve bodies, valve parts, machine tool housings, and brake drums.

Gray cast iron microstructure

2. *Spheroidal graphite (Ductile) cast iron .*

a. Ductile cast iron, also known as nodular iron or spheroidal graphite iron, the free graphite precipitates from the melt as spherical particles rather than flakes, This is accomplished through the addition of small amounts of magnesium or cerium, resulting in higher strength and toughness compared with gray cast iron of similar composition.

b. It is widely used in crankshafts.



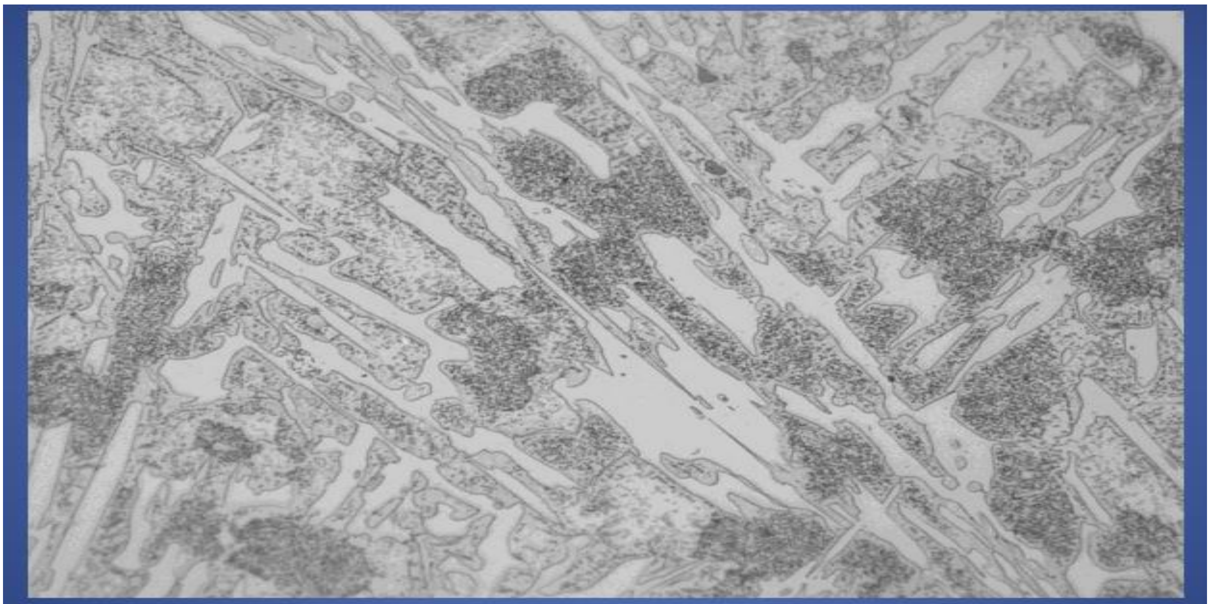
Spheroidal cast iron microstructure

3. *White cast iron .*

a. White CIs are hard and brittle and cannot be machined easily. White CI is the only member of the CI family in which carbon is present only as carbides. Because of the absence of graphite, it has a light appearance.

b. Most white cast irons contain less than 4.3% carbon, with low silicon contents to inhibit the precipitation of carbon as graphite.

c. White cast iron derives its name from the white, crystalline crack surface observed when a casting fractures.



White Cast Iron Microstructure

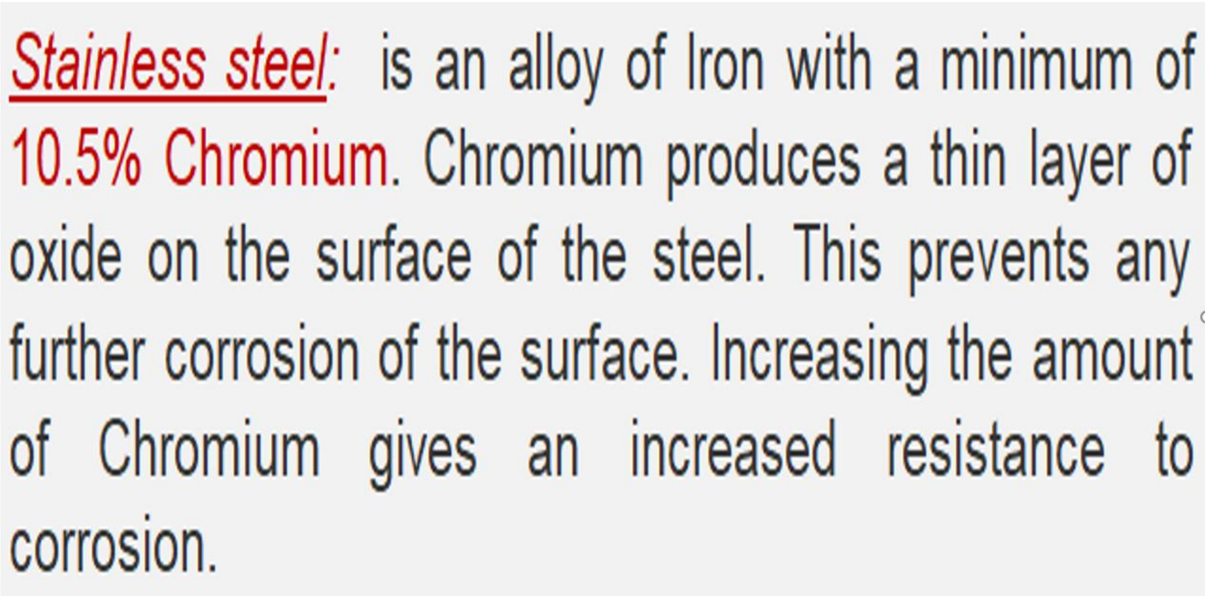
4. Malleable cast iron.

a. The microstructure provides properties that make malleable irons ideal for applications where toughness and machinability are required,

b. Malleable cast iron is produced by heat treating white cast iron.

c. Malleable cast iron has been widely used for automotive, agricultural and railroad equipment; and pipe fittings.

Malleable Cast Iron Microstructure



Stainless steel: is an alloy of Iron with a minimum of 10.5% Chromium. Chromium produces a thin layer of oxide on the surface of the steel. This prevents any further corrosion of the surface. Increasing the amount of Chromium gives an increased resistance to corrosion.

Heat Treatments of Steel

Part 1 Annealing & Normalizing

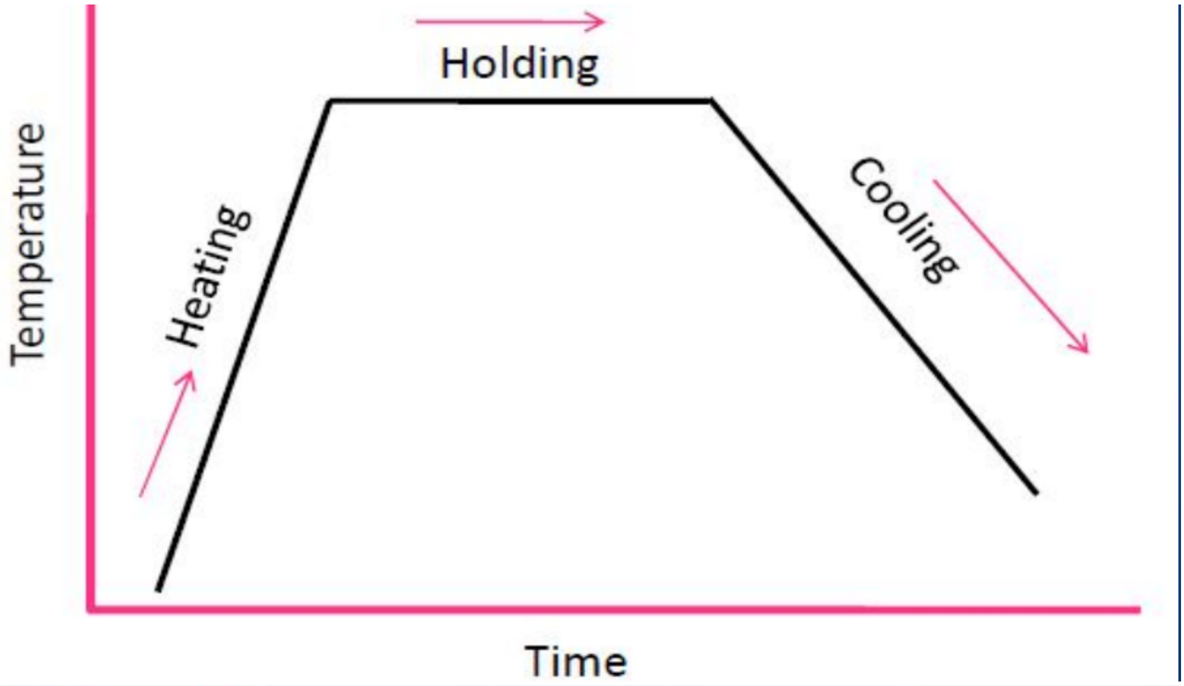
Heat treatment:

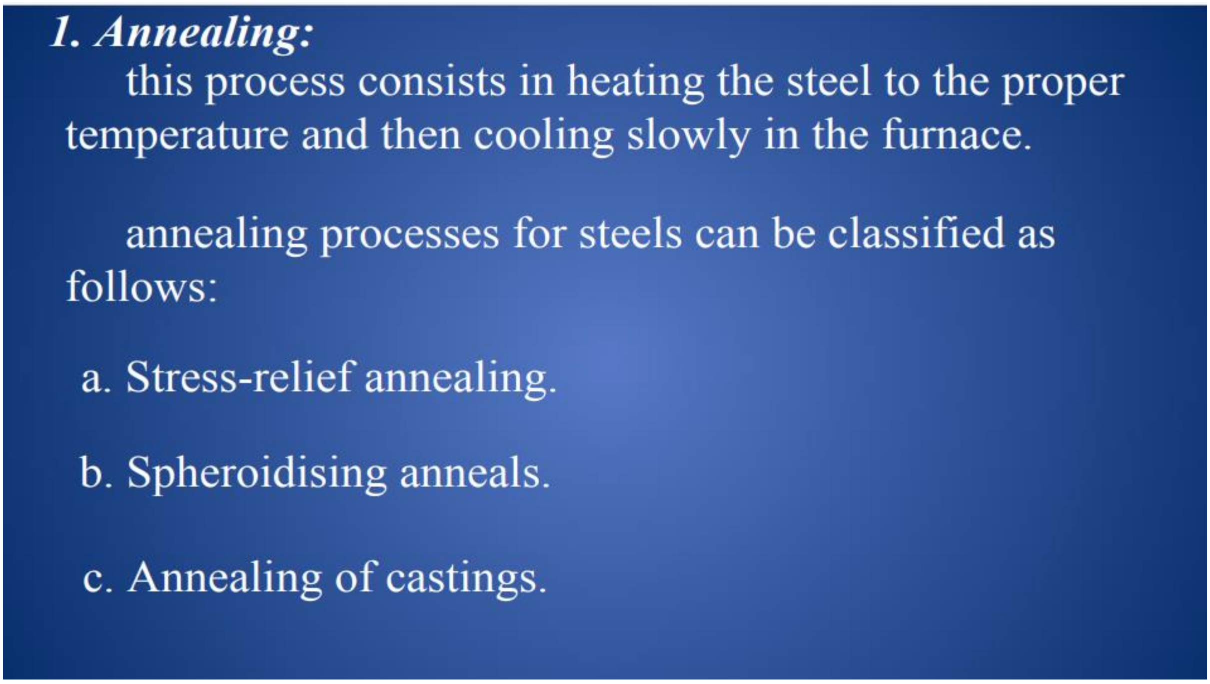
a combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties.

Types of Heat treatment:

the various heat-treatment processes can be classified as follows:

1. Annealing.
2. Normalising.
3. Hardening.
4. Tempering.




1. Annealing:

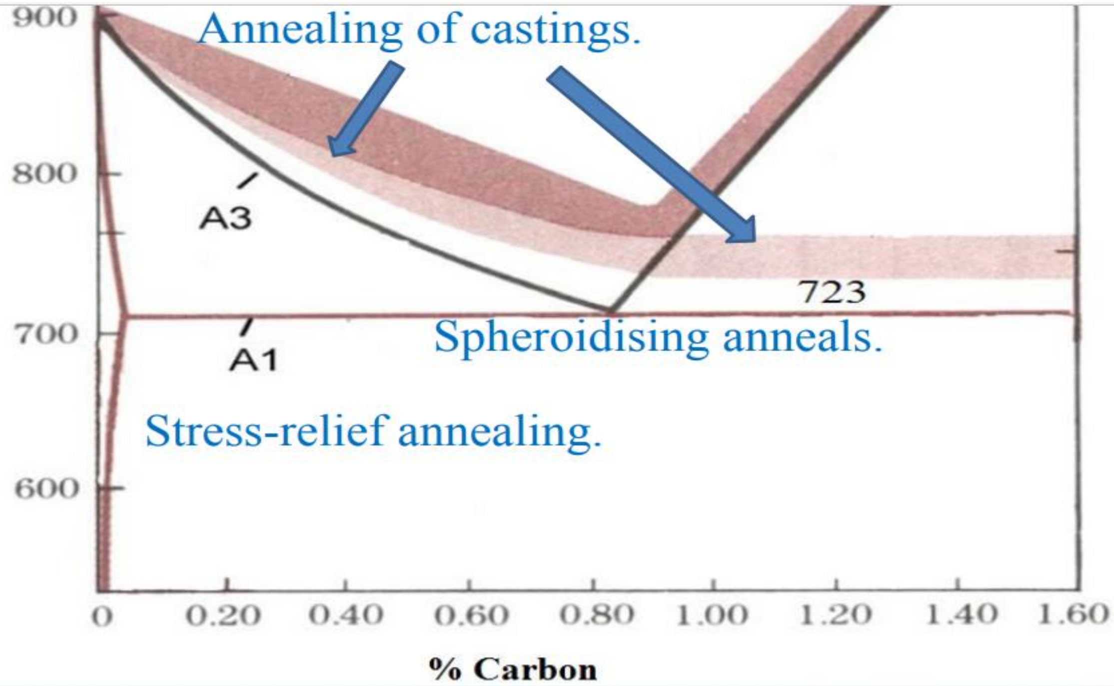
this process consists in heating the steel to the proper temperature and then cooling slowly in the furnace.

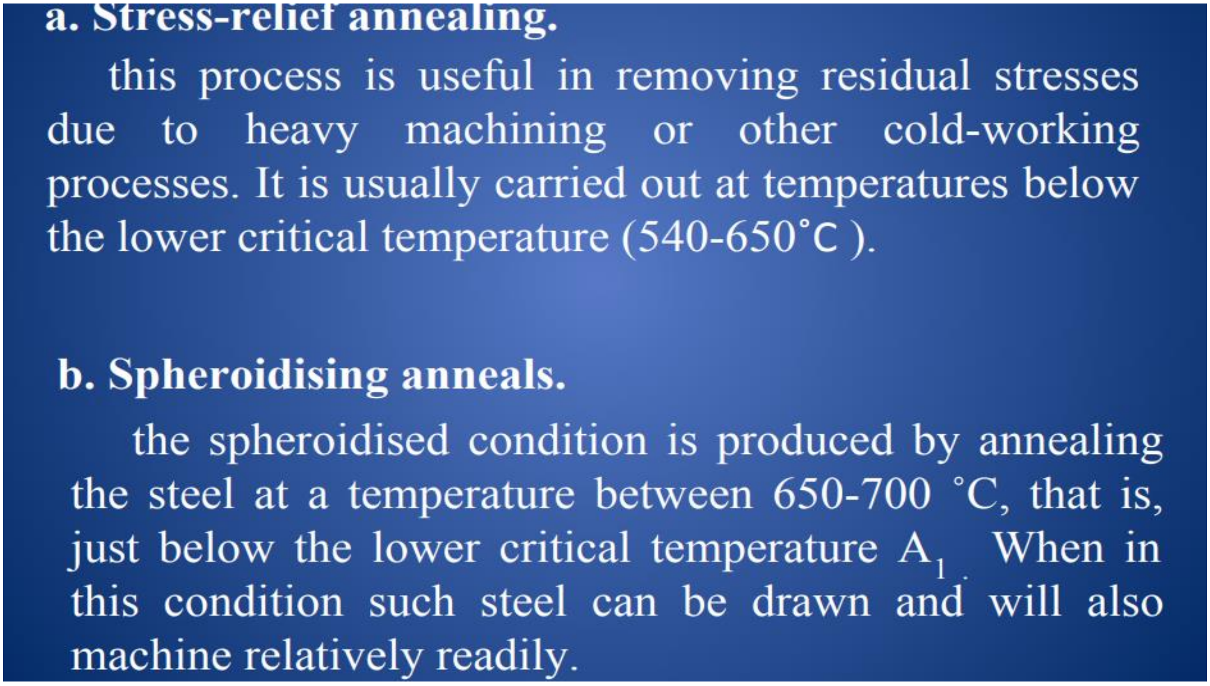
annealing processes for steels can be classified as follows:

a. Stress-relief annealing.

b. Spheroidising anneals.

c. Annealing of castings.

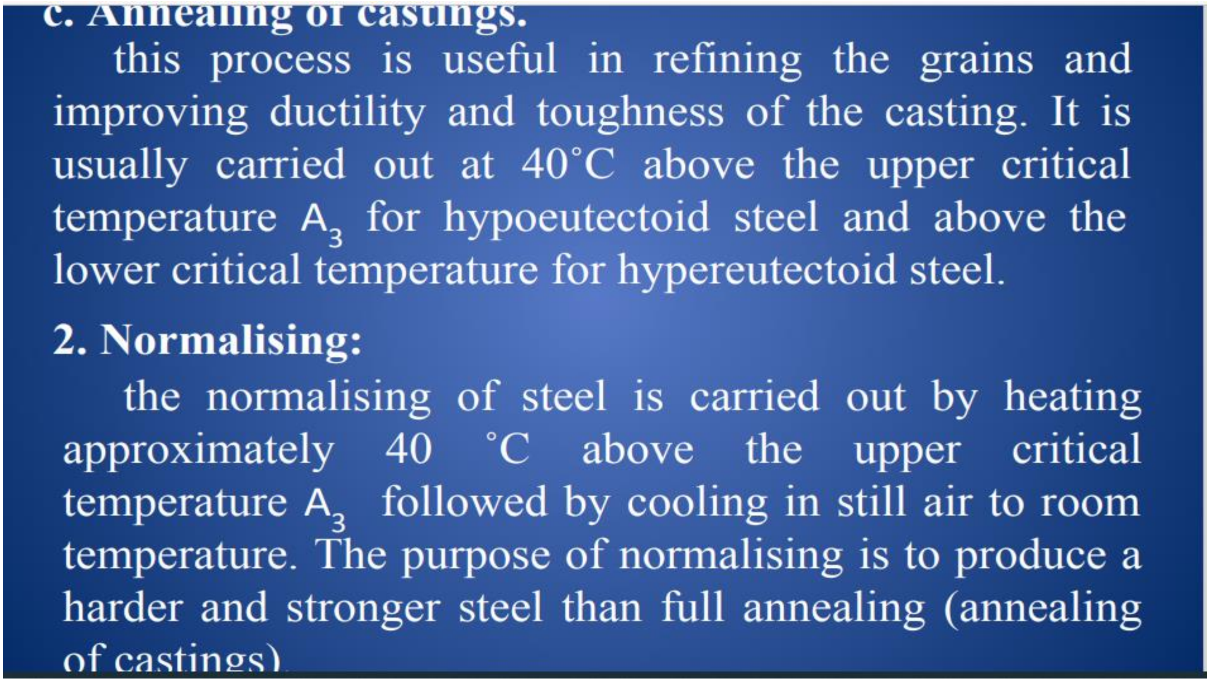



a. Stress-relief annealing.

this process is useful in removing residual stresses due to heavy machining or other cold-working processes. It is usually carried out at temperatures below the lower critical temperature (540-650˚C).

b. Spheroidising anneals.

the spheroidised condition is produced by annealing the steel at a temperature between 650-700 ˚C, that is, just below the lower critical temperature A_1. When in this condition such steel can be drawn and will also machine relatively readily.

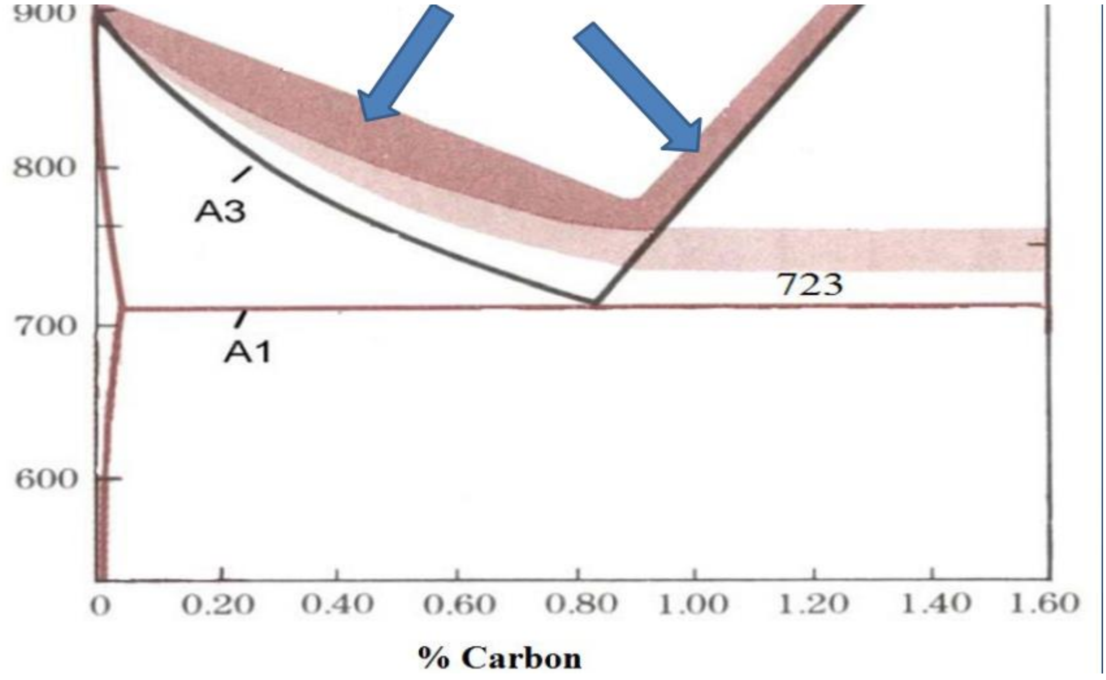


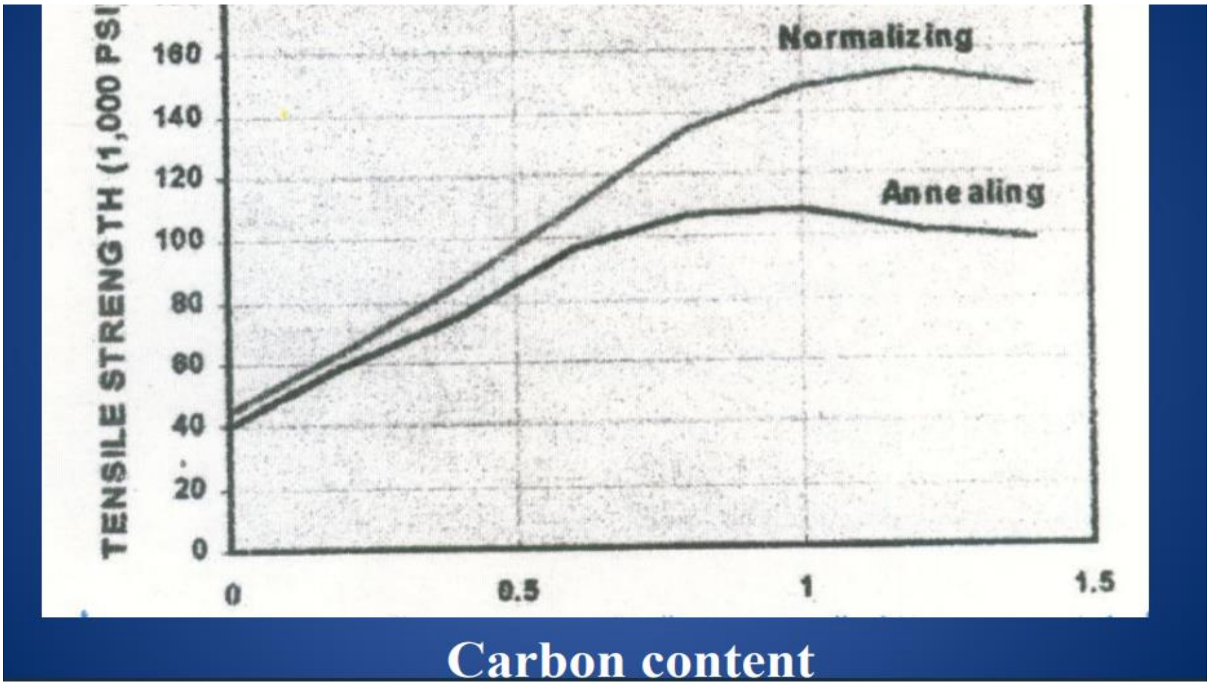
c. Annealing of castings.

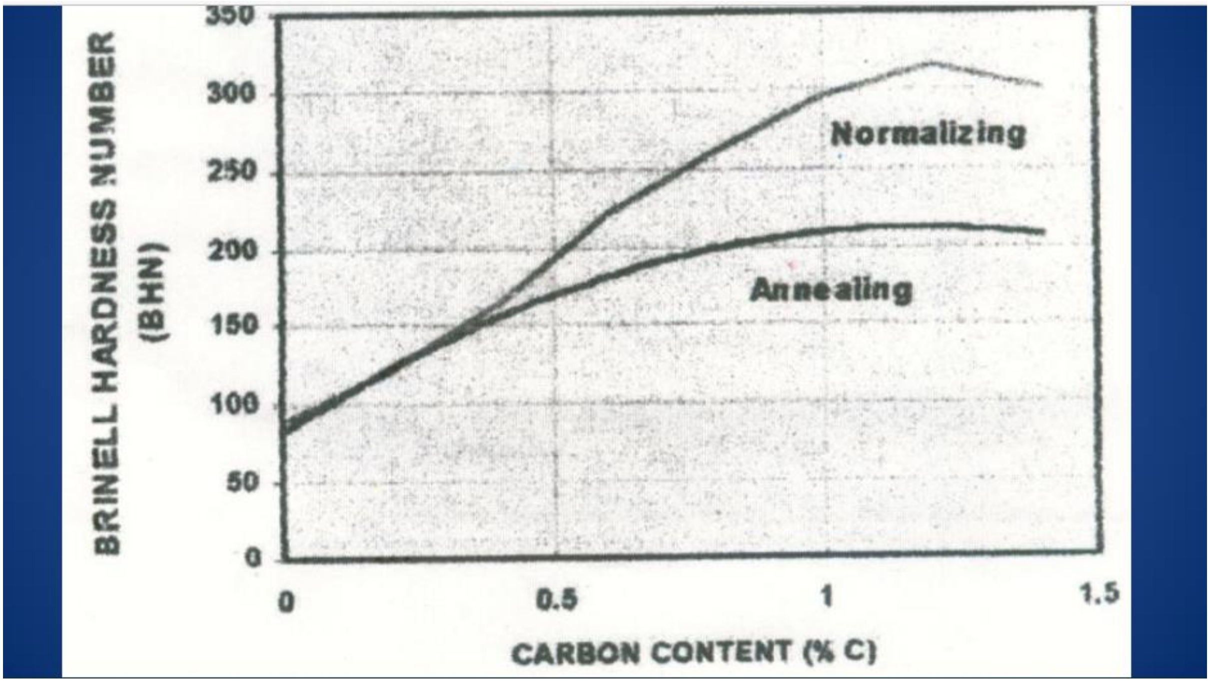
this process is useful in refining the grains and improving ductility and toughness of the casting. It is usually carried out at 40˚C above the upper critical temperature A_3 for hypoeutectoid steel and above the lower critical temperature for hypereutectoid steel.

2. Normalising:

the normalising of steel is carried out by heating approximately 40 ˚C above the upper critical temperature A_3 followed by cooling in still air to room temperature. The purpose of normalising is to produce a harder and stronger steel than full annealing (annealing of castings).

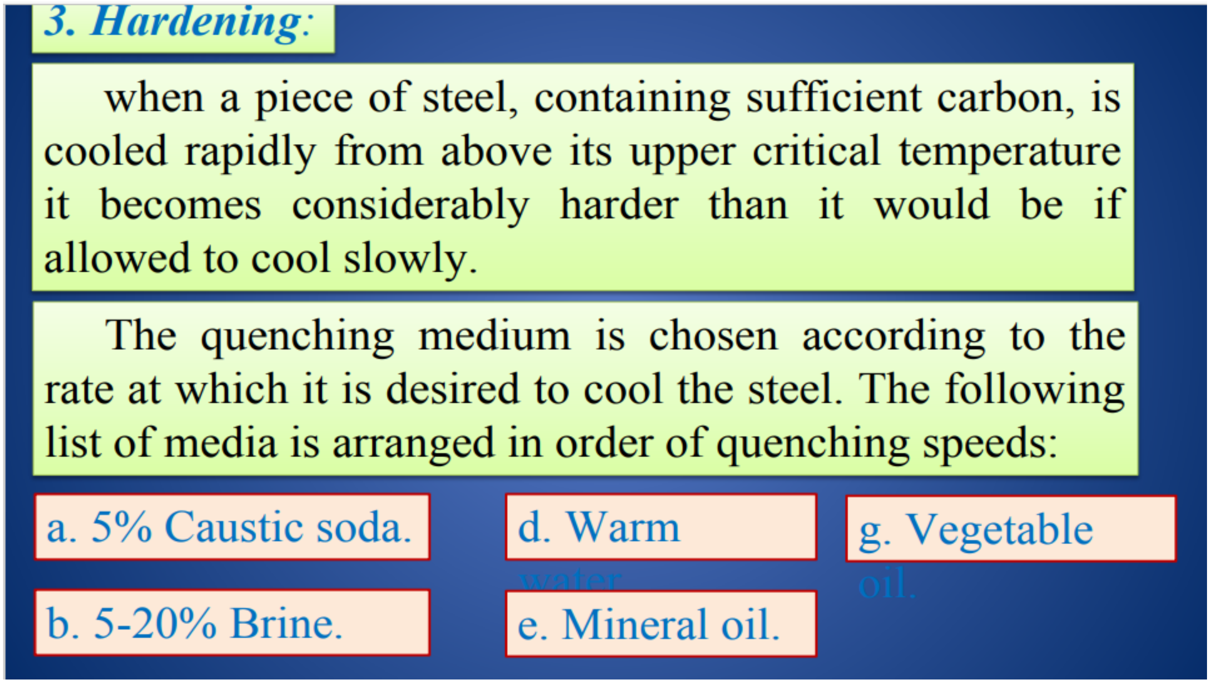



TENSILE STRENGTH (1,000 PSI
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
Normalizing
Annealing
Carbon content


BRINELL HARDNESS NUMBER (BHN)
350
300
250
200
150
100
50
0
0
0.5
1
1.5
Normalizing
Annealing
CARBON CONTENT (% C)

Heat Treatments of Steel

Hardening & Tempering



3. Hardening:

when a piece of steel, containing sufficient carbon, is cooled rapidly from above its upper critical temperature it becomes considerably harder than it would be if allowed to cool slowly.

The quenching medium is chosen according to the rate at which it is desired to cool the steel. The following list of media is arranged in order of quenching speeds:

a. 5% Caustic soda.

b. 5-20% Brine.

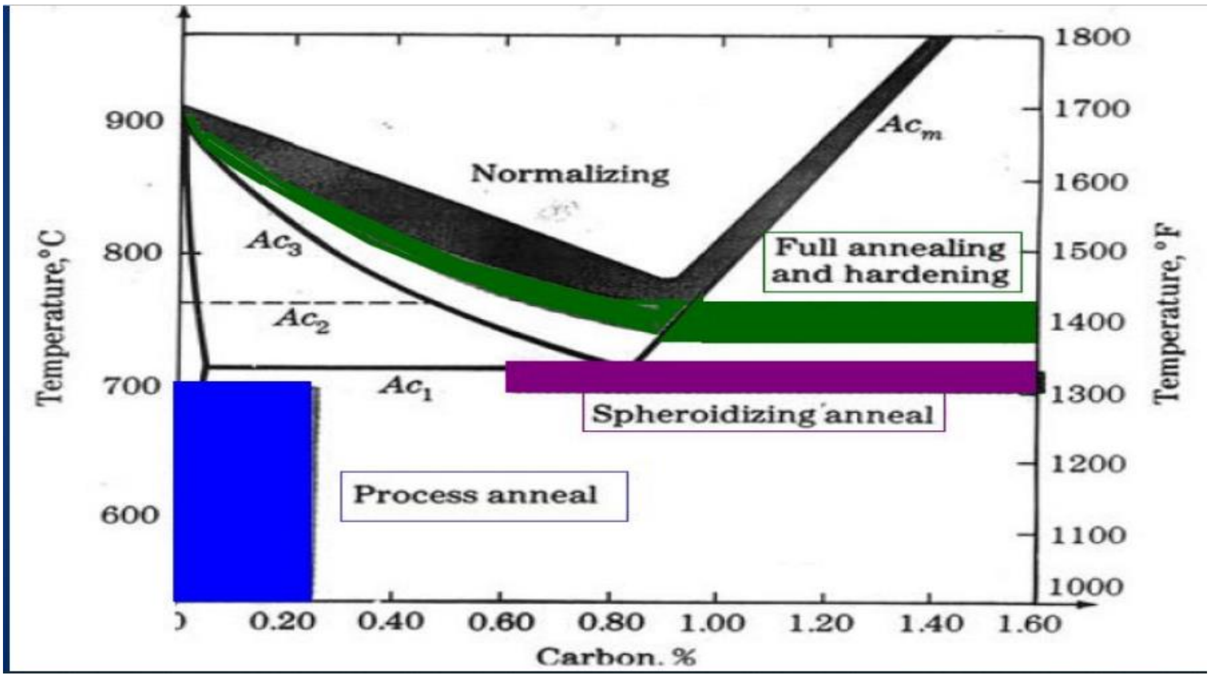
d. Warm water

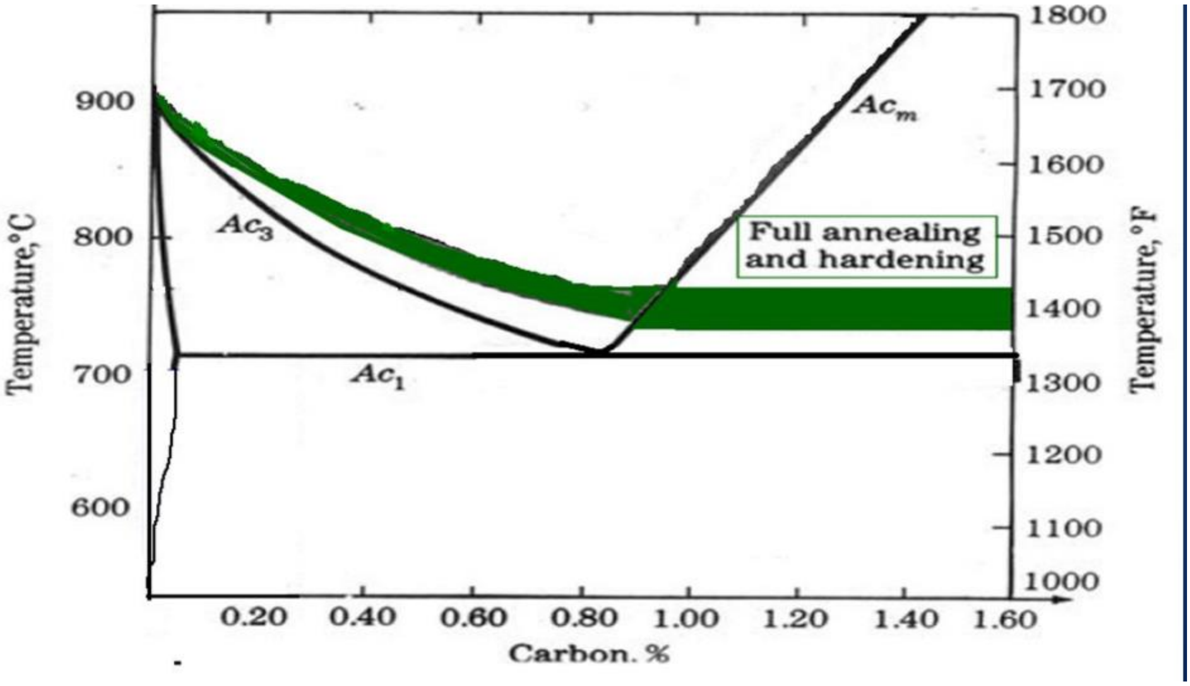
e. Mineral oil.

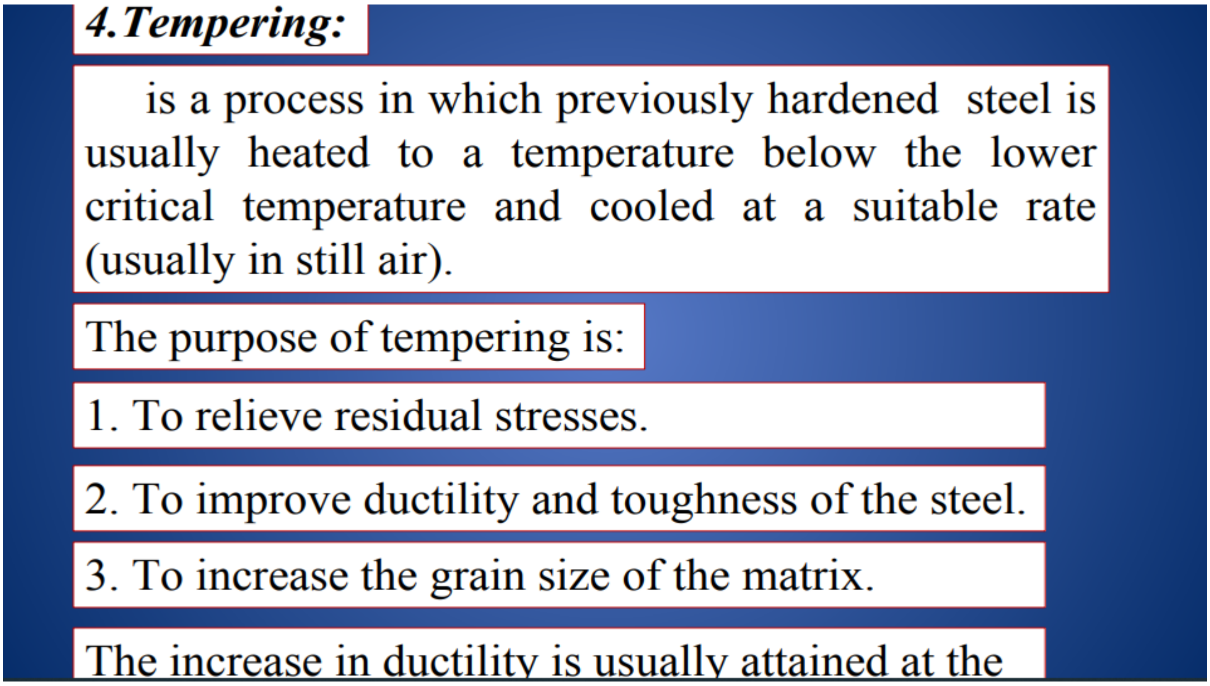
g. Vegetable oil.

The quenching medium is chosen according to the rate at which it is desired to cool the steel. The following list of media is arranged in order of quenching speeds:

a. 5% Caustic soda.
b. 5-20% Brine.
c. Cold water.
d. Warm water.
e. Mineral oil.
f. Animal oil.
g. Vegetable oil.







4. Tempering:

is a process in which previously hardened steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate (usually in still air).

The purpose of tempering is:

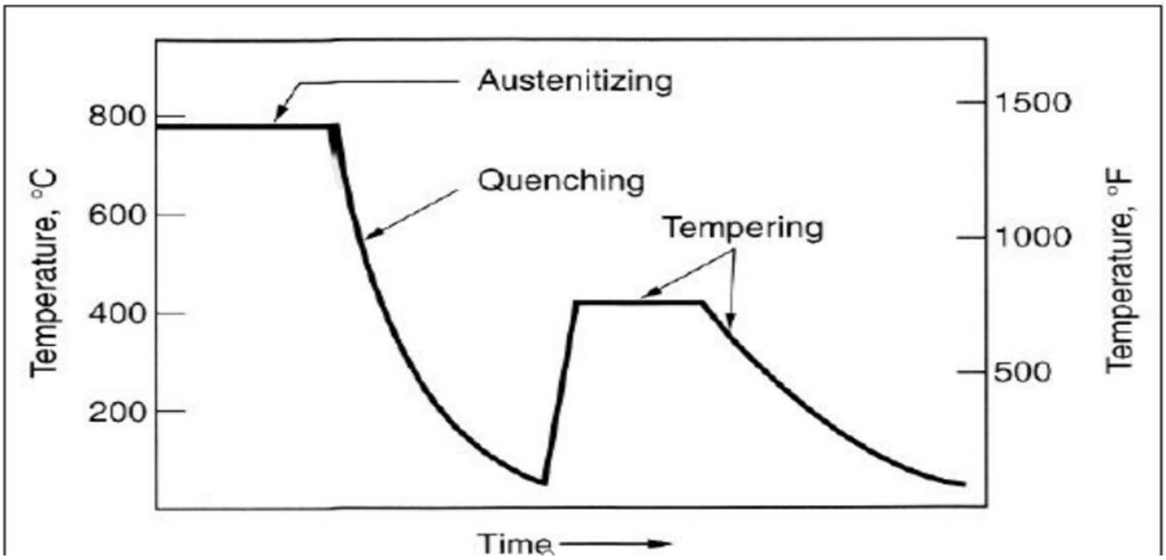
1. To relieve residual stresses.
2. To improve ductility and toughness of the steel.
3. To increase the grain size of the matrix.

The increase in ductility is usually attained at the

The purpose of tempering is:

1. To relieve residual stresses.
2. To improve ductility and toughness of the steel.
3. To increase the grain size of the matrix.

The increase in ductility is usually attained at the sacrifice of the hardness or strength.



Surface Hardening

Many machine parts such gears shafts railroad need to be hard at surface to resist wear and fatigue and also be ductile and tough to withstand impact loads.

This demand can be achieved by using Surface Hardening.

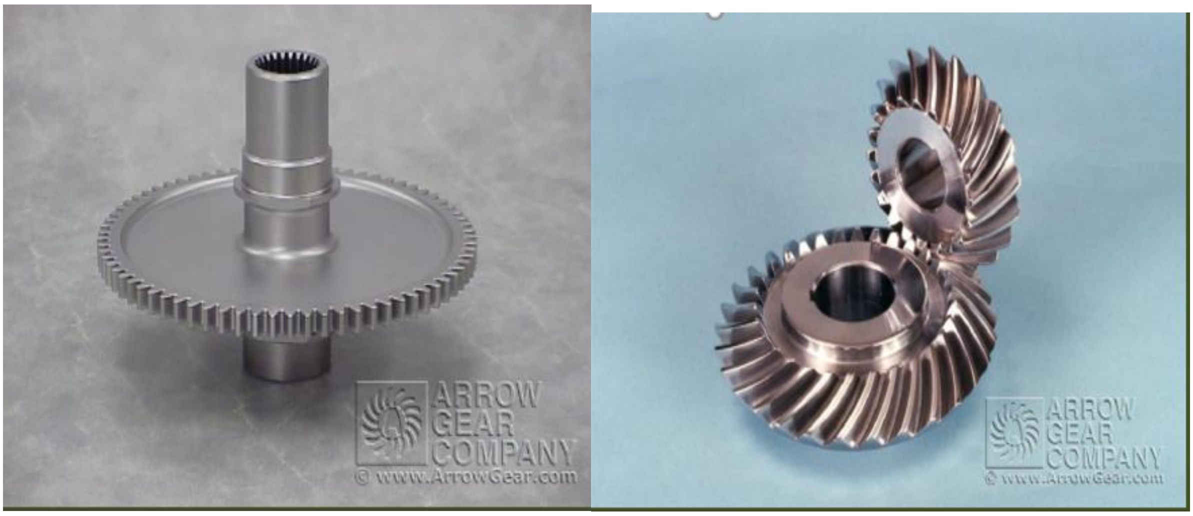
Surface Hardening: is a process by which a steel is given a hard, wear resistant surface, while retaining a ductile but tougher interior.

Surface hardening is usually done for the following reasons:

1. To improve wear
2. To improve resistance to high contact stresses.
3. To improve fracture toughness.
4. To improve fatigue resistance, and, sometimes:
5. To improve corrosion resistance.

Surface hardening techniques can be classified into two major categories:

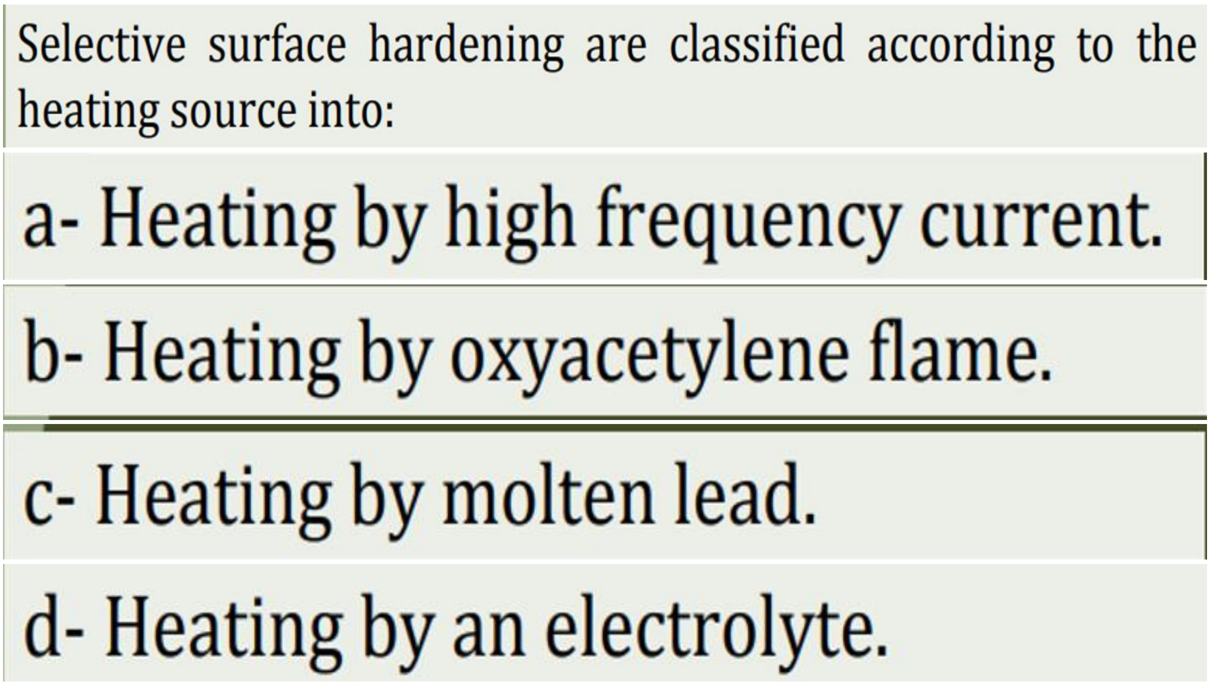
1. Processes that do not change the surface chemical composition (selective surface hardening or local thermal surface hardening)
2. Processes that change the surface chemical composition (case hardening or thermochemical processes).



1. Processes that do not change the surface chemical composition:

These processes are also called localised heat treatment because only the surface is austenitised and quenched to produce martensite.

The basic requirement for these processes is that the steel must have sufficient carbon and hardenability to achieve the required hardness at the surface (medium carbon steels are usually suited for these processes)



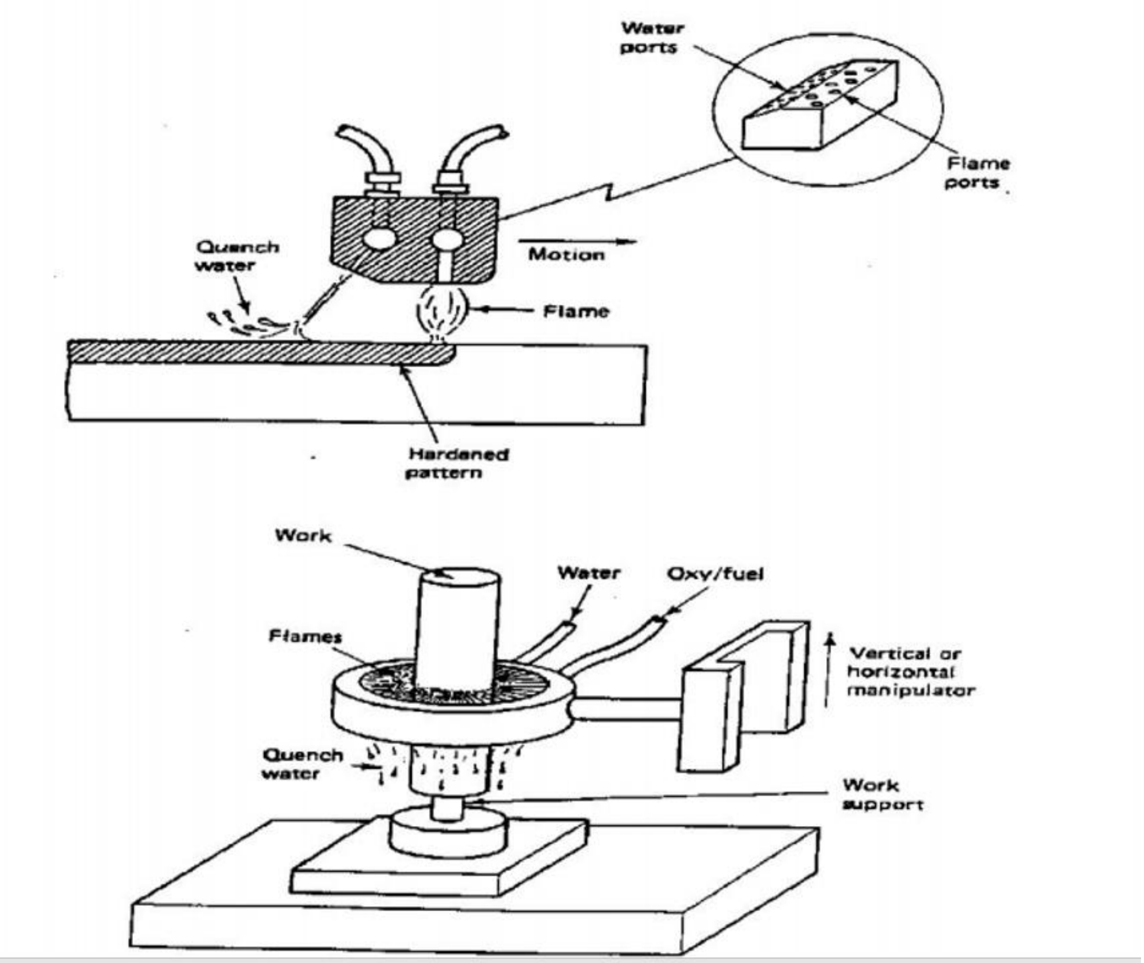
Selective surface hardening are classified according to the heating source into:

a- Heating by high frequency current.

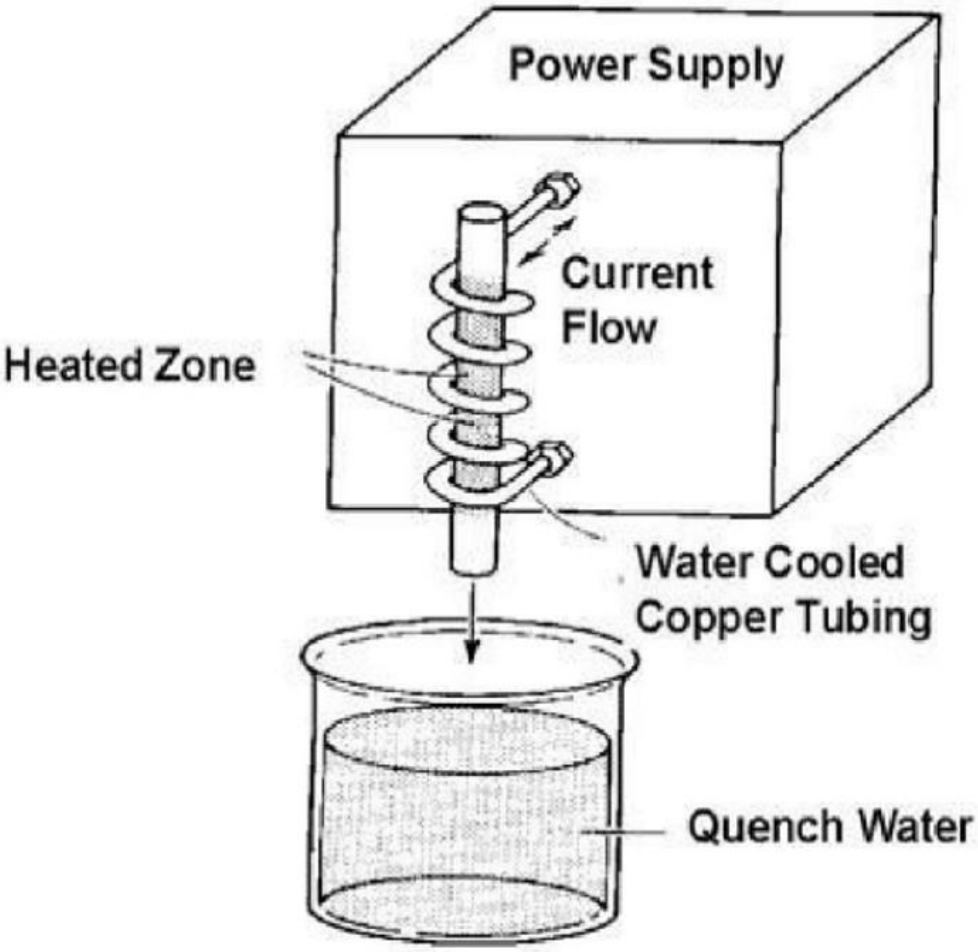
b- Heating by oxyacetylene flame.

c- Heating by molten lead.

d- Heating by an electrolyte.



Flame Hardening



Surface hardening

Induction Hardening

2. Case hardening (thermochemical processes):

Case hardening methods include:

a. Carburizing

b. Nitriding

c. Carbo-nitriding

d. Cyaniding

Surface hardening

a. Carburizing:

is a hardening process in which carbon is introduced into the surface layer of the steel.

The depth of carburized layer depends on:

a- Chemical composition of steel.

b- Carburizing media (solid, liquid, or gas).

c- Time and temperature of carburizing.

Surface hardening

The carburizing layer consists of:

a- at the surface, eutectoid steel layer such as 0.8 %carbon or pearlite only.

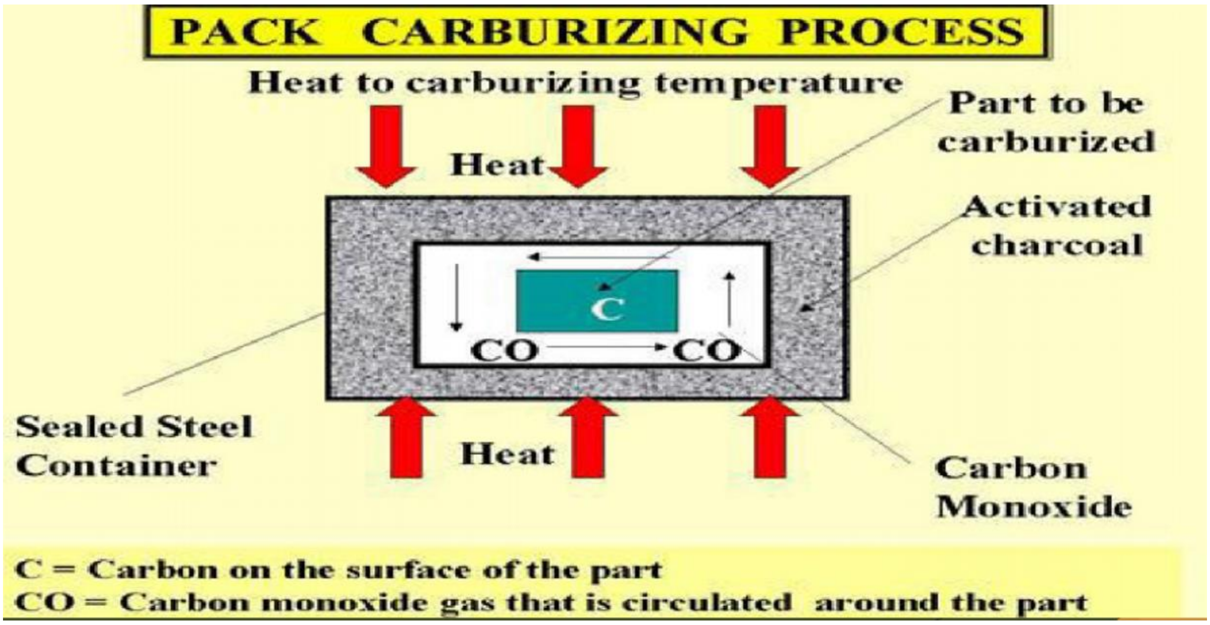
b- at the core hypo eutectoid steel layer i.e. ferrite+pearlite. Carburising is done on low carbon steel (< 0.25 %C)

Carburized layer thickness is usually (0.1 – 5 mm) thick packed – carburizing mixture consist of (75 – 80 %charcoal + 25 – 20 % either sodium carbonate (Na_2Co_3) or Barium carbonate ($BaCo_3$) as catalyst.

Surface hardening

The carburising time varies between 4 – 70 hours.

The carburizing process does not harden the steel, it only increases the carbon content to a desired depth below the surface.



Surface hardening

Pack Carburizing

Procedure:

a. In pack carburising, the steel piece is packed in a steel container and completely surrounded with charcoal.

b- Put the box inside the furnace. Heat to 950℃.

c- After the temperature reached 950℃ switches off the power after (3 hr).

Surface hardening

d. The charcoal is treated with sodium carbonate (Na2Co3) or Barium carbonate (BaCo3), which promotes the formation of CO.

e. CO reacts with the low carbon steel surface to form atomic C, which diffuses into the steel.

f. Quenching is difficult in pack carburising. Usually the part is allowed to cool slowly and then hardened and tempered.

Surface hardening

After the furnace cools to room temperature, heat-treat the steel Specimen as follows:

a- Normalizing the steel specimen from 900℃ to toughen the core.

b- Water quench from 760℃ to harden the surface.

c- Temper at 200℃ to release internal stresses.