ME6403 ENGINEERING MATERIALS AND METALLURGY

Objective :-

To impart knowledge on the structure, properties, treatment, testing and applications of metals and non-metallic materials so as to identify and select suitable materials for various engineering applications.

UNIT 1 ALLOYS AND PHASE DIAGRAMS

Constitution of alloys- Solid Solutions, Substitutional and interstitial - Phase diagrams, Isomorphous, eutectic, eutectoid, Peritectic and Peritectoid reactions, Iron-Carbon equilibrium diagram. Classification of Steel and cast iron microstructure, properties and application.

UNIT 1 ALLOYS AND PHASE DIAGRAMS

Types of alloys :-

(1) There are two types of alloys.

(2) Ferrous alloys and non-ferrous alloys.

(3) In ferrous alloys, iron is the prime constituent and for the improvement of its mechanical and physical properties, various elements as Ni, Cr, Mn and W are added.

(4) There are different types of plain carbon steels depending upon the carbon percentage and majority of the materials used in engineering are plain carbon steels.

(5) In non-ferrous alloys, prime constituent is not iron but other elements like Cu, Ni, Ti, Al, Mg and so on.

Types of ferrous alloys :-

(1) Majority of engineering components are made from ferrous alloys as plain carbon steels, cast irons and alloy steels.

(2) There are three main factors for the use of ferrous alloys: (a) iron ore exists in abundance in the Earth's crest, (b) extraction of iron from ores and manufacture of steel and cast irons are economical and (c) iron alloys are extremely versatile and can be made as per the requirements of mechanical and physical properties.

(3) Ferrous alloys are susceptible to corrosion and oxidation. For the protection from corrosion, alloying elements such as chromium and nickel are added to produce stainless steels.

(4) Special-purpose steels are developed for specific requirements like (a) high-temperature application, (b) cryogenic temperature applications, (c) application in measuring instruments and steel with minimum co-efficient of thermal expansion and (d) high-speed cutting tools.

PLAIN CARBON STEELS

Plain carbon steels are divided into various categories as follows:

1. Low-carbon steel (C < 0.25 %)
2. Medium-carbon steel (C 0.25 - 0.60 %)
3. High-carbon steel (C > 0.60 %)
4. Hypoeutectoid steel (C < 0.80 %)
5. Eutectoid steel (C = 0.80 %)
6. Hyper eutectoid steel (C > 0.8 %)

Types of Steels

★ Based on the degree of deoxidation, steels are classified as killed, semi-killed and rimmed steels.

★ Killed steels are those, which had been strongly deoxidized and there is no gas evolution during solidification.

★ The degree of deoxidation is lower in semi-killed steel.

★ Rimmed steels are those, which either have not been deoxidized or have been partially deoxidized.

★ Rimmed steels, being low in carbon and silicon content can be heated for rolling into sheets, thin plates, strips and tubes.

* Based on the method of fabrication, Steels are classified as wrought Steels and Cast Steels.

* Wrought Steels are shaped by plastic deformation and Cast Steels can be Cast in moulds.

Effect of Carbon Content :-

* With the increase in Carbon Content, tensile Strength and hardness increase linearly, but ductility decreases rapidly.

* Steel with C=1.3 % is very brittle.

Specification of Steels :-

- As per Indian Standards, Steels are designated as per chemical Composition and mechanical Properties.

1. "Fe" is used to indicate Steel based on min. tensile Strength.
   eg: Fe 400 Steel having min. σ_{ut} = 400 MPa.

2. "FeE" is used to indicate Steel designation based on min. Yield strength. eg: FeE 250 Steel having min. σ_{yp} = 250 MPa.

"Q" Stands for quality of the Steel :

Q1 : non-ageing quality.

Q2 : Flake-free Steel

Q3 : Given Size Controlled

Q4 : inclusion-Controlled Steel.

Q5 : Steel with guaranteed homogeneity.

eg: Fe 450 Q4 indexing-Controlled Steel with min. σ_{ut} = 450 MPa.

W: (W_1, W_2) weldability

B: (0, 2, 4) resistance to brittle fracture

V: notch Charpy impact Strength

W: (S_1-S_7) Surface Condition of Steel.

D: (1-3) formability

F: (1-13) Surface finish

T: treatment of steel.

T_1: Shot peened

T_2: hard drawn

T_8: normalized.

T_5: annealed

T_7: Solution treated

T_8: Solution treated and aged

T_{13}: Case hardened

T_{14}: Hardened and tempered

H: elevated temp.-guaranteed Prop.

L: Low temp.-guaranteed Prop.

C: carbon % (multiplied by 100)

T: tool steel

C or T is followed by a no. representing avg. manganese content multiplied by ten.

eg: 95T15, Carbon tool steel having avg. carbon content of 0.95 % and Mn content of 1.5 %.

Low and Medium Alloy Steels with 10 % Alloy content:

Description of these steels are as follows,

1. A number indicating 100 times the average % of C.
2. Chemical Symbol of alloying element.
3. Avg. % of alloying element multiplied by a factor, given in table.

Multiplying factor for Alloy Steels:

Chemical Symbol of Alloying element	Multiplying factor
Co, Cr, Mn, Ni, Si, W	4
Al, Be, Cu, Mo, Nb, Pb, Ta, Ti, Zr	10
P, S, N	100

eg: 40 Ni 8 Cr 4 Mo 2, low alloy Steel with 0.4 % C, 2 % Ni, 1 % Cr and 0.2 % Mo

High-alloy Steels (with more than 10 % of alloy content): The designation of these steels starts with alphabet X after which is put number, i.e. 100 times of avg. Carbon content, and next Symbols for alloying elements and % of alloying element rounded off to nearest integer. Symbols indicating Specific characteristics such as weldability and quality are placed in the last.

eg: XT70W18Cr4V1, high alloy tool steel, with 0.7 C, 18% tungsten, 4% chromium and 1% vanadium.

Different applications of Steels are as follows:-

1. Low-Carbon Steels (C < 0.25 %)

- These Steels are unresponsive to heat treatment for the purpose of forming martensitic structure.
- These are strengthened by cold working.
- The microstructure consist of ferrite and pearlite.
- These are ductile, tough, Machinable and weldable.

Appl.: Automobile body components and Structural Shapes.

2. Medium-Carbon Steels (C 0.25-0.60 %)

- These Can be heat treated by austenizing, quenching and then tempering to improve mechanical properties.
- They have tempered martensitic Structure.

appl: Railway wheels, tracks, Gears, Crank shaft, etc..

Prop.: Wear resistance, high Strength and toughness.

3. High-carbon steels (C 0.6-1.4 %)

- Hardest and Strongest, but least ductile steels, always used in hardened and tempered Conditions.
- These are wear resistant & provide Sharp cutting edge.
- The tools and die steels are high-carbon alloys with Cr, V, W and Mo as alloying elements.

4. High - Strength Low-alloy Steels (HSLA)

These are plain, low. Carbon steels with alloying elements Cu, V, Ni and Mo (total 10 per cent) and possess high strengths.

Maraging Steels :-

They are well known for their high yield to tensile strength ratio, excellent fracture toughness and resistance to hydrogen embrittlement.

Composition - C $<0.03\%$
Ni 25
Co 7-10
Mo 3-5
Ti 1.75
Al 0.2
Beryllium, niobium and tungsten in small %.

These are used in aircraft under carriage parts, portable bridges and booster motor in missiles, $\sigma_{ut} = 1800$ MPa.

SOLID SOLUTIONS

1. A Solid Solution is a homogeneous mixture of two or more kind of atoms in a Solid State or more than two types of atoms combined in a single-space lattice.

2. If two or more different types of metals are mixed in their liquid State, they form a liquid Solution.

3. When this mixture is Solidified, the Solid may retain the homogeneity that was present in the liquid State.

4. In this, the components of different types of atoms form a common crystal lattice.

5. The Component whose lattice is retained is called the Solvent. and the Solute atom may occupy a vacant lattice site in the parent metal.

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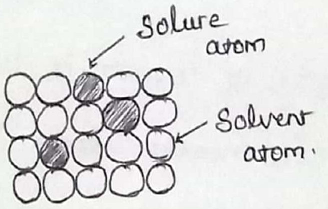

Material Science and Metallurgy (

- U.C. Jindal
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Two dimensional Substitutional Solid Solution.

- Brass is a Solid Solution of Copper and Zinc.
- A typical composition of brass contains 64% Copper and 36% Zinc.
- The Copper atoms are Solvent atoms and the Zinc atoms are Solute atoms.
- The Solid Solutions are of two types - Substitutional solid Solution and Interstitial Solid solution.

eg: Ni-Cu, Au-Ag, Ag-Cu and Fe-C

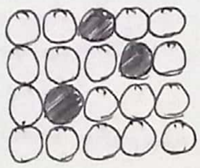
Substitutional Solid Solution :-

In a Substitutional Solid Solution, the solute atom substitutes the atoms of solvent in the Crystal Structure.

The crystal structure of the parent element is unchanged, but the lattice may be distorted by the presence of the solute atoms.

In a substitutional Solid Solution, the two atoms are equal or approximately equal in diameter and the crystal structure of the two elements must be the Same.

Brass is alloy of copper and zinc.



Disordered Substitutional Solid Solution

Ordered Substitutional Solid Solution.

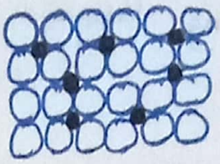
The atomic diameter of copper is 1.278 Å and that of Zinc is 1.332 Å and the two metals form Substitutional Solid Solution.

Substitutional Solid Solutions are further classified into disordered substitutional Solid Solution and ordered substitutional Solid Solution.

If the disordered Substitutional Solid Solution is heated to its recrystallization temperature and then cooled very slowly, the atoms are rearranged due to the diffusion that takes place during cooling.

This results in uniformity and definite ordering of the atoms in the lattice structure. This structure is said to be ordered substitutional Solid solution.

Interstitial Solid Solution



two-dimensional interstitial solid solution.

In an interstitial solid solution, the diameter of the solute atom is very small when compared to the solvent atoms.

These are formed when atoms of small atomic radii fit into the void spaces of the larger solvent atoms.

The diameters of carbon, boron and nitrogen atoms are less than 1A° and can fit in the crystal structure of iron, nickel and manganese as interstitial solid solution.

PHASE DIAGRAMS

- The solidification of a metal or an alloy is clearly understood by means of a phase diagram.

- A plot with the temperature on the vertical scale and the percentage of composition by weight on the horizontal scale is termed a phase diagram.

- The phase diagram is also known as constitutional diagram.

- In a phase diagram, to specify completely the state of a system in equilibrium, it is necessary to specify the three independent variables — temperature, pressure and composition, which are externally controllable.

- If there is no variation in pressure, then the metal equilibrium can be expressed in terms of two independent variables namely temperature and composition.

Cooling Curves:-

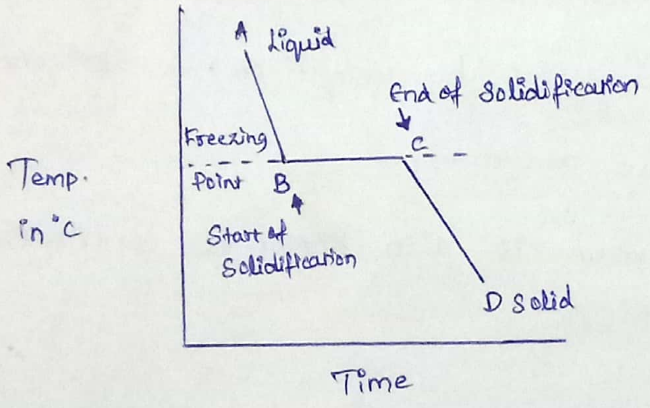
The phase diagrams are usually constructed from the data of cooling curve obtained by plotting falling temperature versus time for small selected alloys, which are allowed to cool under equilibrium condition.

The simplest type of curve is obtained by taking the temperature readings at fixed intervals of time with the aid of a pyrometer.

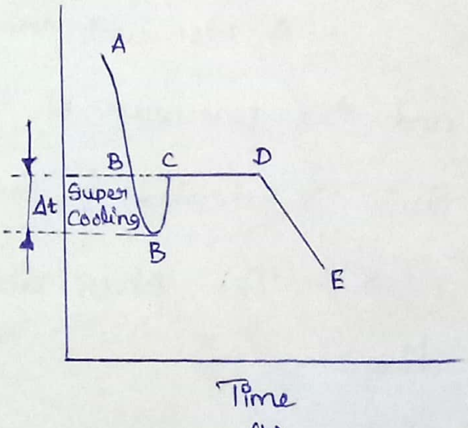
This curve is used for studying the changes that occur during the solidification of alloys.

If a plot is drawn between temperature and time at a constant composition, the resulting cooling curve shows a change of slope when a phase change occurs.

Solidification of Pure metals:-



(a)



(b)

The pure metals melt and solidify at the same temperature which may be termed as melting point or freezing point.

These metals are cooled under equilibrium conditions from the molten state till they solidify.

A time-temperature diagram is shown in figure.

Liquid metal cools from A to B.

The crystal begins to form at B. From B to C molten metal liberates latent heat of fusion and the temperature remains Constant until the entire liquid metal is solidified.

Between B and C, the metal is partially solid and partially liquid.

On further cooling, i.e from C to D, Solid metal tends to reach the room temperature.

In real Systems, a certain amount of under-cooling occurs before the Solidification starts.

That is, the melt is maintained in a metastable State at a temperature below the freezing point and most of the cooling curves are as shown in figure (b).

Nucleation of solid does not start at point B, but it starts at point B', i.e. liquid metal has super-cooled by an amount Δt. This is known as Super-cooling or under cooling.

Construction of Phase diagram:-

Solidus line and liquidus line:-

The line obtained by joining the points showing the beginning of Solidification is called the liquidus line.

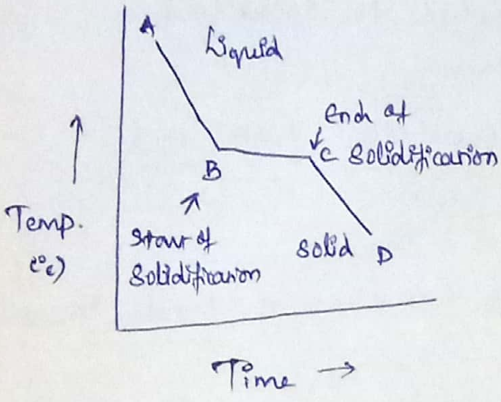
The liquidus line indicates the lowest temperature at which a given alloy of the Series in the liquid starts to freeze.

20|11|15 The lower line of the diagram is known as the Solidus.

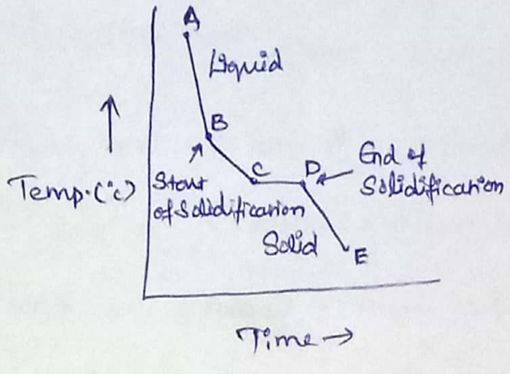
Cooling Curve for binary Alloy :-

Solidification of Alloy :-

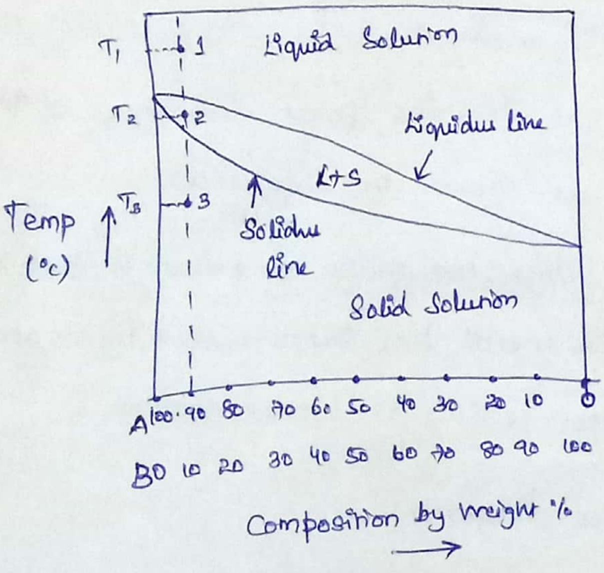
Type - 1



Type-2 (Eutectic solidification)



Intrepretation of Phase diagram :-



Prediction of
Phase

Eutectic reaction:

For a mixture with two components at a fixed pressure, the eutectic reaction can only happen at a fixed chemical composition and temperature called the eutectic point.

It describes the thermodynamic equilibrium conditions where a liquid Coexists with two solid phases.

The microstructure of solid that results from the transformation consist of alternate layers of α and B phases that form simultaneously during the transformation.

EUTECTOID REACTION

It describes the phase-change reaction of an alloy in which, on cooling, a single solid phase transforms into two other solid phases.

PERITECTIC REACTION

It describes the isothermal reversible reaction of a liquid phase and a solid phase to form a second solid phase during cooling.

GIBBS'S PHASE RULE

* The number of variable factors which define the state of a system is called the degree of freedom.

* Number of degrees of freedom is the quantity of independent external or internal variables like temperature, pressure and concentration which may change the formation of new phase in the system.

* Gibb proved that "number of degrees of freedom" of a system in equilibrium condition is related to the number of components and the number of phases.

Mathematically, it can be expressed as

$$P+F = C+N$$

Where,

P - number of phases in the system

F - number of degrees of freedom

C - number of components in the system

N - number of external factors such as temperature and pressure.

Usually in metallurgical process the pressure will not be considered as a variable as it is fixed at 1 atm. Pressure. Thus, the eqn. becomes,

$$P+F = C+1 \quad (\because N=2 \text{ i.e } T \text{ and } P)$$

here N= 1

Eutectic Reaction:-

$$\text{Liquid} \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \text{Solid 1} + \text{Solid 2}$$

Peritectic Reaction:-

$$\text{Solid} + \text{liquid} \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \text{New solid}$$

Eutectoid Reaction:-

$$\text{Solid 1} \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \text{Solid 2} + \text{Solid 3}$$

eg: austenite decomposing into pearlite (ferrite + cementite)

Peritectoid Reaction:-

It is a very rare reaction. In this reaction, the two solid phases, a pure metal and the other solid solution, react at peritectoid temperature to form a new solid phase.

$$\text{Solid 1} + \text{Solid 2} \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \text{New Solid 3.}$$

IRON CARBON PHASE DIAGRAM

It graphically represents the changes that take place when two variables, such as temperature and overall composition, are varied.

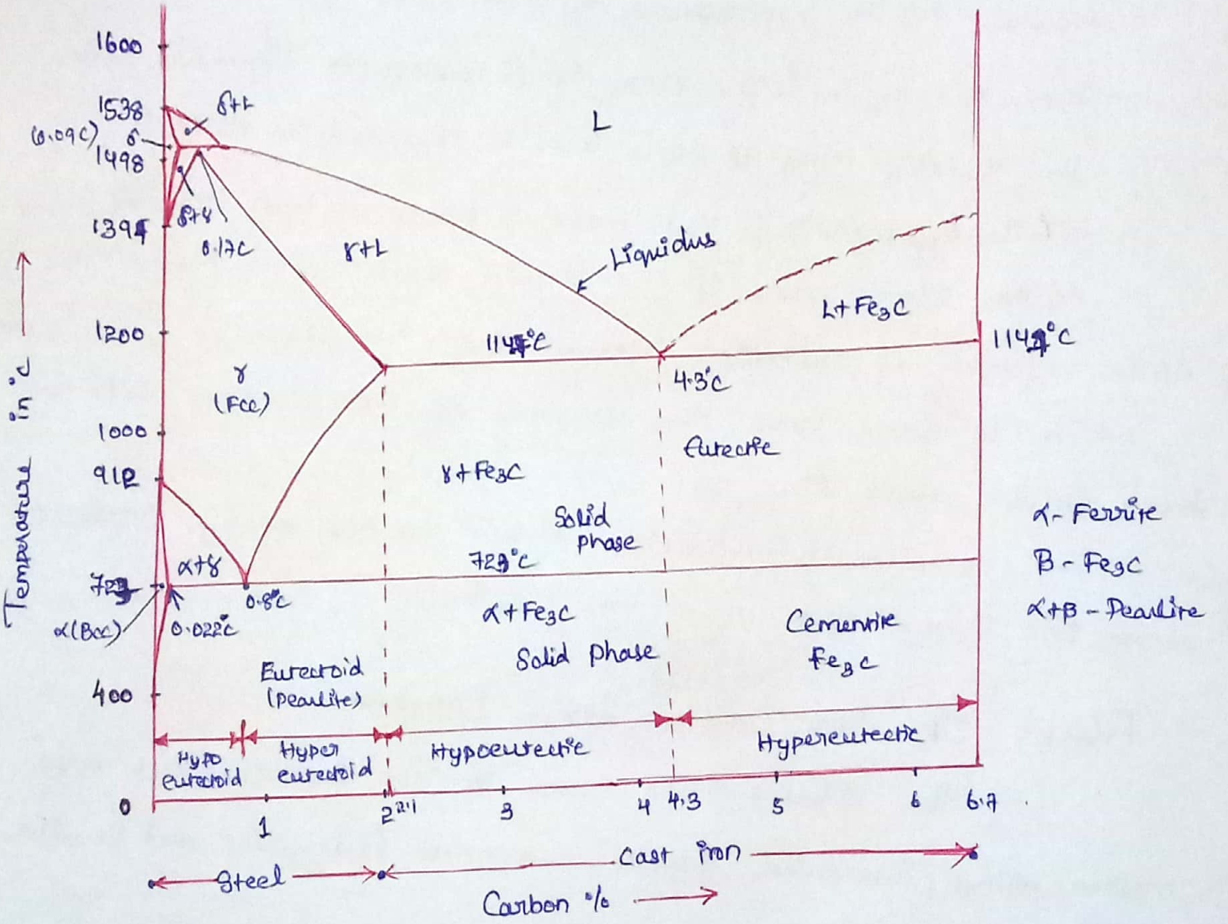
This equilibrium diagram has temperature on vertical scale and % of composition by weight as horizontal scale.

The composition on horizontal scale represents only 6.67 % by weight. This is because, a maximum of 6.67 % carbon can only be added to molten iron at which it becomes saturated.

Any further addition of carbon will not make it dissolve in iron; but it rather floats on the surface due to low density.

This phase diagram is also known as $Fe-Fe_3C$ phase diagram.

It is constructed by using a number of cooling curves with carbon varying from 0 to 6.67% similar to nonferrous diagrams. The effects of carbon addition to iron are shown in figure.



When carbon dissolves in molten iron, the solidification temperature of the resulting iron carbon alloy decreases.

Iron carbon alloys which contain upto 2% carbon are known as "Steel". Iron carbon alloys holding more than 2% carbon are called "Cast iron".

Upto 0.8% carbon steels are called as hypoeutectoid steels.

The carbon content from 0.8% to 2% is called hypereutectoid steel. Similarly, from 2% to 4.43% carbon is called hypoeutectic cast iron and 4.33% to 6.67% cast iron is called hypereutectic cast iron.

Pure Iron melts or solidifies at 1538°c. Further when upto 4.3% Carbon is added to molten iron, the Solidification temperature decreases to 1148°C This is indicated by a line ABC on the diagram.

Beyond 4.3% Carbon, the temperature increases as shown in figure. This is represented by a line CD on the diagram.

From the figure, the line ABCD represents liquidus line.

The melting point of pure iron is marked as point A.

Similarly, point D is the melting point of iron carbide.

As the temperature of the liquid falls along the line ABCD, crystals of austenite separate from the liquid.

In the same way, the crystals of iron carbide separate from liquid along line CD.

The complete solidification of iron carbon alloys produce along the line HJECF called the Solidus.

PHASES OF IRON CARBIDE PHASE DIAGRAM

The phases that occur in iron carbon alloys are molten alloys, austenite, ferrite, cementite, ledeburite and Pearlite.

δ- Ferrite :-

When a low Carbon Steel crystallizes at 1538°C, the Solid that appears is in BCC Crystal Structure called δ-ferrite.

At 1498°C, because of higher temperature the solubility of Carbon in δ-ferrite is very small between 0.1% and 0.15%.

It is soft, ductile and converted into γ solid solution by reacting with residue liquid of iron at 1394°c.

Austenite :-

Austenite is an interstitial Solid Solution of Carbon upto 2% at 1,148°c and it is FCC in crystal Structure.

It is normally unstable at room temperature and is nonmagnetic. On cooling below 727°c, it starts transferring into ferrite and pearlite.

Ferrite :

The Structural modification of pure iron at room temperature is known as ferrite.

It is an interstitial solid solution of small amounts of carbon dissolved in BCC crystal structure.

The maximum solubility of carbon is 0.022% at 727°c and 0.008% at room temperature. Ferrite is Soft, ductile and is of low strength among all phases of iron carbon alloys.

Cementite :-

When carbon in iron exceeds the solubility limit, it forms a second phase which is commonly known as cementite. This is also called iron carbide (Fe_3C) and it contains upto 6.67% carbon by weight and has orthorhombic crystal structure.

It is a typical compound of low tensile strength but high compressive strength and ferromagnetic. It is hardest structure in iron carbide system.

Pearlite :-

The mechanical mixture of ferrite and cementite formed at 727°c on very slow cooling is known as pearlite.

It consist of alternate layers of ferrite and cementite.

It is a product of eutectoid transformation.

Pearlite is fairly soft and its hardness lies between that of ferrite and cementite. It appears like a fingerprint in structure.

Ledeburite :-

Ledeburite is eutectic lamellar mixture of austenite and cementite. It contains 6.67 % carbon and is formed at 1148°C by eutectic reaction.

Further, ledeburite is unstable and transfers into ferrite and cementite at 727°C.

Cementite is hard but brittle and pearlite is also fairly hard. Therefore, the transformed ledeburite is also hard and brittle.

Cast Iron :-

An alloy of iron that contains 2%-4% Carbon along with varying amounts of Silicon and manganese and traces of impurities such as sulphur and phosphorus is called cast iron.

Commercially cast irons have the carbon range b/w 2.2% and 4.3%.

All cast irons are low in terms of ductility and hence cannot be rolled.

According to the shapes of the free carbon available in the microstructure, the cast irons are classified into four types which are discussed below.

Gray Cast Iron :-

It contains 2.5% - 3.8% Carbon, 1.1% - 2.8% Silicon, 0.4% - 1% manganese, 0.15% phosphorous and 0.1% Sulphur.

Microstructure consist of ferrite and flake graphite.

It can be cast into any shape in a Sand mould, and it possess the lowest melting point of the ferrous alloys.

It has high resistance to wear, high comp. strength and high vibration damping capacity.

App: Water pipes, manhole covers, IC engine blocks, piston rings and machine components.

White cast Iron :-

Its named from the fact that its freshly broken surface shows a bright white fracture.

This is because, the carbon present in them is in Combined form as Cementite and pearlite.

It contains 1.8% - 3.6% Carbon, 0.5% - 2% Si, 0.2% - 0.8% Mn, 0.18% phosphorus and 0.1% Sulphur.

Microstructure consist of iron carbide along with pearlite.

It has excellent abrasive wear resistance and brittleness.

App: It can be cast only in sand moulding and is mainly used for producing malleable cast iron and wear-resistance Component machine parts.

Malleable Cast Iron :-

It is obtained from hard and brittle white iron through controlled heat conversion process.

It is having all the carbon in the free form in irregular shapes.

It contains 2.3 % Carbon, 0.6% - 1.3% Si, 0.2% - 0.6% Mn and 0.15 % phosphorous.

Microstructure consist of dark graphite in a ferrite matrix.

It possess high yield strength and high Young's modules and it possesses good wear resistance.

App: Railroad, agricultural implements and conveyor chain links.

Nodular Cast Iron or Spheroid Graphite Iron :-

In nodular cast iron, graphite appears as round shape instead of flakes as in gray cast iron.

It is obtained by adding small amount of Mg or Cerium in the molten gray cast iron.

It contains 3.2% - 4.2 % Carbon, 1.1% - 3.5% Si, and 0.3% - 0.8% Mn.

Microstructure consist of nodules surrounded by ferrite.

It is highly ductile and machinable with excellent castability and wear resistance.

App: Ic engines, earth moving machinery, valves and fittings, pipes and flywheels.