Cast Irons

11.1 INTRODUCTION

Cast irons are basically the alloys of iron and carbon in which the carbon varies between 2.0 to 6.67 % i.e. more than the solubility limit of carbon in austenite and less than the carbon content of cementite. Commercial cast irons are complex in composition and contain carbon in the range of 2.3 to 3.75% with other elements such as silicon, phosphorus, sulphur and manganese in substantial amount. Because of their poor ductility and malleability, they can not be forged, rolled, drawn, or pressed into the desired shape; but are formed by melting and casting with or without machining to the required final shape and size, and hence the name "cast irons".

Cast irons are typical in respect of following characteristics as compared to steels.

(i) They are the cheapest amongst the commercial alloys. The raw materials i.e. pig iron, cast iron scrap, steel scrap, ferro-silicon, high silicon pig iron, iron ore, limestone, coke, etc. used in the manufacture of cast iron are relatively cheap.

(ii) They are easier to melt because of their lower melting temperature (1150 – 1250°C) as compared to steels (melting temperature 1350 – 1500°C).

(iii) They have excellent castability due to high fluidity of melt and low shrinkage during solidification.

(iv) Their corrosion resistance is fairly good.

(v) Various types of cast irons (discussed below) have typical properties. White cast iron has high hardness and high resistance to wear and abrasion. Gray cast iron has excellent machinability and very good damping capacity. It is relatively insensitive to the presence of notches and also has good bearing properties and compressive strength. Malleable and nodular cast irons have plasticity and strength sufficient to achieve a useful degree of toughness and impact resistance.

(vi) By proper alloying, good foundry control and suitable heat treatment, the properties of any type of cast iron can be easily adjusted over a wide and useful range.

(vii) In general, they are brittle and their mechanical properties are inferior to steels.

CLASSIFICATION OF CAST IRONS

st irons are classified according to various criteria as below :

n the basis of furnace used in their manufacture :

Cupola cast irons
Air furnace cast irons
Electric furnace cast irons
Duplex cast irons (which have been melted in one type of furnace and refined, alloyed, or superheated in another furnace)

On the basis of composition and purity :

) Low carbon, low silicon cast irons
) High carbon, low sulphur cast irons
) Nickel alloy cast irons, etc.

On the basis of microstructure and appearance of fracture :

) White cast irons. (All the carbon is in the combined form i.e. as cementite and the fracture is white).

2) Malleable cast irons. (They contain free carbon i.e. graphite in the form of irregular spheroids called as temper carbon graphite nodules i.e. rosettes. They are produced from white cast irons by a heat treatment called malleablizing heat treatment or malleablization).

3) Gray cast irons. (They contain free carbon i.e. graphite in the form of flakes and the fracture is gray in colour).

4) Nodular cast irons. (They contain free carbon i.e. graphite in the form of nodules or spheroids. They are produced from special grades of gray cast iron by the addition of small amount of magnesium just prior to pouring).

5) Mottled cast irons. (They contain microstructures typical of both white cast iron and gray cast iron. Except by accident, mottled structure is normally produced only as the transition layer between the white cast iron surface and gray cast iron centre of a chilled casting).

(6) Chilled cast irons. (They show white cast iron on the surface and gray cast iron in the centre).

(7) Alloy cast irons. (They may be of any of the above general types but are significantly modified in structure, properties, or both by the addition of alloying elements).

3 FACTORS INFLUENCING MICROSTRUCTURE

Microstructure (and also properties) of cast irons are influenced by the following factors.

(i) **Amount of total carbon :** Carbon is a graphitizer. With increasing carbon, the dency of graphitization i.e. formation of graphite by the decomposition of cementite (Fe_3C 3Fe + C) becomes more and hence leads to the formation of gray cast iron. With higher bon and slower cooling, the matrix may become ferrite. At a moderate cooling rate and with less amount of carbon, the cast iron may solidify without graphitization giving all carbon in the combined form and is identified as white cast iron.

(ii) **Amount of silicon** : Silicon is a strong graphitizer and promotes graphitization i.e. decomposition of cementite to iron and graphite and hence its amount is controlled to control the amount of graphitization. The amount of silicon varies from 0.5 to 3.0 % in various commercial cast irons. With lower amount of silicon, the cast iron solidifies as white and with higher amount, it solidifies as gray at a moderate cooling rate.

The effect of alloying elements and silicon on graphitization is described in terms of the silicon equivalent by the following equation.

$$\begin{aligned}\text{Si equivalent} &= \%\,\text{Si} + 3\,(\%\,\text{C}) + \%\,\text{P} + 0.3\,(\%\,\text{Ni}) + 0.3\,(\%\,\text{Cu}) + 0.5\,(\%\,\text{Al}) \\ &\quad - 0.25\,(\%\,\text{Mn}) - 0.35\,(\%\,\text{Mo}) - 1.2\,(\%\,\text{Cr}) \qquad \ldots (11.1)\end{aligned}$$

Non-carbide forming elements Ni, Cu and Al have positive factors i.e. they promote the graphitization whereas carbide forming elements Mn, Mo, and Cr have negative factors which limit the graphitization.

(iii) **Amount of phosphorus :** Phosphorus is also a strong graphitizer like silicon and its content varies from 0.1 to 0.3 %. Most of the phosphorus combines with iron and forms iron phosphide (Fe_3P). This iron phosphide separates out as eutectic mixture with cementite and austenite. This ternary eutectic of iron phosphide, cementite, and austenite is called *steadite*. Steadite has a freezing temperature of about 980°C and is the last to solidify and therefore occupies interdendritic regions. A relatively small percentage of phosphorus produces large volume of steadite and hence with higher amount of phosphorus, the steadite areas may merge to form a continuous network around the primary dendrites of austenite. Steadite is brittle and therefore, it reduces toughness and increases the brittleness of cast irons. Due to this, the amount of phosphorus must be carefully controlled to obtain optimum mechanical properties. However, phosphorus increases the fluidity of cast irons and makes them easy to cast into thin and complex sections. A typical appearance of steadite is shown in Fig. 11.1.

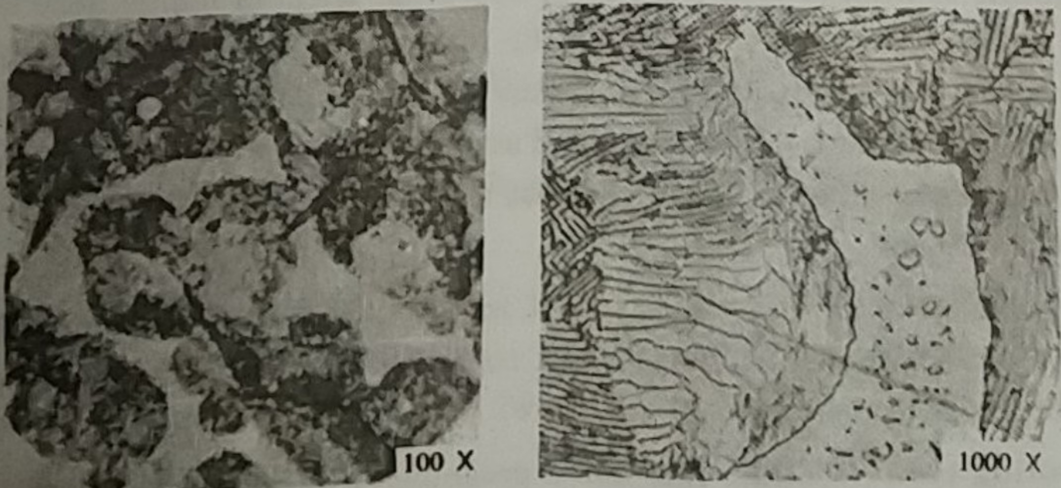


Fig. 11.1 : Microstructure of a gray cast iron showing steadite.

Increasing silicon and phosphorus have almost similar effect as increasing the carbon o the microstructures of cast irons. Their effect in terms of carbon is considered an equivalent carbon is found out as below :

$$\text{Equivalent carbon} = \text{Total carbon} + 1/3\ (\text{Silicon} + \text{Phosphorus})$$

i.e.

$$E.C = T.C + 1/3\ (Si + P) \qquad \ldots(11.2$$

For a given cast iron, equivalent carbon may be used for predicting the amount o graphitization (or graphitization tendency) similar to that without silicon and phosphorus containing the same amount of total carbon by using Fe – Fe_3C equilibrium diagram. Carbon equivalent value can also be used to predict whether the alloy will solidify as hypoeutectic, eutectic, or hypereutectic. It also predicts the chilling tendency of a given section at constant pouring temperature, cooling rate and alloying elements.

(iv) **Amount of sulphur :** Sulphur combines with iron and forms iron sulfide (FeS) which is a hard and brittle compound. Due to its low melting point, it appears at interdendritic regions in a solidified casting and increases the brittleness of casting. Addition of manganese reduces the detrimental effect of sulphur. Sulphur has greater affinity for manganese than for iron and hence, in the presence of manganese, the reaction product is manganese sulphide (MnS) instead of iron sulphide (FeS). MnS appears as small and widely distributed inclusions of rounded or polyhedral shape. Unless MnS is present in large amount, it has little effect on the properties of cast iron. The usual sulphur content of any cast iron is between 0.06 to 0.12%.

Also sulphur in the form of FeS promotes the formation of iron carbide without participating in its formation. It has a strong effect as carbide stabilizer and about 0.01 % sulphur is sufficient to neutralise the graphitizing influence of 0.15% silicon. However, when sulphur is present as MnS, it has almost no influence on carbide or graphite formation.

(v) **Amount of Manganese :** The most important effect of manganese is to reduce the brittleness likely to be introduced due to the formation of iron sulphide. It takes care of sulphur by forming manganese sulphide. Any excess amount of manganese present after combining with all sulphur and forming MnS serves as an useful alloying element. The usual amount of manganese in any commercial cast iron varies between 0.5 to 1.0% (5 to 8 times the amount of sulphur).

In addition to the above elements, cast irons may contain alloying elements such as nickel, chromium, molybdenum, magnesium, copper, aluminium, boron, etc. which are added to obtain the desired properties and structure.

(vi) **Cooling rate :** Cooling rate has a pronounced effect on the microstructure of cast irons. Rapid cooling suppresses the graphitization (i.e. decomposition of Fe_3C to $3Fe \div C$) and results in white structure. Slow cooling favours the graphitization of Fe_3C and may result in gray structure. This results in different structures in thin and thick sections of a casting or in a large casting in which the cooling rate varies from surface to centre.

Presence of relative amounts of various elements in cast irons greatly influence their microstructure for the given conditions of casting. The extent of graphitization or chill depth depends on the amount of graphitizing elements, particularly silicon, present in the cast iron alongwith its equivalent carbon i.e. relative amounts of silicon and carbon determine whether a cast iron will contain cementite, graphite, or both as shown in Fig. 11.2.

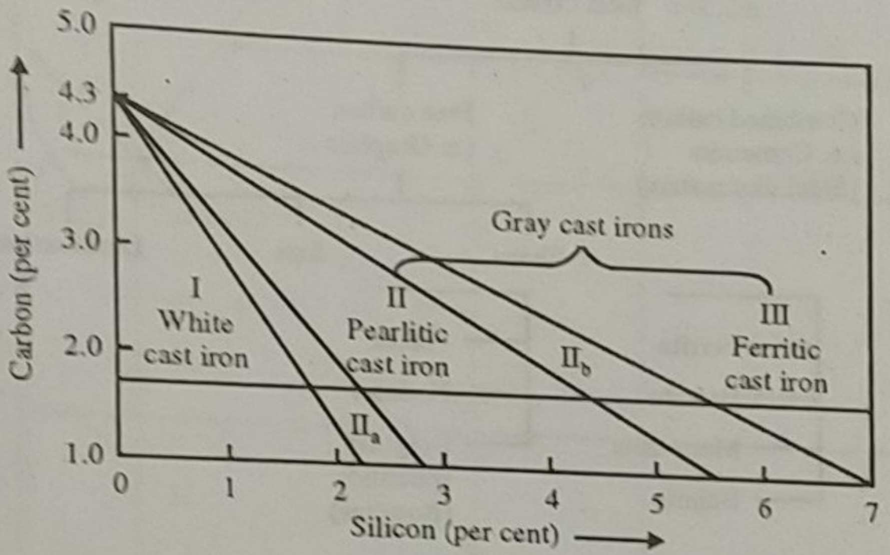
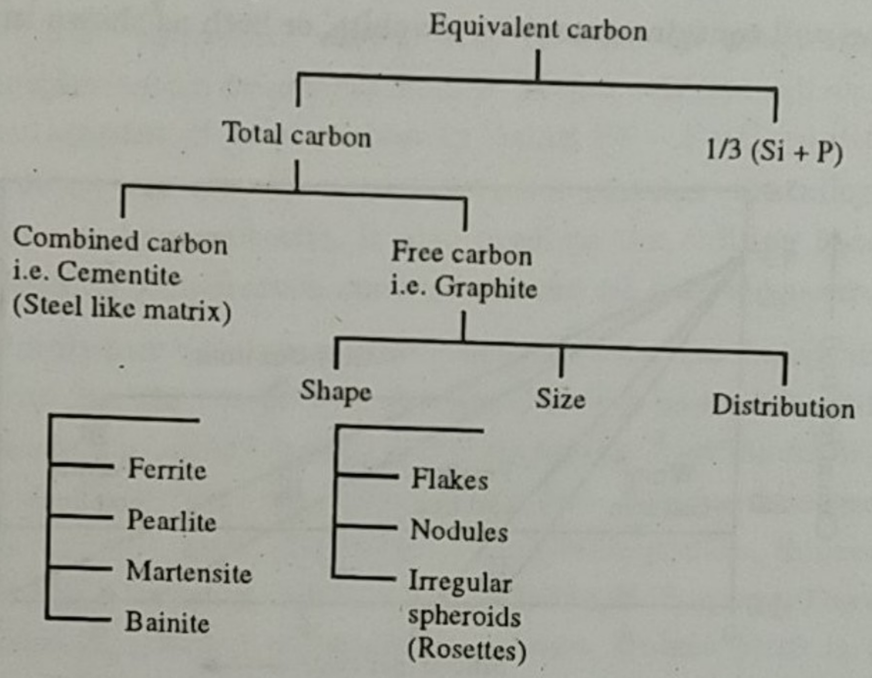


Fig. 11.2 : Diagram showing the relation between structures with carbon and silicon content of cast iron. (Maurer)

In region I, cementite is stable and the structure is that of white cast iron. In region I there is sufficient silicon to cause graphitization of all the cementite except the eutectoi cementite (i.e. the cementite in pearlite). This results in gray cast iron with pearlitic matri In region III, the large amount of silicon promotes the decomposition of all the cementite ar results in the formation of ferrite and graphite, giving a gray cast iron with ferritic matrix. region IIa, the structures are typical of mottled cast iron and IIb, the matrix is pearlitic ferritic.

The properties of cast irons not only depend on the amount of graphite and type matrix but also depend on the shape, size, and distribution of graphite present in the ca irons. Graphite is very soft and weak material and therefore, graphite occupied spac behave almost similar to empty spaces like notches. The amount of graphite can controlled by controlling the total carbon and the amount of graphitizing elemen particularly silicon; shape, size and distribution of graphite can be controlled by addition certain alloying elements, and the matrix can be controlled by controlling the cooling rate by a suitable heat treatment. Due to this, it is easy to control the properties of cast iron over a wider limit and because of low cost, they become an attractive engineering materia for large number of general purpose applications. The overall factors influencing th mechanical properties of a cast iron are shown below :



The various types of cast irons based on microstructure and appearance of fracture are described below in detail.

11.4 WHITE CAST IRONS

In these cast irons, all the carbon is present in the form of combined carbon (i.e. cementite) and there is no free carbon (i.e. graphite). The appearance of a fractured surface is white because of absence of graphite and hence the name is "white cast iron". Since there is no graphitization, the solidification of a white cast iron and the resulting microstructural changes can be exactly indicated by the Fe – Fe_3C equilibrium diagram. The graphitization is suppressed by controlling the chemical composition and cooling rate. Lower silicon content, lower carbon content and rapid cooling results in the prevention of decomposition of cementite.

(A) Cooling of a hypoeutectic cast iron with 3.0% carbon :

The above cast iron is indicated at 3.0% carbon on Fe – Fe_3C equilibrium diagram in Fig. 11.3 and cooling from the molten state is explained below.

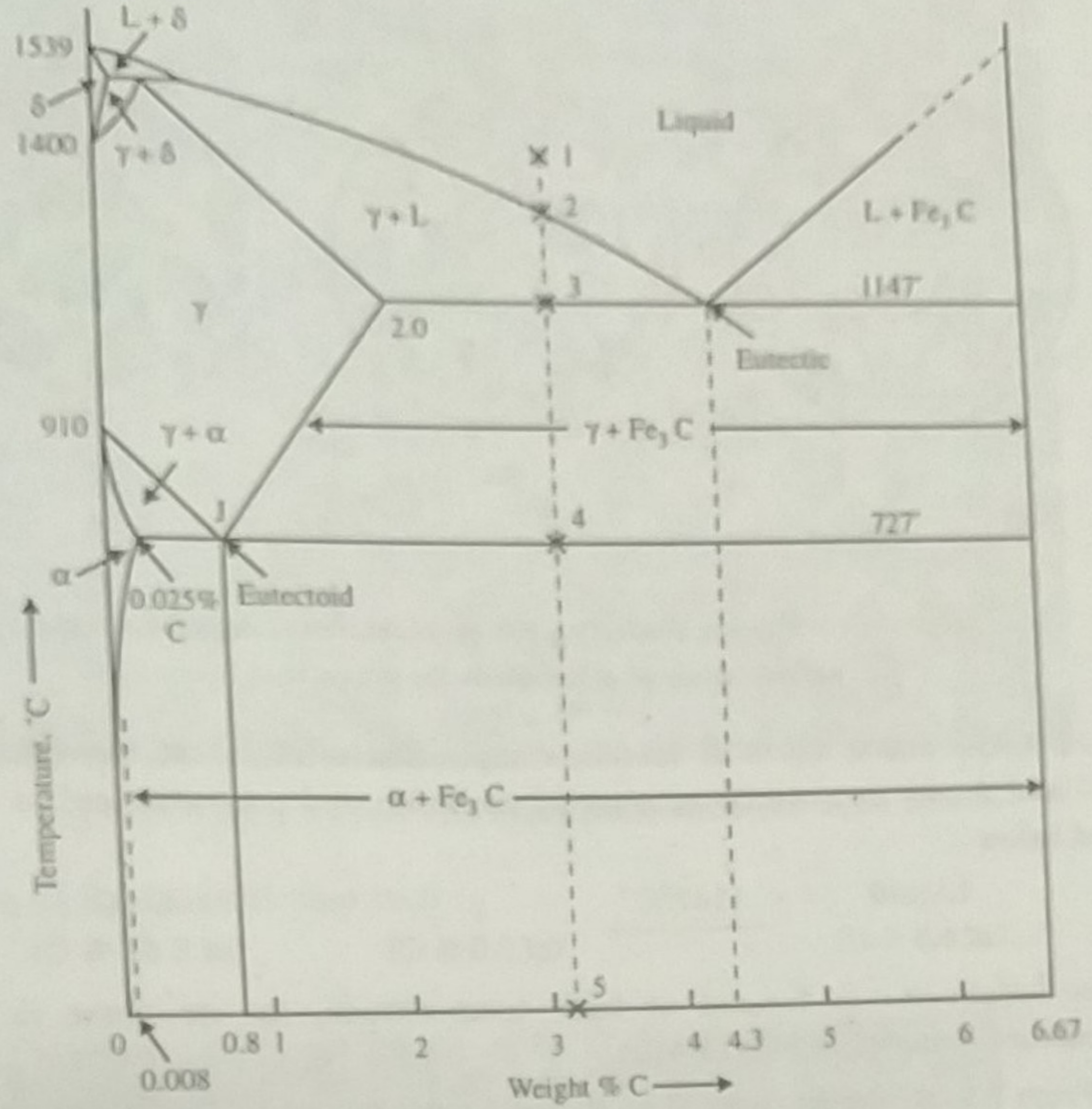


Fig. 11.3 : Fe – Fe_3C equilibrium diagram used to explain the cooling of 3.0% carbon alloy.

(i) From 1 to 2, the alloy is in the liquid state and there is no change in the state of the alloy.

(ii) Just below 2, austenite starts separating out from the liquid and further cooling will increase the amount of austenite. This continues upto 3. This primary or proeutectic austenite is in the dendritic form since it is separating out from the liquid state. The amount of austenite according to lever rule at just above 3 will be :

$$\text{Amount of austenite (of 2.0\% carbon)} = \frac{4.3-3.0}{4.3-2.0} = 56.5\%$$

The remaining 43.5% of the alloy still exists in the liquid state with 4.3% carbon. Th microstructure is shown in Fig. 11.4 (a).

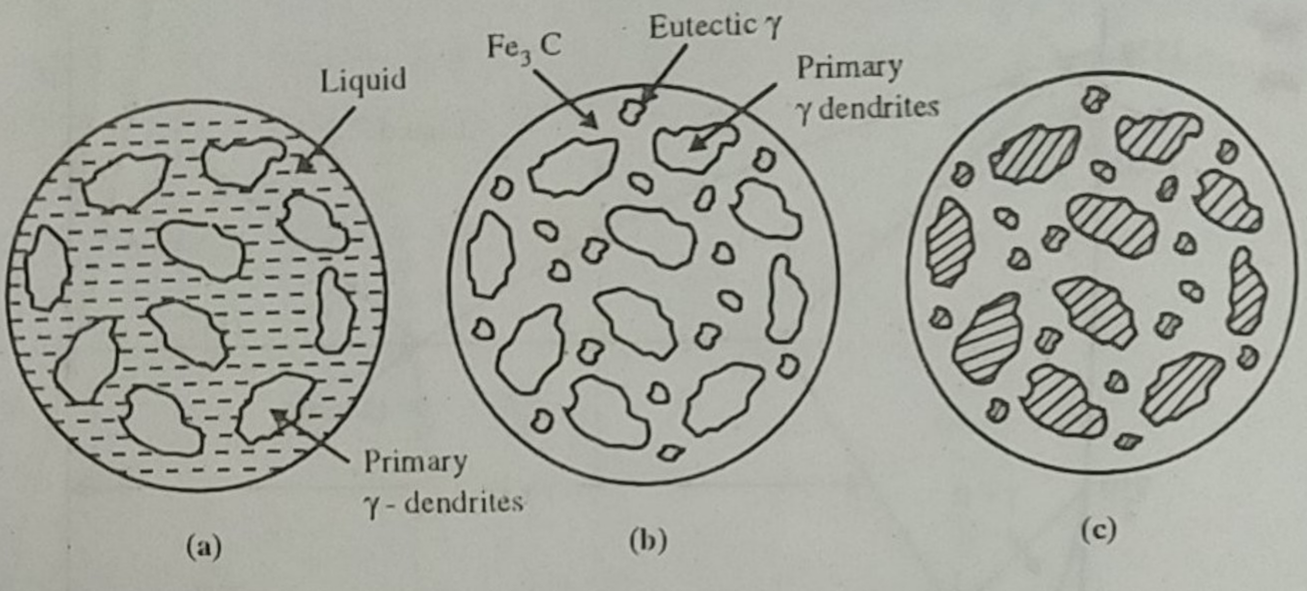


Fig. 11.4 : Figures illustrating the microstructural changes during solidification of a hypoeutectic white cast iron.

(iii) At 3, the above liquid of eutectic composition solidifies at constant temperature (1147°C) and forms an eutectic mixture of austenite and cementite called ledeburite as indicated below :

$$\underset{\text{(of 4.3 \% C)}}{\text{Liquid}} \xrightarrow{1147^\circ\text{C}} \underset{\text{(of 2.0 \% C)}}{\gamma} + \underset{\text{(of 6.67 \% C)}}{Fe_3C}$$

Since ledeburite is formed at high temperature, its structure is coarse. The microstructure is shown in Fig. 11.4 (b).

(iv) From 3 to 4, almost there is no change in the morphology of the existing structure. However, due to the decrease in solubility of carbon in austenite, it (i.e. both primary and eutectic austenite) rejects Fe_3C to the adjacent eutectic cementitic areas. Due to this, the amount of Fe_3C increases. The Fe_3C which separates out from point 3 to 4 is called proeutectoid cementite.

(v) At 4, all the austenite (i.e. primary as well as eutectic) transforms isothermally to an eutectoid mixture of ferrite and cementite i.e. pearlite.

$$\underset{\text{(of 0.8 \% C)}}{\gamma} \xrightarrow{727^\circ\text{C}} \underset{\text{(of 0.025 \% C)}}{\alpha} + \underset{\text{(of 6.67 \% C)}}{Fe_3C}$$

The microstructure is shown in Fig. 11.4 (c).

(vi) From 4 to 5, there is almost no change in microstructure except slight increase in the amount of Fe_3C due to the decrease in solubility of carbon in ferrite from 0.025% to 0.008%.

At room temperature the microstructure consists of dendritic areas of transformed austenite i.e. pearlite in a matrix of transformed ledeburite (Fe_3C + pearlite). A typical microstructure of a hypoeutectic cast iron is shown in Fig. 11.5.