

1.2 Metallurgy of steel

When carbon in small quantities is added to iron, 'Steel' is obtained. Since the influence of carbon on mechanical properties of iron is much larger than other alloying elements. The atomic diameter of carbon is less than the interstices between iron atoms and the carbon goes into solid solution of iron. As carbon dissolves in the interstices, it distorts the original crystal lattice of iron.

This mechanical distortion of crystal lattice interferes with the external applied strain to the crystal lattice, by mechanically blocking the dislocation of the crystal lattices. In other words, they provide mechanical strength. Obviously adding more and more carbon to iron (upto solubility of iron) results in more and more distortion of the crystal lattices and hence provides increased mechanical strength. However, solubility of more carbon influences negatively with another important property of iron called the 'ductility' (ability of iron to undergo large plastic deformation). The α -iron or ferrite is very soft and it flows plastically. Hence we see that when more carbon is added, enhanced mechanical strength is obtained, but ductility is reduced. Increase in carbon content is not the only way, and certainly not the desirable way to get increased strength of steels. More amount of carbon causes problems during the welding process. We will see later, how both mechanical strength and ductility of steel could be improved even with low carbon content. The iron-carbon equilibrium diagram is a plot of transformation of iron with respect to carbon content and temperature. This diagram is also called iron-iron carbon phase diagram (Fig. 1.2). The important metallurgical terms, used in the diagram, are presented below.

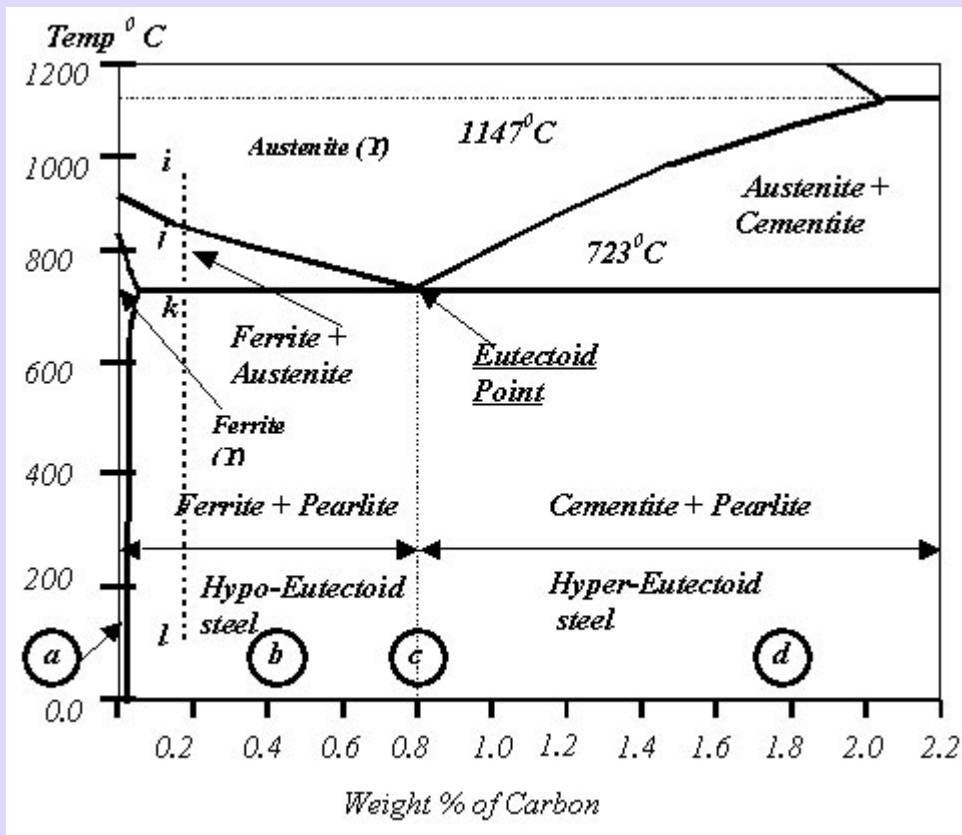


Fig 1.2. The iron – iron carbon phase diagram

Ferrite (α): Virtually pure iron with body centered cubic crystal structure (bcc). It is stable at all temperatures up to 910°C. The carbon solubility in ferrite depends upon the temperature; the maximum being 0.02% at 723°C.

Cementite: Iron carbide (Fe_3C), a compound iron and carbon containing 6.67% carbon by weight.

Pearlite: A fine mixture of ferrite and cementite arranged in lamellar form. It is stable at all temperatures below 723°C.

Austenite (γ): Austenite is a face centred cubic structure (fcc). It is stable at temperatures above 723°C depending upon carbon content. It can dissolve up to 2% carbon.

The maximum solubility of carbon in the form of Fe_3C in iron is 6.67%. Addition of carbon to iron beyond this percentage would result in formation of free carbon or graphite in iron. At 6.67% of carbon, iron transforms completely into cementite or Fe_3C (Iron Carbide). Generally carbon content in structural steels is in the range of 0.12-

0.25%. Upto 2% carbon, we get a structure of ferrite + pearlite or pearlite + cementite depending upon whether carbon content is less than 0.8% or beyond 0.8%. Beyond 2% carbon in iron, brittle cast iron is formed.

1.2.1 The structural steels or ferrite – pearlite steels

The iron-iron carbide portion of the phase diagram that is of interest to structural engineers is shown in Fig.1.2. The phase diagram is divided into two parts called “hypoeutectoid steels” (steels with carbon content to the left of eutectoid point [0.8% carbon]) and “hyper eutectoid steels” which have carbon content to the right of the eutectoid point. It is seen from the figure that iron containing very low percentage of carbon (0.002%) called very low carbon steels will have 100% ferrite microstructure (grains or crystals of ferrite with irregular boundaries) as shown in Fig 1.2. Ferrite is soft and ductile with very low mechanical strength. This microstructure at ambient temperature has a mixture of what is known as ‘pearlite and ferrite’ as can be seen in Fig. 1.2. Hence we see that ordinary structural steels have a pearlite + ferrite microstructure. However, it is important to note that steel of 0.20% carbon ends up in pearlite + ferrite microstructure, only when it is cooled very slowly from higher temperature during manufacture. When the rate of cooling is faster, the normal pearlite + ferrite microstructure may not form, instead some other microstructure called bainite or martensite may result.

We will consider how the microstructures of structural steel are formed by the slow cooling at 0.2% carbon. At about 900°C, this steel has austenite microstructure. This is shown as point ‘i’ in Fig. 1.2. When steel is slowly cooled, the transformation would start on reaching the point ‘j’. At this point, the alloy enters a two-phase field of ferrite and austenite. On reaching the point, ferrite starts nucleating around the grain boundaries of austenite as shown in Fig. 1.3(a). By slowly cooling to point 'k', the ferrite grains grow in size and diffusion of carbon takes place from ferrite regions into the austenite regions as shown in Fig. 1.3(b), since ferrite cannot retain carbon above 0.002% at room temperature.

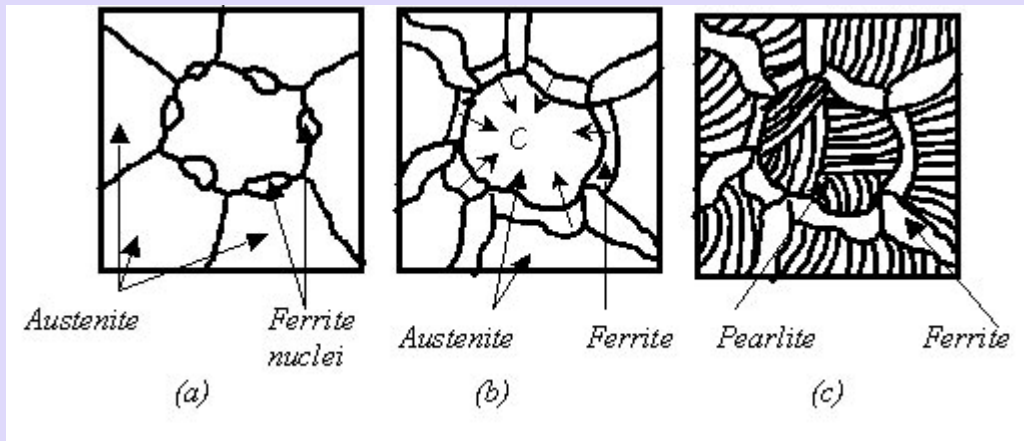


Fig 1.3. Different stages of formation of pearlite

At this point it is seen that a network of ferrite crystals surrounds each austenite grain. On slow cooling to point 'I' the remaining austenite gets transformed into 'pearlite' as shown in Fig 1.3(c). Pearlite is a lamellar mixture of ferrite and cementite. The amount of 'pearlite' for a given carbon content is usually calculated using the lever rule assuming 0% carbon in ferrite as given below:

$$\text{Volume fraction of Pearlite} = \frac{\% \text{ of Carbon}}{0.8\% \text{ of Carbon}}$$

For example for microstructure of a 0.2% carbon steel would consist of a quarter of pearlite and three- quarters of ferrite. As explained earlier, ferrite is soft and ductile and pearlite is hard and it imparts mechanical strength to steel. The higher the carbon content, the higher would be the pearlite content and hence higher mechanical strength. Conversely, when the pearlite content increases, the ferrite content decreases and hence the ductility is reduced.

1.2.2 Strengthening structural steels

Cooling rate of steel from austenite region to room temperature produces different microstructures, which impart different mechanical properties. In the case of structural steels, the (pearlite + ferrite) microstructure is obtained after austenitising, by cooling it very slowly in a furnace. This process of slow cooling in a furnace is called 'annealing'. As, mentioned in the earlier section, the formation of pearlite, which is

responsible for mechanical strength, involves diffusion of carbon from ferrite to austenite. In the annealing process sufficient time is given for the carbon diffusion and other transformation processes to get completed. Hence by full annealing we get larger size pearlite crystals as shown in the cooling diagram in Fig. It is very important to note that the grain size of crystal is an important parameter in strengthening of steel. The yield strength of steel is related to grain size by the equation

$$f_y = f_0 + \frac{k}{\sqrt{d}} \quad (1.1)$$

Where f_y is the yield strength, f_0 is the yield strength of very large isolated crystals (for mild steel this is taken as 5 N/mm^2) and 'k' is a constant, which for mild steel is $38 \text{ N/mm}^{3/2}$. From Eq.1.1 we see that decreasing the grain size could enhance the yield strength. We will see in the following section as to how this reduction of grain size could be controlled. The grain size has an influence both in the case of mechanical strength and the temperature range of the ductile-brittle transition (temperature at which steel would become brittle from a ductile behaviour). When steel is fully annealed, there is enough time for the diffusion or shuffling of carbon atoms and larger crystallization is possible. However, if we increase the cooling rate, then transformation that generally needs a specified time, would not keep up with the falling temperature. When we normalise (cool in air) steel, we obtain a small increase in the ferrite content and a finer lamellar pearlite. Since pearlite is responsible for mechanical strength, decrease in its grain size we get improved mechanical strength. Hence we see that another method of increasing the mechanical strength of steel is by normalising.

Structural steel sections are produced by hot rolling process, which involves the temperature range of austenite. During rolling at this high temperature, the heavy mechanical deformation results in finer size grains. In addition to that, rolling at the temperature of austenite, they are allowed to cool in air (normalising) and hence both the procedures aid the formation of smaller size crystals and hence increased mechanical strength.

1.2.3 Rapid cooling of steels

In the earlier section we saw that steel is made to under-cool by normalizing (by giving lesser cooling time than required by the equilibrium state of the constitutional diagram), it results in finer microstructure. However, if we cool steel very rapidly, say quenching in cold water, there is insufficient time for the shuffling or diffusion of carbon atoms and hence the formation of ferrite + pearlite is prevented. However, such a fast cooling results in 'martensite'. Slightly less rapid cooling could result in a product called 'bainite' which is dependent on the composition of steel. Bainite is formed above a temperature of about 300°C and between a cooling rate of 8.4°C/sec to 0.0062°C/sec. Martensite is formed by rapid cooling rate less than 8.4°C/sec. Very slow cooling, say full annealing does not form both Martensite and Bainite.

Martensite is very hard and less ductile. Martensitic structure is not desirable in structural steel sections used in construction, because its welding becomes very difficult. However, high strength bolts and some other important accessories have predominantly martensitic structure. The hardness of martensite is a function of carbon content. When martensite is heated to a temperature of 600°C it softens and the toughness is improved. This process of reheating martensite is called tempering. This process of quenching and tempering results in very many varieties of steel depending upon the requirement for hardness, wear resistance, strength and toughness.

1.2.4 Inclusions and alloying elements in steel

Steel contains impurities such as phosphorous and sulphur and they eventually form phosphides and sulphides which are harmful to the toughness of the steel. Hence it is desirable to keep these elements less than 0.05%. Phosphorous could be easily removed compared to sulphur. If manganese (Mn) is added to steel, it forms a less harmful manganese sulphide (MnS) rather than the harmful iron sulphide. Sometimes calcium, cerium, and other rare earth elements are added to the refined molten steel. They combine with sulphur to form less harmful elements. Steel treated this way has good toughness and such steels are used in special applications where toughness is the criteria. The addition of manganese also increases the under cooling before the start of the formation of ferrite+ pearlite. This gives fine-grained ferrite and more evenly divided pearlite. Since the atomic diameter of manganese is larger than the atomic diameter of iron, manganese exists as 'substitutional solid solution' in ferrite crystals, by displacing the smaller iron atoms. This improves the strength of ferrite because the distortion of crystal lattice due to the presence of manganese blocks the mechanical movement of the crystal lattices. However, manganese content cannot be increased unduly, as it might become harmful. Increased manganese content increases the formation of martensite and hence hardness and raises its ductile to brittle transition temperature (temperature at which steel which is normally ductile becomes brittle). Because of these reasons, manganese is restricted to 1.5% by weight. Based on the manganese content, steels are classified as carbon-manganese steels ($Mn > 1\%$) and carbon steels ($Mn < 1\%$). In recent years, micro alloyed steels or high strength low alloy (HSLA) steels have been developed. They are basically carbon manganese steels in which small amounts of aluminium, vanadium, niobium or other elements are used to help control the grain size.

These steels are controlled rolled and/or controlled cooled to obtain fine grain size. They exhibit a best combination of strength and toughness and also are generally weldable without precautions such as preheating or post heating. Sometimes 0.5% molybdenum is added to refine the lamellar spacing in pearlite, and to make the pearlite evenly distributed. Today steel with still higher performance are being developed all over the world to meet the following specifications such as: (a) high strength with yield strength of 480 MPa and 690 MPa, (b) excellent weldability without any need for preheating, (c) extremely high toughness with charpy V notch values of 270 N-m @ 23°C compared with current bridge design requirement of 20 N.-m @ 23°C, and (d) corrosion resistance comparable to that of weathering steel. (The terminology used above has been discussed later in this chapter). The micro alloyed steels are more expensive than ordinary structural steels, however, their strength and performance outweighs the extra cost.

Some typical structural steels with their composition range and properties and their relevant codes of practice, presently produced in India, are given in Tables 1.1. These steels are adequate in many structural applications but from the perspective of ductile response, the structural engineer is cautioned against using unfamiliar steel grades, without checking the producer supplied properties. Weldability of steel is closely related to the amount of carbon in steel. Weldability is also affected by the presence of other elements. The combined effect of carbon and other alloying elements on the weldability is given by “carbon equivalent value (Ceq)”, which is given by

$$Ceq = \%C + \% Mn/6 + (\% Cr + \% Mo + \% V)/5 + (\% Ni + \% Cu)/15$$

The steel is considered to be weldable without preheating, if $Ceq < 0.42\%$. However, if carbon is less than 0.12% then Ceq can be tolerated upto 0.45%.

Table 1.1 Chemical composition of some typical structural steels

Type of steel	Designation	IS code:	C	S	Mn	P	Si	Cr		Carbon equivalent
Standard structural steel	Fe410A	2062	0.23	0.50	1.5	0.50	-	-	SK	0.42
	Fe410B	2062	0.22	0.45	1.5	0.45	0.4	-	Sk	0.41
	Fe410C	2062	0.20	0.40	1.5	0.40	0.4	-	K	0.39
Micro alloyed high strength steel	Fe440	8500	0.20	0.50	1.3	0.50	0.45	-	-	0.40
	Fe540	8500	0.20	0.45	1.6	0.45	0.45	-	-	0.44
	Fe590	8500	0.22	0.45	1.8	0.45	0.45	-	-	0.48
K- killed steel SK- Semi Killed steel (Explained in section 1.4.2)										

1.2.5 Stainless steels

In an iron-chromium alloy, when chromium content is increased to about 11%, the resulting material is generally classified as a stainless steel. This is because at this minimum level of chromium, a thin protective passive film forms spontaneously on steel, which acts as a barrier to protect the steel from corrosion. On further increase in chromium content, the passive film is strengthened and achieves the ability to repair itself, if it gets damaged in the corrosive environment. 'Ni' addition in stainless steel improves corrosion resistance in reducing environments such as sulphuric acid. It also changes the crystal structure from bcc to fcc thereby improving its ductility, toughness and weldability. 'Mo' increases pitting and crevice corrosion in chloride environments.

Stainless steel is attractive to the architects despite its high cost, as it provides a combined effect of aesthetics, strength and durability.

Stainless steels are available in variety of finishes and it enhances the aesthetics of the structure. On Life Cycle cost Analysis (LCA), stainless steel works out to be economical in many situations. Increased usage of stainless steel in the construction sector is expected, as awareness on LCA improves among architects and consulting engineers.

