

## ***An Introduction to Steel***

**7.10** The military or industrial power of a nation has long been associated with its ability to produce steel. The might of sixteenth-century Spain was not unconnected with the quality of Toledo steel blades whilst in Britain at about that time the introduction of laws limiting the felling of trees for charcoal production, testified to the quantity of steel then being manufactured. Later, the growth of the Industrial Revolution in Britain gave her world supremacy in steel production as a result of the development of iron and steel making by Dud Dudley and Abraham Darby and, subsequently, by Huntsman, Bessemer, Gilchrist and Thomas. Towards the end of the great Victorian era Britain was manufacturing most of the world's steel and ruling an Empire on which the 'sun never set'.

During the present century depletion—and eclipse—of our home ore supplies combined with the development of vast ore deposits overseas has completely altered the situation. The USA and the CIS (formerly the USSR) owe their material power largely to the presence of high-grade iron ore within, or near to, their own considerable territories putting them among the world leaders in steel production. Britain currently occupies eleventh position behind the CIS, Japan, the USA, PR China, Germany, Italy, Republic of Korea, Brazil, the Benelux Group and France having fallen from the third position she held in the 'steel league' at the end of the Second World War. Many other countries too are increasing their steel-making capacities, generally from ore deposits within their own territories, so that outputs are approaching that of Britain. Of the big steel producers West Germany and Japan, as well as Britain, have to import a large proportion of their ore requirements.

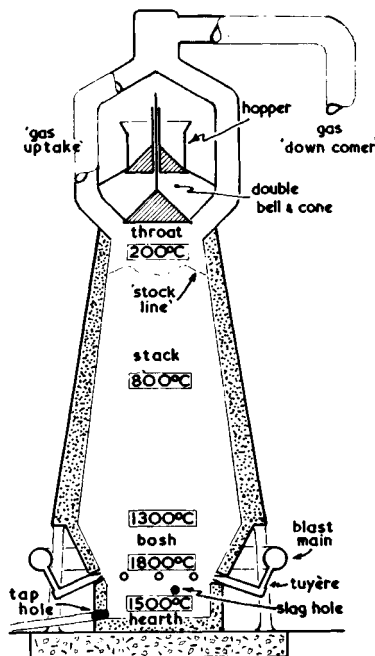
**7.11** The highest quality iron ores are the oxides magnetite,  $\text{Fe}_3\text{O}_4$ , and hematite,  $\text{Fe}_2\text{O}_3$ , some deposits of the former containing almost 70% of the metal. British home-produced ore is low-grade material of the carbonate or hydroxide type, high in phosphorus and containing as little as 20% iron. Fortunately it occurs near to the surface as 'sedimentary' deposits which can be mined by open-cast methods. For this reason three-quarters of the ore used in British blast furnaces has to be imported in the form of

high-grade concentrates from Swedish Lapland, Africa, Canada or Venezuela. The principal *ore* producing countries are (in order of production): CIS, PR China (and DPR Korea), Brazil, Australia, the USA, India, Canada, South Africa, Sweden, Venezuela, Liberia, Mauretania and France.

## Pig Iron Production

**7.20** The smelting of iron ore takes place in the blast furnace (Fig. 7.1). This is a shaft-type furnace some 60 m or more in height and having an output capacity of up to 10 000 tonnes per day. The refractory lining of such a furnace is designed to last for several years since once the furnace goes 'on blast' it would not be economical to shut down for re-lining. Production takes place on a 365 days-a-year basis, though 'damping down'—with the blast turned off or reduced—has to be used for interruptions such as strikes.

Ore, coke and limestone are charged to the furnace through the double bell-and-cone gas-trap system, whilst a pre-heated air blast is blown in through tuyères near the base of the furnace. In order to reduce coke consumption still further and also increase furnace output fuel oil is some-

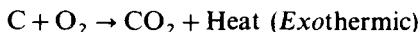


**Fig. 7.1** The iron blast furnace. The complete structure may be sixty or more metres in height.

times injected with the air blast. At regular intervals of several hours both tap hole and slag hole are opened in order to run off, first the slag and then the molten pig iron. The holes are then re-plugged with clay.

**7.21** The smelting operation involves the following main chemical reactions:

(i) Coke in the region of the tuyères burns completely—

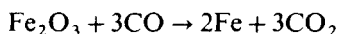


Just above the tuyères the carbon dioxide is reduced by the white-hot coke to carbon monoxide—



On balance the overall reaction is strongly exothermic, so that the temperature remains high.

(ii) As the carbon monoxide, which is a powerful reducing agent, rises through the charge it reduces the iron(III) oxide (in the ore)—

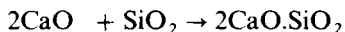


(The reduction occurs in three stages:  $\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4 \rightarrow \text{FeO} \rightarrow \text{Fe}$ .) This reaction takes place in the upper part of the furnace where the temperature is too low for the iron so formed to melt. It therefore remains as a spongy mass until it moves down into the lower part of the furnace where it melts and runs down over the white-hot coke dissolving carbon, sulphur, manganese, phosphorus and silicon as it goes. Apart from carbon—which is absorbed from the coke—these elements are dissolved following their reduction from compounds present as impurities in the original ore.

(iii) At the same time as this reduction is taking place, the earthy waste or 'gangue' associated with the ore combines with lime (formed by the decomposition of limestone added with the charge) to produce a fluid slag:



Limestone      Lime



Calcium silicate (slag)

The function of the lime here is to liquefy the gangue. The latter, being composed largely of silica, would not *melt* at the blast-furnace temperature and must therefore be attacked chemically to form a low melting-point slag which will run from the furnace.

**7.22** The furnace is tapped at regular intervals, the iron generally being stored in the molten state in a 'mixer' prior to transfer to the steel-making plant. Some may be cast as 'pigs' for subsequent re-melting.

In the early days of this century an average blast furnace produced about 100 tonnes of pig iron per day but modern furnaces with outputs of 10 000

tonnes per day are in operation both here and abroad. The approximate quantities of materials in both charge and products for the daily 'throughput' of a medium sized blast furnace would be:

<i>Charge (tonnes)</i>		<i>Products (tonnes)</i>	
Ore (say 50% iron)	4 000	Pig iron	2 000
Coke	1 800	Slag	1 600
Limestone	800	Blast furnace gas	10 800
Air	8 000	Dust	200
Total	<u>14 600</u>	Total	<u>14 600</u>

The slag produced is of low value and is used mainly for 'filling' purposes—railway ballast, road making, concrete aggregate and for the manufacture of slag wool (for thermal and acoustic insulation). It should not be confused with the 'basic slag' used in agriculture which is a by-product of steel-making processes.

One item in the above table which may surprise the reader is the enormous volume of both air and resultant blast-furnace gas involved in the production of a tonne of pig iron. An upwards flow of gas on this scale demands a very *porous* charge in the furnace to allow the passage of gas. For this reason the bulk of the ore used and particularly powdery imported 'concentrates', have to be 'agglomerated' before being charged to the furnace. This involves sintering the fine material to produce strong large lumps. Any fine ore or dust is blown out at the top of the furnace by the upwards rush of gas. The coke too must be strong enough so that it does not crush under the enormous pressure of the charge. Hence special coking-coal is used in its production.

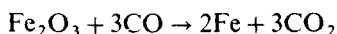
**7.23** The blast-furnace gas contains considerable amounts of carbon monoxide which remain unused during reduction of the ore. Since the gas has a useful calorific value the blast furnace performs a secondary role as a giant gas producer and all of this gas is utilised as fuel. After being cleaned of dust much of it is burned in the Cowper stoves which, in turn, pre-heat the in-going air blast. Two such regenerator stoves are required for each blast furnace. One is being re-heated by the burning blast-furnace gas whilst the other is pre-heating the in-going air. The surplus gas is utilised in many ways in an integrated steel-making plant, eg for raising electric power or for firing different types of re-heating furnace used around the plant.

**7.24 Pig iron** is a complex alloy. In addition to iron it contains up to 10% of other elements, the chief of which are carbon, silicon, manganese, sulphur and phosphorus. These elements are absorbed as the reduced iron melts and runs down through the white-hot coke and slag. The total amount of carbon is usually 3–4% and it may be present either as iron carbide,  $\text{Fe}_3\text{C}$  (also called *cementite*) or as un-combined carbon (*graphite*). A high silicon content of 2.5% or more favours the formation of graphite during solidification so that a fractured surface of the solid iron is grey and the iron is called a 'grey iron'. A low silicon content on the other hand, say 0.5%, will favour the formation of iron carbide,  $\text{Fe}_3\text{C}$ , during solidifi-

cation and the resultant iron will be a 'white iron' since the fractured surface will show white iron carbide. However, the *rate* of solidification of the iron also affects the formation of either graphite or iron carbide as it does in cast iron (15.30). Some grades of pig iron—generally those low in sulphur and phosphorus—are used for the manufacture of iron castings but the bulk of pig iron produced is transferred, still molten, to the steel-making plant.

**7.25 Direct Reduction Processes** The increasing scarcity of coke suitable for use in the blast furnace has led to the development of alternative methods of iron production. Whilst the bulk of iron produced still comes from the blast furnace, these new methods of iron production will doubtless become much more important during the next two decades.

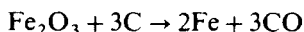
In some of these processes 'pelletised' high-grade ore is fed continuously into a slowly rotating kiln which is fired by natural gas or other hydrocarbons. The fuel provides the necessary heat and also carbon monoxide which effects chemical reduction of the ore:



In a similar process the ore is contained in enclosed retorts through which a mixture of carbon monoxide and hydrogen—derived from natural gas—circulates. Having reduced the ore in the first retort, the 'diluted' gas is then burned to heat the second retort, and so on. Moving-grate furnaces are also used to carry the ore through a reducing flame provided by the partial combustion of natural gas.

The processes mentioned briefly above employ gaseous fuels to heat and reduce the charge, but in other methods cheap solid fuels such as coke breeze or even lignite are used. The product of these processes is known as 'sponge iron'. It is reasonably pure iron but unfortunately is still mixed with the gangue present in the original ore. Since this gangue is mainly silica it must be fluxed with lime when the sponge iron is subsequently remelted for steel making.

**7.26 Electric Iron Smelting Processes** These are also used where coke is expensive, relative to the cost of electricity, as in Scandinavia. These processes more nearly resemble blast-furnace smelting except that heat is supplied by an electric arc rather than by coke, though low-grade coke is used as the reducing agent. The coke is mixed with the ore and fed into a reaction hearth where carbon electrodes provide the heating current. The ore is reduced by the hot coke:

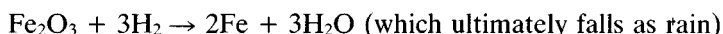


Unlike the direct reduction processes mentioned above where sponge iron is produced, the end-product here is a molten pig iron. The gas leaving the reduction chamber is very rich in carbon monoxide so it is cleaned and used as an energy source in the same way as blast-furnace gas.

Electric smelting of iron has the advantage that it produces less carbon dioxide, whereas for every tonne of pig iron tapped from the blast furnace

some 3.5 tonnes of CO<sub>2</sub> finds its way—by whatever route—into the atmosphere. Thus a large blast furnace producing 10 000 tonnes of pig iron per day is responsible for discharging into the environment about 12 million tonnes of CO<sub>2</sub> every year. This joins the outflow of all other carbon-burning enterprises in promoting the ‘greenhouse effect’.

An alternative method of smelting iron would seem to be by using hydrogen as a reducing agent:



The hydrogen would be provided by the electrolysis of water, using electricity from nuclear power. This is very expensive, and the anti-nuclear lobby would react; but do we have any long-term choice if the Earth itself is not to ‘go critical’ in a rather different sense? In the short term a much more efficient reclamation of scrap steel would help. Instead we allow millions of tonnes to rust and ‘escape’ into the environment every year.

## The Manufacture of Steel

**7.30** Prior to the introduction of the first blast furnaces during the fourteenth century, iron had always been reduced as a *solid* metal by heating a mixture of the ore and charcoal in a hearth-type furnace. Quite small hand-powered bellows were used to provide the air blast and the temperature attained was not high enough to melt the iron released by chemical action from the ore. Instead particles of iron, mixed with large amounts of slag, collected at the bottom of the hearth. These porous masses, called *blooms*, were then hammered so that much of the molten slag was expelled and a bar of relatively pure iron containing some remnant slag particles was the result. By repeatedly forge-welding such bars together and rehammering into a new bar, the slag particles were elongated into fibres (Pl. 11.1b) and *wrought iron* was produced. Later the reduction hearth was replaced by a small shaft-type furnace and much larger bellows were driven by water power. The temperature reached was sufficient to melt the reduced iron and so the first pig iron ran from a blast furnace. This pig iron was then remelted in an open hearth so that the impurities were oxidised and relatively pure iron, of consequently higher melting point, crystallised out. This was then forged to produce wrought iron as before. Oxidation of the remelted pig iron in this way was later known as ‘puddling’.

Being of quite high chemical purity wrought iron had a good resistance to corrosion as is shown by examples of nineteenth-century shipbuilding. Thus the hull of the four-masted sailing ship *Munoz Gamero* built in 1875 but now lying at Punta Arenasin, Chile, shows a remarkably high state of preservation of her puddled iron plates.

**7.31** By the Middle Ages wrought iron had been manufactured, by one method or another, for some four thousand years and it is reasonable to suppose that sooner or later some ancient craftsman would have noticed

that 'wrought iron' could be hardened by cooling it in water provided that it had been heated in a charcoal fire for a sufficiently long time. This ultimately led to the manufacture of steel by what was later called the *Cementation Process*. Bars of wrought iron were packed into stone boxes along with charcoal and heated at about 900°C for a week. Carbon diffused into the solid wrought iron\* and the product was forged to give a more homogeneous steel. Such production methods were expensive and steel was used only as a tool material. In the meantime wrought iron continued to be used for structural and constructional work and was not finally abandoned until the Tay Bridge disaster of 1879 when it was probably quite wrongly blamed for the collapse of the railway bridge.

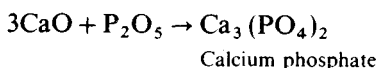
**7.32** In 1742 Benjamin Huntsman, a Sheffield clock maker, decided that his clock springs were breaking because they lacked homogeneity, due largely to the presence of slag in the wrought iron from which the cementation steel had been manufactured. He therefore melted bars of cementation steel so that most of the slag was lost. In this way he ultimately perfected *crucible cast steel* for which Sheffield became justly famous.

**7.33** Modern mass-production methods of steel manufacture began in 1856 when Henry Bessemer attempted to speed up wrought-iron manufacture by blowing air *through* a charge of molten pig iron contained in a pear-shaped 'converter'. Due to the high rate of the chemical reactions involved in the oxidation of impurities such as carbon, silicon and manganese in the pig iron, the temperature ran so high that, instead of solid pure iron crystallising out, the final product remained molten in the converter and had to be cast. After preliminary difficulties had been overcome, *low-carbon steel* suitable for constructional purposes became available for the first time and soon the Bessemer process was established for the mass-production of steel.

Since the Bessemer process was a very rapid production method—the complete 'blow' lasted some half-hour—there was little time available to control the composition and quality of the product. This led to the introduction of the open-hearth process by Siemens-Martin in 1865. In this process pig iron could be melted and refined along with large quantities of steel scrap which was becoming available towards the end of the nineteenth century. The main advantage however, was that the complete refining process in the open-hearth took some eight to ten hours so that there was ample time for control and adjustment of the composition of the product.

Until 1878 only those pig irons low in sulphur and phosphorus were suitable for steel making since, unlike silicon, manganese and carbon, these impurities were not oxidised and removed in the slag. Then came the research of Thomas and Gilchrist which enabled large quantities of high-phosphorus pig iron available in Britain to be converted to steel. To achieve this they added lime to the furnace charge thus producing a *basic slag* which would combine with phosphorus after the latter had been oxidised:

\* The process was similar in principle to modern methods of carburising for case-hardening (19.20).



This calcium phosphate joined the basic slag.

Thus both the Bessemer and open-hearth processes flourished in Britain and, subsequently, elsewhere for almost a century. In either case the process was said to be 'acid' or 'basic'. The acid processes were so called because they utilised low-phosphorus pig irons and therefore did not require the addition of lime to the charge. The slag formed was acid since it contained an excess of silica (derived from oxidised silicon) and to match this the furnace was lined with silica bricks. Those pig irons rich in phosphorus required the charge to be treated with lime and this produces a basic slag. This *basic* slag would quickly attack ordinary *acid* silica brick furnace linings and so furnaces used in basic steel making had to be lined with a *basic* refractory such as 'burnt' magnesite (MgO) or 'burnt' dolomite (MgO.CaO).

**7.34** As low-phosphorus ore became scarce in Britain more and more steel was produced by basic processes. Gradually the basic open-hearth became the dominant steel-making process because of its capability of producing high-quality steel from high-phosphorus raw materials. Nevertheless vast quantities of *mild* steel continued to be made by the Bessemer process; though one of its chief disadvantages was that since only the impurities present in the initial pig iron were available as fuel, to keep the charge molten during the 'blow' no scrap could be added and the pig iron composition had to be between close limits.

Of the air blown into the Bessemer converter only 20% by volume had a useful function in oxidising the impurities. This of course was the oxygen. The remaining 80% (mainly nitrogen) entered the converter cold and emerged as hot gas, thus carrying heat away from the converter and reducing the thermal efficiency of the process. Moreover small amounts of nitrogen dissolved in the steel during the 'blow'. This increased the hardness of the product and frustrated the demand for mild steel of increasing ductility by the motor-car manufacturers and others.

**7.35** In 1952 a new approach to these problems was made in steel plants at Linz and Donawitz in Austria. Here, instead of blowing air through molten pig iron as in the Bessemer process, pure oxygen was injected into the surface of molten pig iron via a water-cooled 'lance'. This process—called the *L-D process*—was made possible by the introduction of cheap 'tonnage' oxygen and though this was the first major steel-making process not to be developed in Britain, it is only fair to say that Bessemer had been aware of the advantages of using oxygen rather than air in his original process. Unfortunately in the nineteenth century oxygen was far too expensive to produce on a large scale.

## Basic Oxygen Steelmaking (BOS)

**7.36** Following the introduction of L-D steelmaking in 1952 a spate of modifications of the process followed. Thus both the Kaldor process



(Sweden) and the Rotor process (West Germany) were popular for a time and it is inevitable that variations of the general oxygen method will continue to be developed. Up to the time of publication all such modifications have had the following features in common:

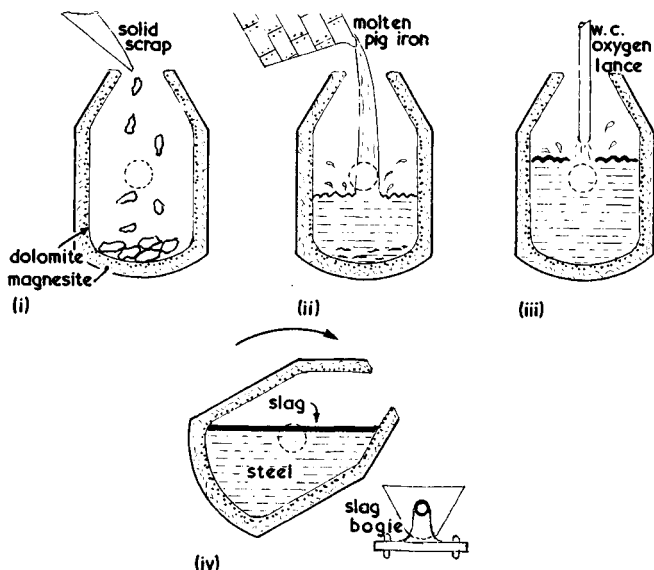
- (i) an oxygen blast is used to oxidise impurities in the original raw material, these oxidised impurities being drawn off in the slag;
- (ii) the processes are chemically basic so that phosphorus removal is effective.

The BOF (basic oxygen furnace) is a pear-shaped vessel of up to 400 tonnes capacity, lined with magnesite bricks covered with a layer of dolomite. Scrap is first loaded into the converter followed by the charge of molten pig iron. Oxygen is then blown at the surface of the molten charge through a water-cooled lance which is lowered through the mouth of the converter (Fig. 7.2).

As soon as the oxidising reaction commences lime, fluorspar and millscale are admitted to the converter to produce a slag on the surface which will collect the impurities oxidised from the charge. At the end of the 'blow' the slag is run off first and the charge of steel then transferred to a ladle for casting as ingots.

BOS has the following major advantages over competing processes:

- (i) It is rapid—the cycling time is about forty-five minutes;
- (ii) Nitrogen contamination is very low so that deep-drawing quality mild steel is produced;



**Fig. 7.2** Stages in the manufacture of steel in a BOF.

The water-cooled oxygen lance may be up to 0.5m in diameter and its tip between 1 and 3m above the surface of the charge—depending upon the composition of the latter.

(iii) Thermal efficiency is high because heat is not carried away by nitrogen as in the former Bessemer process. Hence the charge may include 40%—and in some circumstances 50%—scrap;

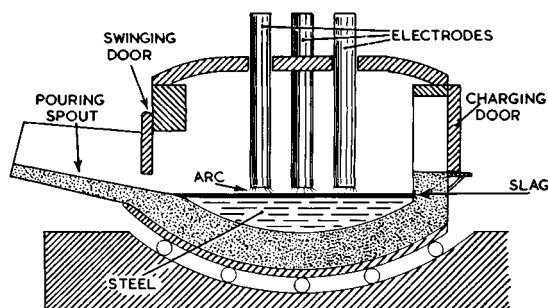
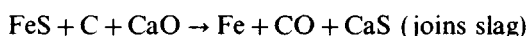
(iv) A wide variety of both scrap and pig iron can be used.

The development of BOS has rendered the Bessemer process completely obsolete whilst the open-hearth process is now used only in Eastern Europe, India and a few Latin American plants.

## Electric Arc Steelmaking

**7.37** This is the only alternative steelmaking process which is significant at present and its operation is complementary to BOS rather than competitive. Originally electric-arc furnaces were used for the manufacture of small amounts of high-grade tool steels and alloy steels. In a modern integrated steel plant it is widely used to melt process scrap and other medium-grade material which can be bought cheaply and then up-graded to produce very high-quality steel. By this means the high cost of electrical energy is largely offset. As electricity offers a chemically neutral method of providing heat, the chemical conditions in the furnace can be altered at will to produce either oxidising or *reducing* slags. The latter favour the removal of sulphur from the charge, making the process one in which sulphur removal is definite.

The furnace (Fig. 7.3) employs carbon rods which strike an arc on to the charge. The lining is basic allowing the addition of lime and millscale in order to produce a basic oxidising slag for the effective removal of phosphorus from the charge as well as any remnant silicon or manganese. Often the slag is then removed to be replaced by a basic *reducing* slag composed of lime, anthracite and fluorspar. This removes sulphur from the charge:



**Fig. 7.3** The principles of the electric-arc furnace for steelmaking.

Hence the main advantages of the arc process are:

- (i) Removal of sulphur is reliable;
  - (ii) Conditions are chemically 'clean' and contamination of the charge is impossible;
  - (iii) Temperature can be accurately controlled;
  - (iv) Carbon content can be adjusted between fine limits;
  - (v) The addition of alloying elements can be made with precision.
- Currently about a quarter of Britain's steel production comes from electric processes. The remainder is from BOS.

## The Microstructural Nature of Carbon Steels

**7.40** Despite the development of many sophisticated alloys in recent years ordinary steel seems likely to remain the most important engineering alloy available. Hence it has been considered desirable to make a preliminary study of the structures and properties of carbon steels at this stage in preparation for a more detailed study later in the book.

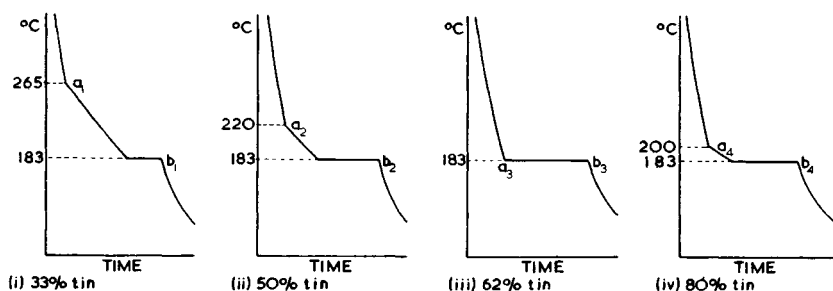
It is impossible adequately to study the structure of a steel, or any other alloy, without reference to what are called 'thermal equilibrium diagrams'—or 'phase diagrams'. Probably some readers will have been introduced to the iron-carbon thermal equilibrium diagram during preliminary studies of materials science. The purpose of this chapter is to clarify such ideas as those readers may have formulated on the subject and also to introduce other readers to this important field of physical metallurgy. Both phase diagrams in general, and that for iron and carbon in particular, will be discussed in succeeding chapters. We will begin by studying the method of construction and also the interpretation of a simple thermal equilibrium diagram by reference to some tin-lead alloys.

**7.41** Most readers will be aware that there are two main varieties of tin-lead solder. Best-quality tinman's solder contains 62% tin and 38% lead\* and its solidification begins and ends at the same temperature—183°C (Fig. 7.4(iii)). Plumber's solder, however, contains 33% tin and 67% lead, and whilst it begins to solidify at about 265°C, solidification is not complete until 183°C (Fig. 7.4(i)). Between 265 and 183°C, then, plumber's solder is in a pasty, partly solid state which enables the plumber to 'wipe' a joint with the aid of his 'cloth' (20.21).

From observations such as these it can be concluded that the temperature range over which a tin-lead alloy solidifies depends upon its composition. On further investigation it will be found that an alloy containing 50% tin and 50% lead will begin to solidify at 220°C, and be completely solid at 183°C; whilst one containing 80% tin and 20% lead will begin to solidify at 200°C and finish solidifying at 183°C.

From the data accumulated above we can draw a diagram which will indicate the state in which any given tin-lead alloy (within the range of

\* Whilst for reasons of economy tinman's solder often contains less than 62% tin (20.21), the latter composition is ideal, since the solder will melt and freeze quickly at a fixed temperature.

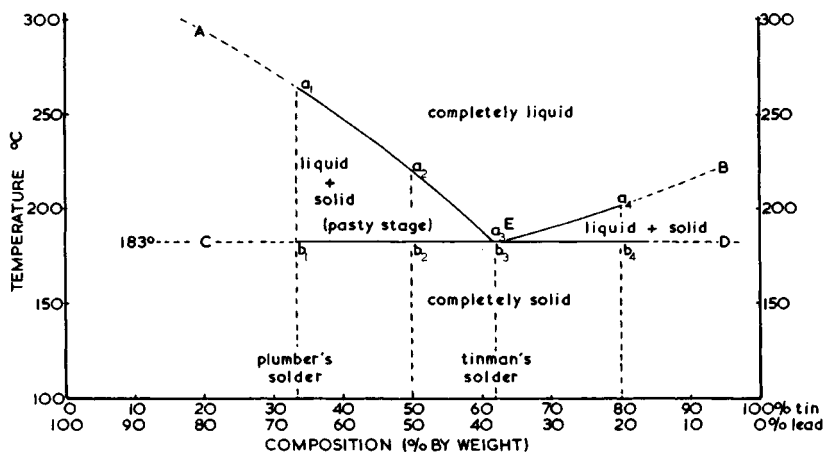


**Fig. 7.4** Temperature/time cooling curves for various tin/lead alloys. Points (a) indicate the temperature at which solidification begins, and points (b) the temperature at which it ends.

compositions investigated) will exist at any given temperature (Fig. 7.5). This diagram has been obtained by plotting the temperatures at which the alloys mentioned above begin and finish solidifying, on a temperature-composition diagram. All points— $a_1, a_2, a_3, a_4$ —at which the various alloys begin to solidify, are joined, as are the points— $b_1, b_2, b_3, b_4$ —where solidification is complete.

Any alloy represented in composition and temperature by a point above *AEB* will be in a completely molten state, whilst any alloy similarly represented by a point below *CED* will be completely solid. Likewise, any alloy whose temperature and composition are represented by a point between *AE* and *CE* or between *EB* and *ED* will be in a part liquid-part solid state.

**7.42** Such a diagram is of great use to the metallurgist, and is called a *thermal-equilibrium diagram*—or *phase diagram*. The meaning of the term



**Fig. 7.5** A diagram showing the relationship between composition, temperature and physical state for the range of tin/lead alloys studied. This is part of the tin/lead thermal equilibrium diagram.

'equilibrium' in this thermodynamical context will become apparent as a result of later studies in this book, but for the moment we will consider an everyday example which goes some way to illustrate its meaning.

On a hot summer's day we can produce a delightfully refreshing drink by putting a cube of ice into a glass of lager. The contents of the glass, however, are not in thermal equilibrium with the surroundings, and as heat-transfer takes place into the lager the ice ultimately melts and the liquid warms up, so that the whole becomes more homogeneous if less palatable. Rapid cooling, as we shall see later, often produces an alloy structure which, like the ice and lager, is not in thermal equilibrium at room temperature. The basic difference between the ice-lager mixture and the non-equilibrium metallic structure is that the former is able to reach 'structural' equilibrium with ease, due to the great mobility of the constituent particles, but in the case of the metallic structure rearrangement of the atoms is more difficult, since they are retained by considerable forces of attraction in an orderly pattern in a crystal lattice. A non-equilibrium metallic structure produced by rapid cooling may therefore be retained permanently at room temperature.

**7.43** If we assume that a series of alloys has been cooled slowly enough for structural equilibrium to obtain, then the thermal-equilibrium diagram will indicate the relationship which exists between composition, temperature and microstructure of the alloys concerned. By reference to the diagram, we can, for an alloy of any composition in the series, find exactly what its structure or physical condition will be at any given temperature. We can also in many cases forecast with a fair degree of accuracy the effect of a particular heat-treatment on the alloy; for in modern metallurgy heat-treatment is not a process confined to steels, but is applied also to many non-ferrous alloys. These are two of the more important uses of the thermal-equilibrium diagram as a metallurgical tool. Let us now proceed with our preliminary study of the iron-carbon alloys, with particular reference to their equilibrium diagram.

**7.50** Plain carbon steels are generally defined as being those alloys of iron and carbon which contain up to 2.0% carbon. In practice most ordinary steels also contain appreciable amounts of manganese residual from a deoxidation process carried out prior to casting. For the present, however, we shall neglect the effects of this manganese and regard steels as being simple iron-carbon alloys.

**7.51** As we have seen (3.14), the pure metal iron, at temperatures below 910°C, has a body-centred cubic structure, and if we heat it to above this temperature the structure will change to one which is face-centred cubic. On cooling, the change is reversed and a body-centred cubic structure is once more formed. The importance of this reversible transformation lies in the fact that up to 2.0% carbon can dissolve in face-centred cubic iron, forming what is known as a 'solid solution',\* whilst

\* We shall deal more fully with the nature of solid solutions in the next chapter, and for the present it will be sufficient to regard a solid solution as being very much like a liquid solution in that particles of the added metal are absorbed without visible trace, even under a high-power microscope, into the structure of the parent metal.

in body-centred cubic iron no more than 0.02% carbon can dissolve in this way.

**7.52** As a piece of steel in its face-centred cubic form cools slowly and changes to its body-centred cubic form, any dissolved carbon present in excess of 0.02% will be precipitated, whilst if it is cooled rapidly enough such precipitation is prevented. Upon this fact depends our ability to heat-treat steels—and, in turn, the present advanced state of our twentieth-century technology.

**7.53** The solid solution formed when carbon atoms are absorbed into the face-centred cubic structure of iron is called *Austenite* and the extremely low level of solid solution formed when carbon dissolves in body-centred cubic iron is called *Ferrite*. For many practical purposes we can regard ferrite as having the same properties as pure iron. In most text-books on metallurgy the reader will find that the symbol  $\gamma$  ('gamma') is used to denote both the face-centred cubic form of iron and the solid-solution austenite, whilst the symbol  $\alpha$  ('alpha') is used to denote both the body-centred cubic form of iron existing below 910°C and the solid-solution ferrite. The same nomenclature will be used in this book.

When carbon is precipitated from austenite it is not in the form of elemental carbon (graphite), but as the compound iron carbide,  $\text{Fe}_3\text{C}$ , usually called *Cementite*. This substance, like most other metallic carbides, is very hard, so that, as the amount of carbon (and hence, of cementite) increases, the hardness of the slowly cooled steel will also increase.

**7.54** Fig. 7.5 indicates the temperatures at which *solidification* begins and ends for any homogeneous *liquid* solution of tin and lead. In the same way Fig. 7.6 shows us the temperatures at which *transformation* begins and ends for any *solid* solution (austenite) of carbon and face-centred cubic iron. Just as the melting point of either tin or lead is lowered by adding each to the other, so is the allotropic transformation temperature of face-centred cubic iron altered by adding carbon. Fig. 7.6 includes only a part of the whole iron-carbon equilibrium diagram, but it is the section which we make use of in the heat-treatment of carbon steels. On the extreme left of this diagram is an area labelled 'ferrite'. This indicates the range of temperatures and compositions over which carbon can dissolve in body-centred cubic ( $\alpha$ ) iron. On the left of the sloping line *AB* all carbon present is dissolved in the body-centred cubic iron, forming the solid-solution ferrite, whilst any point representing a composition and temperature to the right of *AB* indicates that the solid-solution  $\alpha$  is saturated, so that some of the carbon contained in the steel will be present as cementite. The significance of the slope of *AB* is that the solubility of carbon in body-centred cubic iron increases from 0.006% at room temperature to 0.02% at 723°C. Temperature governs the degree of solubility of solids in liquids in exactly the same way.

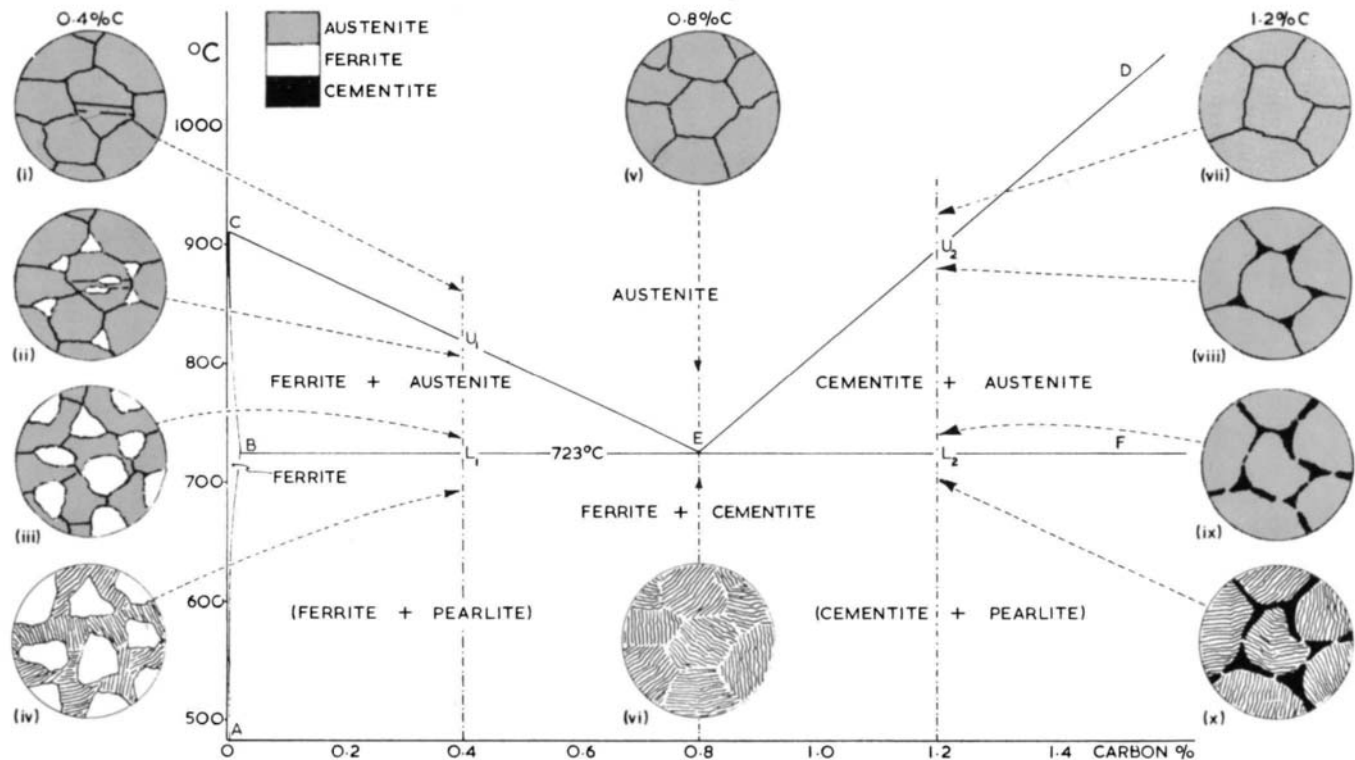
**7.55** We will now study the transformations which take place in the structures of three representative steels which have been heated to a temperature high enough to make them austenitic and then allowed to cool slowly. If a steel containing 0.40% carbon is heated to some temperature above  $U_1$  it will become completely austenitic (Fig. 7.6(i)). On cooling

again to just below  $U_1$  (which is called the 'upper critical temperature' of the steel), the structure begins to change from one which is face-centred cubic to one which is body-centred cubic. Consequently, small crystals of body-centred cubic iron begin to separate out from the austenite. These body-centred cubic crystals (Fig. 7.6(ii)) retain a small amount of carbon (less than 0.02%), so we shall refer to them as crystals of ferrite. As the temperature continues to fall the crystals of ferrite grow in size at the expense of the austenite (Fig. 7.6(iii)), and since ferrite is almost pure iron, it follows that most of the carbon present accumulates in the shrinking crystals of austenite. Thus, by the time our piece of steel has reached  $L_1$  (which is called its 'lower critical temperature') it is composed of approximately half ferrite (containing only 0.02% carbon) and half austenite, which now contains 0.8% carbon. The composition of the austenite at this stage is represented by  $E$ . Austenite can hold no more than 0.8% carbon in solid solution at this temperature (723°C), therefore, as the temperature falls still farther, the carbon begins to precipitate as cementite. At the same time ferrite is still separating out and we find that these two substances, ferrite and cementite, form as alternate layers until all the remaining austenite is used up (Fig. 7.6(iv)). This laminated structure of ferrite and cementite, then, will contain exactly 0.8% carbon, so that it will account for approximately half the volume of our 0.4% carbon steel. It is an example of what, in metallurgy, we call a *eutectoid* (8.43). This particular eutectoid is known as *Pearlite* because when present on the etched surface of steel it acts as a 'diffraction grating', splitting up white light into its component spectrum colours and giving the surface a 'mother of pearl' sheen. In order to be able to see these alternate layers of ferrite and cementite of which pearlite is composed, a metallurgical microscope capable of a magnification in the region of 500 diameters is necessary.

Any steel containing less than 0.8% carbon will transform from austenite to a mixture of ferrite and pearlite in a similar way when cooled from its austenitic state. Transformation will begin at the appropriate upper critical temperature (given by a point on  $CE$  which corresponds with the composition of the steel) and end at the lower critical temperature of 723°C. The relative amounts of ferrite and pearlite will depend upon the carbon content of the steel (Fig 7.7), but in every case the ferrite will be almost pure iron and the pearlite will contain exactly 0.8% carbon.

**7.56** A steel containing 0.8% carbon will not begin to transform from austenite on cooling until the point  $E$  is reached. Then *transformation* will begin and end at the same temperature (723°C), just as tinman's solder *solidifies* at a single temperature (183°C). Since the steel under consideration contained 0.8% carbon initially, it follows that the final structure will be entirely pearlite (Fig 7.6(vi)).

**7.57** A steel which contains, say, 1.2% carbon will begin to transform from austenite when the temperature falls to its upper critical at  $U_2$ . Since the carbon is this time in excess of the eutectoid composition, it will begin to precipitate first; not as pure carbon but as needle-shaped crystals of cementite round the austenite grain boundaries (Fig 7.6(viii)). This will cause the austenite to become progressively less rich in carbon, and by the



**Fig. 7.6** Part of the iron-carbon thermal equilibrium diagram.



time a temperature of 723°C has been reached the remaining austenite will contain only 0.8% carbon. This remaining austenite will then transform to pearlite (Fig 7.6(x)), as in the two cases already dealt with.

Any steel containing more than 0.8% carbon will have a structure consisting of cementite and pearlite if it is allowed to cool slowly from its austenitic state. Since the pearlite part of the structure always contains alternate layers of ferrite and cementite in the correct proportions to give an overall carbon content of 0.8% for the pearlite, it follows that any variation in the total carbon content of the steel above 0.8% will cause a corresponding variation in the amount of primary cementite present. (The terms 'primary cementite' and 'primary ferrite' are used to denote that cementite or ferrite which forms first, before the residual austenite transforms to pearlite.)

A plain carbon steel which contains less than 0.8% carbon is generally referred to as a *hypo-eutectoid* steel, whilst one containing more than 0.8% carbon is known as a *hyper-eutectoid* steel. Naturally enough, a plain carbon steel containing exactly 0.8% carbon is called a *eutectoid* steel.

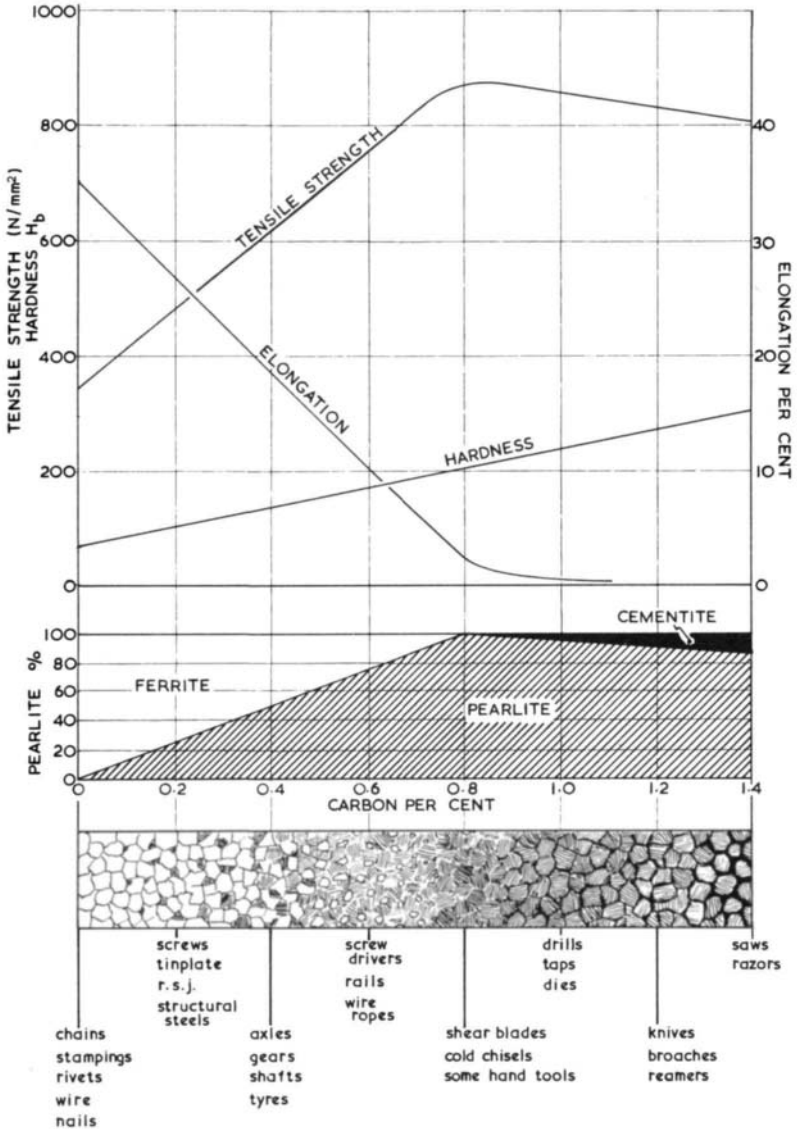
**7.60** So far we have been dealing only with the types of structure produced when plain carbon steels are cooled slowly from the austenitic condition. Such conditions prevail during industrial processes such as normalising and annealing. By very rapid cooling from the austenitic condition, such as would be obtained by water-quenching, another structure, called *Martensite*, is formed. This does not appear on the equilibrium diagram simply because it is not an equilibrium structure. Rapid cooling has prevented equilibrium from being reached.

**7.61** As most readers will already know, martensite is very hard indeed. Unfortunately it is also rather brittle, and the steel is used in this condition only when extreme hardness is required. To increase the steel's toughness after quenching (at the expense of a fall in hardness) the steel can be *tempered*. A modification in the structure will take place depending upon the tempering temperature. This temperature will vary between 250 and 650°C according to the combination of mechanical properties required in the finished component. Whatever temperature is used, tempering assists the microstructure to proceed in some measure back towards equilibrium, with the precipitation of microscopical particles of cementite in varying amounts from the original martensitic structure. The type of structure formed by tempering at about 400°C was formerly known as *Troostite*, whilst that produced in the region of 600°C used to be called *Sorbite*. Metallurgists now discourage the use of these terms for reasons which will be explained later when the heat-treatment of steel is discussed more fully in Chapters 11 and 12.

## The Uses of Plain Carbon Steels

**7.70** By varying the amount of carbon in a steel, and by selecting a heat-treatment programme suited to that carbon content, we are able to produce a vast range of different mechanical properties such as are avail-

able in no other metallic alloy. Moreover, carbon steel is a relatively inexpensive alloy when compared with non-ferrous alloys generally. Small wonder then that steel is by far our most important engineering alloy. Possibly its most serious fault is that it rusts and we must often spend considerable amounts of money on protecting its surface from atmospheric corrosion (21.10).



**Fig. 7.7** A diagram showing the relationship between carbon content, microstructure and mechanical properties of plain carbon steels in the *normalised* condition. Typical uses of these steels are also indicated.

As shown in Fig. 7.7, the hardness of a plain carbon steel increases progressively with increase in carbon content, so that generally the low- and medium-carbon steels are used for structural and constructional work, whilst the high-carbon steels are used for the manufacture of tools and other components where hardness and wear-resistance are necessary.

Commercial plain carbon steels may be classified into five groups as indicated in Table 7.1 which, along with Fig. 7.7, indicates some of the common uses of these alloys.

**Table 7.1**

<i>Type of steel</i>	<i>Percentage carbon</i>	<i>Uses</i>
Dead mild	0.05–0.15	Chain, stampings, rivets, wire, nails, seam-welded pipes, mattresses, hot- and cold-rolled strip for many purposes
Mild	0.10–0.20	Structural steels, RSJ, screws, machine parts, tin-plate, case-hardening, drop-forgings, stampings
	0.20–0.30	Machine and structural work, gears, free-cutting steels, shafting, levers, forgings
Medium carbon	0.30–0.40	Connecting-rods, shafting, wire, axles, fish-plates, crane hooks, high-tensile tubes, forgings
	0.40–0.50	Crankshafts, axles, gears, shafts, die-blocks, rotors, tyres, heat-treated machine parts
	0.50–0.60	Loco tyres, rails, laminated springs, wire ropes
High carbon	0.60–0.70	Drop-hammer dies, set-screws, screw-drivers, saws, mandrels, caulking tools, hollow drills
	0.70–0.80	Band saws, anvil faces, hammers, wrenches, laminated springs, car bumpers, small forgings, cable wire, dies, large dies for cold presses
	0.80–0.90	Cold chisels, shear blades, cold setts, punches, rock drills, some hand tools
Tool steels	0.90–1.00	Springs, high-tensile wire, axes, knives, dies, picks
	1.00–1.10	Drills, taps, milling cutters, knives, screwing dies
	1.10–1.20	Ball bearings, dies, drills, lathe tools, woodworking tools
	1.20–1.30	Files, reamers, knives, broaches, lathe and wood-working tools
	1.30–1.40	Saws, razors, boring and finishing tools, machine parts where resistance to wear is essential

## Exercises

1. Show how the exploitation of new iron ore fields has helped to change the balance of world power during the present century. (7.10)
2. What advantages has 'direct reduction' over the blast-furnace process for pig iron production? (7.25)
3. Outline the essential chemistry common to all modern steel-making processes. (7.33–7.36)
4. Discuss both the economic and technical advantages of modern BOS processes as compared with the obsolete Bessemer process. (7.36)
5. Why has electric-arc steelmaking survived despite the high cost of electric power? (7.37)