

Section 2: THE MICROSTRUCTURAL NATURE OF CARBON STEELS

The Equilibrium Diagram

The phase changes that occur in metals have been studied for many years, the best way of recording and displaying this information is by way of an equilibrium or phase diagram.

A phase diagram is a graphical representation of what is happening in an alloy system. The main system we will look at is the iron-carbon diagram.

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.

Plain carbon steels are generally defined as being those alloys of iron and carbon which contain up to 2.0% carbon.

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

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.

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 γ ('gamma') is used to denote both the face-centred cubic form of iron and the solid solution austenite, whilst the symbol α ('alpha') is used to denote both the body-centred cubic form of iron existing below 910°C and the solid-solution ferrite.

When carbon is precipitated from austenite it is not in the form of elemental carbon (graphite), but as the compound iron carbide, Fe_3C , 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.

Figure 9 shows us the temperatures at which transformation begins and ends for any solid solution (austenite) of carbon and face-centred cubic iron. The allotropic transformation temperature of face-centred cubic iron is altered by adding carbon. Figure 9 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 labeled 'ferrite'. This indicates the range of temperatures and compositions over which carbon can dissolve in body-centred cubic (α) 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 α 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.

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 9(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. 9(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. 9(iii)), and since ferrite is almost pure iron, it follows that most of the carbon present accumulates in the shrinking crystals of austenite. 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. 9(iv)). 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.

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 9), but in every case the ferrite will be almost pure iron and the pearlite will contain exactly 0.8% carbon.

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). Since the steel under consideration contained 0.8% carbon initially, it follows that the final structure will be entirely pearlite (Fig 9(vi)).

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.

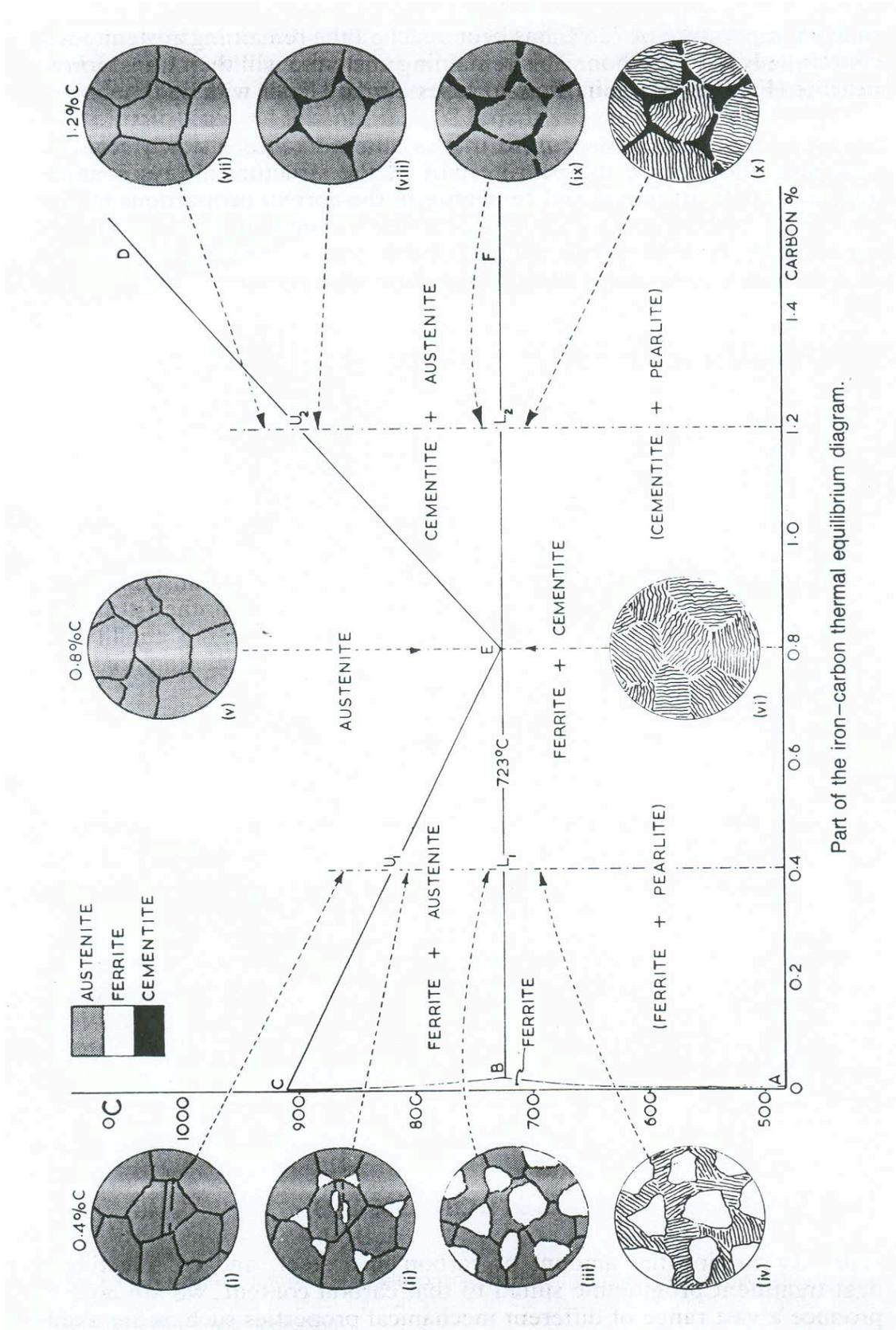
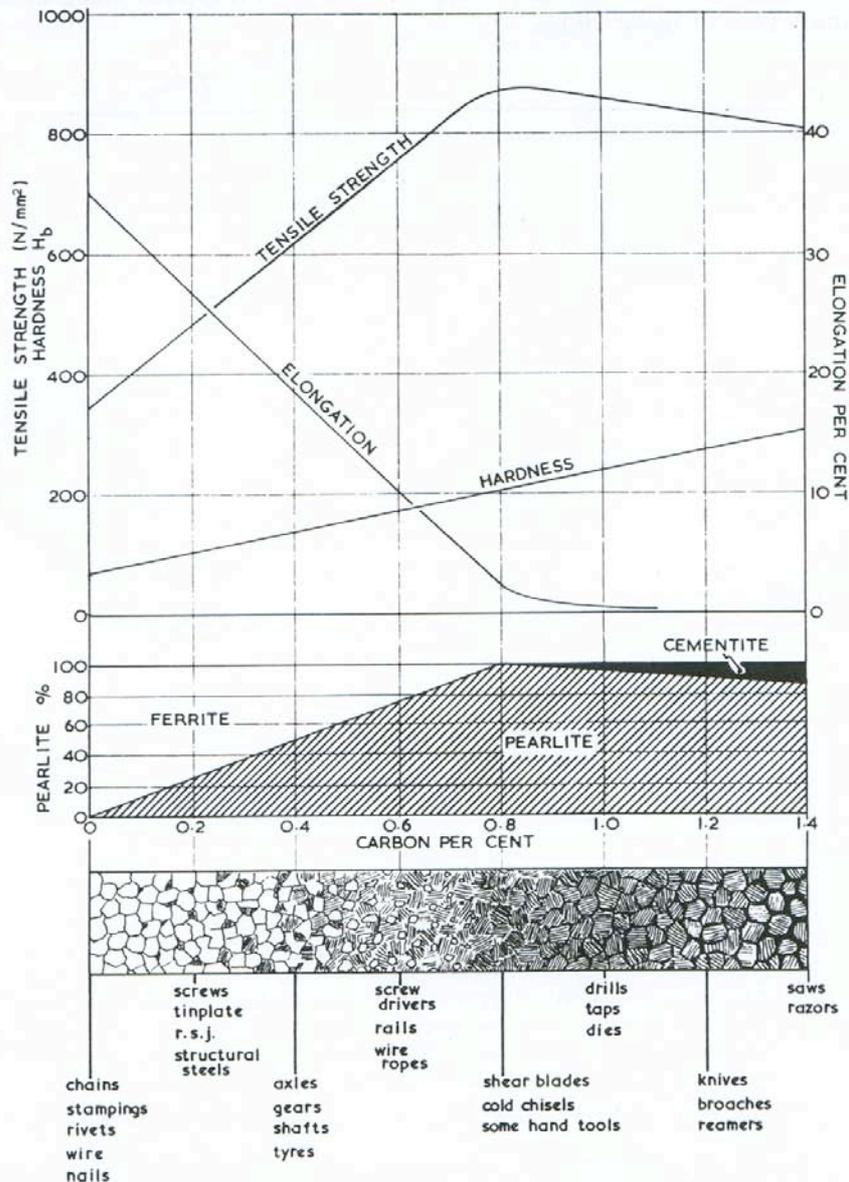


Figure 9: Part of the iron – carbon thermal equilibrium diagram

The Uses of Plain Carbon Steels

As shown in Figure 10, 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.



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.

Figure 10