11______ The Heat-Treatment of Plain Carbon Steels—(I)

11.10 Most modern schoolboys appear to be aware of the fact that a piece of carbon steel can be hardened by plunging it into cold water from a condition of bright red heat. Unfortunately many of them assume that similar treatment will harden *any* metallic material. Which illustrates the danger of feeding unrelated and unexplained facts to schoolboys! Be that as it may there are numerous examples where metallurgical technology has predated its scientific understanding. Steel has been hardened by quenching for many centuries, yet it was only during the present century that a reasonable scientific explanation of the phenomenon was forthcoming.

In the first part of this chapter we shall consider the development of equilibrium structures in steels in greater detail than was possible in Chapter 7. We shall follow this with a study of those heat-treatment processes which depend upon equilibrium being reached in the structure of the steel under treatment.

11.11 What is generally called the 'iron-carbon thermal equilibrium diagram' is illustrated in Fig. 11.1. Strictly speaking it should be named the 'iron-iron carbide metastable system' since, theoretically at least, iron carbide is not a completely stable phase. Nevertheless iron carbide precipitates from austenite, during ordinary conditions of cooling, in preference to the theoretically more stable graphite. Once formed iron carbide—or cementite—is quite stable and for our purposes it will be satisfactory to regard it as an equilibrium phase.

The iron-carbon diagram is of the type dealt with in 9.60, that is, where two substances are completely soluble in each other in the liquid state but are only partially soluble in the solid state. The diagram is modified in shape as a result of the polymorphic changes occurring in iron at 910°C and 1400°C. However, despite the apparent complexity of the diagram, we have only three important phases to consider, namely:



Fig. 11.1 The iron-carbon thermal equilibrium diagram.

- (i) austenite (γ), the solid solution formed when carbon dissolves in face-centred cubic iron in amounts up to 2.0%;
- (ii) ferrite (α), a very dilute solid solution of carbon in body-centred cubic iron and containing at the most only 0.02% carbon;
- (iii) *cementite*, or iron carbide, Fe_3C , an interstitial compound (8.31) of iron and carbon containing 6.69% carbon.

For the sake of clarity the important areas of the iron-carbon diagram are shown in greater detail in Figs. 11.2, 11.3 and 11.4.

The reader may well have seen different values ascribed to the salient points of the iron-carbon diagram, depending upon the age of the publication, its author and even the country of origin. In fact during the professional lifetime of the present author the carbon content of austenite at the eutectoid point has been accepted as 0.89; 0.85; 0.83; 0.80 and 0.77% —and not necessarily in that order! At the same time the eutectoid, or lower critical, temperature has been quoted between 698 and 732°C; whilst the maximum solubility of carbon in austenite (at 1131°C) has been given different values between 1.7 and 2.08%. This lack of precision leading to a variation of no less than 15% in the value ascribed to the carbon content of the eutectoid composition, is due to the large number of variable influences prevailing during the *experimental* determination of these salient points combined with the rather imprecise methods which are available, mainly microexamination, to make such determinations.

Having redrawn the iron-carbon diagrams at each new edition of this book a number of times in the past, this author has decided to settle on



Fig. 11.2 The upper section of the iron-carbon diagram which includes a peritectic transformation.

the 'round' figures of 0.8% and 2.0% as the eutectoid and maximum carbon contents of austenite respectively. However the student should perhaps be warned—take note of the particular values used by your lecturer or you may lose marks in examinations.

11.20 Let us now consider the type of structure likely to be produced in a large steel sand-casting, containing 0.3% carbon, as it solidifies and cools slowly to room temperature. Such an alloy will begin to solidify at temperature T (Fig. 11.2) by forming dendrites of the solid solution δ of composition X. These dendrites will develop and change in composition along XC due to diffusion promoted by the slow rate of cooling, until at 1493°C they will be of composition C (0.1% carbon). The remaining liquid will have become correspondingly enriched in carbon and will be of composition B (0.51% carbon).

$$\frac{\text{Weight of } \delta (0.1\% \text{ carbon})}{\text{Weight of liquid } (0.51\% \text{ carbon})} = \frac{OB}{OC} = \frac{(0.51 - 0.3)}{(0.3 - 0.1)} = \frac{0.21}{0.2} = 1.05/1$$

Application of the Lever Rule (above) indicates that at this stage there will be approximately equal amounts of δ and liquid. At 1493°C a peritectic interaction takes place between the remaining liquid and the dendrites of

 δ , resulting in the disappearance of the latter and the formation of austenite (γ) of composition *P* (0.16% carbon).

 $\frac{\text{Weight of austenite (0.16\% carbon)}}{\text{Weight of liquid (0.51\% carbon)}} = \frac{OB}{OP}$ $= \frac{(0.51 - 0.3)}{(0.3 - 0.16)}$ $= \frac{0.21}{0.14}$ = 1.5/1

Thus there is now one-and-a-half times as much austenite as there is remaining liquid, and, as the temperature falls, the remaining liquid solidifies as austenite which will change in composition along PY. Solidification will be complete at Y and the austenite crystals will be of uniform composition containing 0.3% carbon. Since carbon is dissolved interstitially it can diffuse rapidly through the face-centred cubic structure of the austenite and because our large steel sand-casting will be cooling slowly there will be virtually no coring remaining in the structure.

11.21 Apart from considerable grain growth of the austenite no further change will take place in the microstructure until the line FE (Fig. 11.3) is reached at F'. The temperature represented by F' is called the *upper critical* (or A₃) *temperature* of this 0.3% carbon steel. Thus the upper critical temperature of a steel varies with its carbon content and will be



Fig. 11.3 The 'steel' portion of the iron-carbon diagram.

represented by the appropriate point on FEG. As the temperature of our 0.3% carbon steel falls below F' the face-centred cubic austenite becomes unstable and the polymorphic transformation (3.14) to body-centred cubic ferrite (α) begins. Thus, crystals of ferrite nucleate within the austenite crystals and grow progressively by absorbing the austenite structure. Since the ferrite which forms first contains very little carbon (K) it follows that the shrinking crystals of austenite will become increasingly rich in carbon. Since transformation from austenite to ferrite is accompanied by diffusion the composition of the ferrite will change slightly along KH whilst the austenite will change in composition along F'E. At 723°C (L) the ferrite will contain 0.02% carbon and the remaining austenite 0.8% carbon, and:

$$\frac{\text{Weight of ferrite } (0.02\% C)}{\text{Weight of austenite } (0.8\% C)} = \frac{LE}{LH}$$
$$= \frac{(0.8 - 0.3)}{(0.3 - 0.02)}$$
$$= \frac{0.5}{0.28}$$
$$= 1.79/1$$

Thus there is almost twice as much ferrite present as there is austenite.

11.22 At 723°C the remaining austenite transforms to the eutectoid pearlite by forming alternate layers of ferrite and cementite as previously described (7.55 and 8.43). The temperature, 723°C, at which pearlite is formed is called the *lower critical* (or A_1) *temperature*, and is the same for carbon steels of all compositions since the eutectoid temperature is constant, ie *HEJ* is horizontal. Since the whole of the austenite remaining at 723°C has transformed to pearlite it follows that the proportions ferrite/pearlite will be 1.79/1 as calculated above. That is, the microstructure would show roughly twice as much ferrite as pearlite.

11.23 A 0.8% carbon steel will begin to solidify at approximately 1470°C by depositing dendrites of austenite of composition R (Fig. 11.1) and, when solidification is complete, the structure will consist of crystals of austenite of overall composition 0.8% carbon. As the steel cools slowly, the structure becomes uniform by rapid diffusion and no further structural change will take place until the point E (Fig. 11.3) is reached. For a steel of this composition the upper and lower critical temperatures coincide and the austenitic structure transforms at this temperature to one which is totally pearlitic.

11.24 A 1.2% carbon steel will solidify in a similar way to the 0.8% carbon steel by forming austenite crystals of an overall carbon content of 1.2%. As the temperature falls to the upper critical for this alloy at G' (Fig. 11.3) needles of primary cementite begin to precipitate at the crystal boundaries of the austenite (at least the cementite appears to be needle-like in form in a *two-dimensional* microscope view but in fact we will be seeing cross-sections through flat cementite plates). Since cementite is being deposited the remaining austenite will be rendered less rich in carbon, so



Plate 11.1 11.1A Commercially pure ('Armco') iron, showing crystals of ferrite. \times 100. Etched in 2% nital.

11.1B Wrought iron (longitudinal section), showing slag fibres in a background of ferrite. \times 100. Etched in 2% nital.

11.1C 0.5% carbon steel in the cast condition showing Widmanstätten structure of ferrite (light) and pearlite (dark), \times 50. Etched in 2% nital.



Plate 11.211.2A 0.15% carbon steel in the normalised condition.Ferrite and a small amount of pearlite (dark). \times 100. Etched in 2% nital.11.2B 0.5% carbon steel, normalised.Roughly equal amounts of ferrite and pearlite. \times 100. Etched in 2% nital.11.2C 0.8% carbon steel, normalised.All pearlite. \times 100. Etched in 2% nital.



Plate 11.3 11.3A The structure of lamellar pearlite revealed by a micrograph taken at × 1000. Etched picral-nital. (*Courtesy of United Steel Companies Ltd, Rotherham*) 11.3B 1.3% carbon steel, normalised.

Network of free cementite around the patches of pearlite, \times 100. Etched in 2% Nital. (Courtesy of Hadfields Ltd, Sheffield).

11.3C Similar to 11.3B, but higher magnification reveals the lamellar nature of the pearlite as well as the network of free cementite. \times 750. Etched picral-nital. (Courtesy of United Steel Companies Ltd, Rotherham).

that its composition will move to the left and when the temperature has fallen to 723°C the remaining austenite will contain 0.8% carbon. As before, pearlite will now form, giving a final structure of primary cementite in a matrix of pearlite.

11.25 Thus, in a steel which has been permitted to cool slowly enough to enable it to reach structural equilibrium, we shall find one of the following structures:

(a) With less than 0.006% carbon it will be entirely ferritic. In practice, such an alloy would be classed as commercially pure iron.

(b) With between 0.006% and 0.8% carbon the structure will contain ferrite and pearlite. The relative proportions of ferrite and pearlite appearing in the microstructure will vary according to the carbon content, as shown in Fig. 7.7.

(c) With exactly 0.8% carbon the structure will be entirely pearlitic.

(d) With between 0.8% and 2.0% carbon the structure will consist of cementite and pearlite, in relative amounts which depend upon the carbon content.



Fig. 11.4 The 'ferrite area' of the iron-carbon diagram, showing the very low solubility of carbon in body-centred cubic iron.

11.26 The composition of the pearlite area in the microstructure of any plain carbon steel is always the same, namely 0.8% carbon, and if the overall carbon content is either greater or smaller than this, then it will be compensated for by variation in the amount of either primary ferrite or primary cementite. The hardness of a slowly cooled steel increases directly as the carbon content, whilst the tensile strength reaches a maximum at the eutectoid composition (Fig. 7.7). These properties can be modified by heat-treatment, as we shall see in this chapter and the next.

Impurities in Steel

11.30 Most ordinary steels contain appreciable amounts of manganese, residual from the deoxidation process (3.21). Impurities such as silicon, sulphur and phosphorus (7.21) are also liable to be present in the finished steel. The effect of such impurities on mechanical properties will depend largely upon the way in which these impurities are distributed throughout the structure of the steel. If a troublesome impurity is *heavily cored* in the structure it can be expected to have a far more deleterious effect than if the same quantity of impurity were evenly distributed throughout the structure. Excessive coring concentrates the impurity in the grain-boundary regions often producing the effect of very brittle intergranular films. The extent to which coring of a particular element is likely to occur will be indicated by the distance apart of the solidus and liquidus lines at any temperature on the appropriate equilibrium diagram. Thus in Fig. 11.5A the relative compositions of solid (S) and liquid (L) are very far apart at any temperature and this may lead to excessive coring. Since relatively pure metal is solidifying it follows that the bulk of the impurity element becomes concentrated in the metal which solidifies last-in the grain boundary regions. In Fig. 11.5B, however, the compositions of the solid (S) and the liquid (L) remain close to each other throughout solidification and this will lead to a relatively even distribution of the impurity element throughout the microstructure and a consequent lack of dangerous crystal-boundary concentrations of brittle impurity.





The crystals in solid steel are never extensively cored with respect to silicon and manganese, and since these elements have a high solid solubility in steel they are unlikely ever to appear as separate constituents in the microstructure. In solid solution in amounts up to 0.3% therefore their *direct* effect is minimal. Sulphur and phosphorus, on the other hand, segregate appreciably and if present in sufficient amounts could precipitate during solidification, as their respective iron compounds, at the austenite grain boundaries. The effect would be aggravated by the relatively low solubilities of these elements in steel.

11.31 Manganese is not only soluble in austenite and ferrite but also forms a stable carbide, Mn_3C . In the nomenclature of the heat-treatment shop, manganese 'increases the depth of hardening' of a steel, for reasons which will be discussed in Chapter 13. It also improves strength and toughness. Manganese should not exceed 0.3% in high-carbon steels because of a tendency to induce quench cracks particularly during water-quenching.

11.32 Silicon imparts fluidity to steels intended for the manufacture of castings, and is present in such steels in amounts up to 0.3%. In high-carbon steels silicon must be kept low, because of its tendency to render cementite unstable (as it does in cast iron (15.22)) and liable to decompose into graphite (which precipitates) and ferrite.

11.33 Phosphorus is soluble in solid steel to the extent of almost 1%. In excess of this amount the brittle phosphide Fe_3P is precipitated. In solution phosphorus has a considerable hardening effect on steel but it must be rigidly controlled to amounts in the region of 0.05% or less because of the brittleness it imparts, particularly if Fe_3P should appear as a separate constituent in the microstructure.

In rolled or forged steel the presence of phosphorus is indicated by what are usually termed 'ghost bands' (Fig. 11.6c). These are areas (which



Fig. 11.6 (A) The segregation of iron(II) sulphide (FeS), at the crystal boundaries in steel. \times 750.

(B) The formation of isolated manganese sulphide (MnS) globules when manganese is present in a steel. \times 200.

(C) 'Ghost bands' or areas lacking in pearlite, which indicate the presence of phosphorus. \times 75.

naturally become elongated during rolling) containing no pearlite, but instead, a high concentration of phosphorus. The presence of phosphorus and absence of pearlite will naturally make these ghost bands planes of weakness, particularly since, being areas of segregation, other impurities may be present in the ghosts.

11.34 Sulphur is the most deleterious impurity commonly present in steel. If precautions were not taken to render it harmless it would tend to form the brittle sulphide, FeS. Sulphur is completely soluble in molten steel but on solidification the solubility falls to 0.03% sulphur. If the effects of extensive coring, referred to above, are also taken into account it will be clear that amounts as low as 0.01% sulphur may cause precipitation of the sulphide at the crystal boundaries. In this way the austenite crystals would become virtually coated with brittle films of iron(II) sulphide. Since this sulphide has a fairly low melting point, the steel would tend to crumble during hot-working. Being brittle at ordinary temperatures, iron(II) sulphide would also render steel unsuitable for cold-working processes, or, indeed, for subsequent service of any type.

It would be very difficult, and certainly very expensive, to reduce the sulphur content to an amount less than 0.05% in the majority of steels. To nullify the effects of the sulphur present an excess of manganese is therefore added during deoxidation. Provided that about five times the theoretical manganese requirement is added, the sulphur then forms manganese sulphide, MnS, in preference to iron(II) sulphide. The manganese sulphide so formed is *insoluble in the molten steel*, and some is lost in the slag. The remainder is present as fairly large globules, distributed throughout the steel, but since they are insoluble, they will not be associated with the structure when solidification takes place. Moreover, manganese sulphide is plastic at the forging temperature, so that the tendency of the steel to crumble is removed. The manganese sulphide globules become elongated into threads by the subsequent rolling operations (Fig. 11.6A and B).

11.35 Nitrogen Atmospheric nitrogen is absorbed by molten steel during the manufacturing process. Whether this nitrogen combines with iron to form nitrides or remains dissolved interstitially after solidification (Fig. 11.7), it causes serious embrittlement and renders the steel unsuitable for severe cold-work. For this reason mild steel used for deep-drawing operations must have a low nitrogen content.

Due to the method of manufacture, Thomas steel was particularly suspect and had nitrogen contents as high as 0.02% probably leading to the presence of brittle Fe₄N in the structure (Fig. 11.7). This was more than four times the average nitrogen content of open-hearth steel adequate for deep-drawing operations. Naturally the modern 'oxygen' processes (7.36) can produce mild steel with a very low nitrogen content (below 0.002%), since little or no nitrogen is present in the blast to the molten charge. Such steel is obviously ideal for deep-drawing. It is difficult, however, to prevent some atmospheric nitrogen from being absorbed, since the molten steel is in contact with the atmosphere during teeming.

11.36 Hydrogen ions dissolve interstitially in solid steel and are thus able to migrate within the metal, resulting in embrittlement as shown by



Fig. 11.7 Part of the iron-nitrogen thermal equilibrium diagram.

a loss in ductility. This hydrogen may be dissolved during the steel-making process but is more likely to be introduced from moisture in the flux coating of electrodes during welding, or released at the surface during an electroplating or acid-pickling operation. Hydrogen ions released during surface corrosion may also be absorbed.

The presence of hydrogen in steels can result in so-called 'delayed fracture', that is fracture under a static load during the passage of time. Such failure may occur after several hours at a stress of no more than 50% of the 0.2% proof stress. The effect is very dependent on the strain rate so that whilst ductility is considerably impaired during slow tensile tests, impact values are little affected.

In steels the mechanism of hydrogen embrittlement seems to be associated with the interstitial movement of hydrogen ions to positions at or near lattice faults, and also to regions of high tri-axial stress; in each case causing the nucleation of cracks and consequent premature failure. This would explain why failure is more likely with the passage of time during which hydrogen ions are able to migrate. Much of this dissolved hydrogen can be dispersed during a low-temperature (200°C) annealing process in a hydrogen-free atmosphere.

The Heat-treatment of Steel

11.40 Because of the solid-state structural changes which take place in suitable alloys, steels are among the relatively few engineering alloys which

can be usefully heat-treated in order to vary their mechanical properties. This statement refers, of course, to heat-treatments other than simple stress-relief annealing processes.

Heat-treatments can be applied to steel not only to harden it but also to improve its strength, toughness or ductility. The type of heat-treatment used will be governed by the carbon content of the steel and its subsequent application.

11.41 The various heat-treatment processes can be classified as follows:

- (a) annealing;
- (b) normalising;
- (c) hardening;
- (d) tempering;

(e) treatments which depend upon transformations taking place at a single predetermined temperature during a given period of time (iso-thermal transformations).

In all of these processes the steel is heated fairly slowly to some predetermined temperature, and then cooled, and it is the *rate of cooling* which determines the resultant structure of the steel and, hence, the mechanical properties associated with it. The final structure will be independent of the rate of heating, provided this has been slow enough for the steel to reach structural equilibrium at its maximum temperature. The subsequent rate of cooling, which determines the nature of the final structure, may vary between a drastic water-quench and slow cooling in the furnace.

Annealing

11.50 The term 'annealing' describes a number of different thermal treatments which are applied to metals and alloys. Annealing processes for steels can be classified as follows:

11.51 Stress-relief Annealing The recrystallisation temperature of mild steel is about 500°C, so that, during a hot-rolling process recrystallisation proceeds simultaneously with rolling. Thus, working stresses are relieved as they are set up.

Frequently, however, we must apply a considerable amount of coldwork to mild steels, as, for example, in the drawing of wire. Stress-relief annealing then becomes necessary to soften the metal so that further drawing operations can be carried out. Such annealing is often referred to as 'process' annealing, and is carried out at about 650°C. Since this temperature is well above the recrystallisation temperature of 500°C, recrystallisation will be accelerated so that it will be complete in a matter of minutes on attaining the maximum temperature. Prolonged annealing may in fact cause a deterioration in properties, since although ductility may increase further, there will be a loss in strength. A stage will be reached where grain growth becomes excessive, and where the layers of cementite in the patches of pearlite begin to coalesce and assume a globular form so that the identity of the eutectoid is lost (Fig. 11.8). In fact, the end-product



Fig. 11.8 The spheroidisation of pearlitic cementite.

would be isolated globular masses of cementite in a ferrite matrix. The result of this 'balling-up' of the pearlitic cementite is usually called 'deteriorated' pearlite.

It should be noted that process annealing is a *sub-critical* operation, that is, it takes place below the lower critical temperature (A_1) . Consequently, reference to the iron-carbon diagram is not involved. Although recrystallisation is promoted by the presence of internal energy remaining from the previous cold-working process, there is *no phase change* and the constituents ferrite and cementite remain in the structure throughout the process. The balling-up of the pearlitic cementite is purely a result of surface-tension effects which operate at the temperatures used.

Process annealing is generally carried out in either batch-type or continuous furnaces, usually with some form of inert atmosphere derived from burnt 'town gas' or other hydrocarbons. The carbon dioxide present in such mixtures does not react with the surface of iron at the relatively low temperature of 650°C. At higher temperatures, however, it may behave as an oxidising agent.

11.52 Spheroidising Anneals 'The spheroidisation of pearlitic cementite' may sound a somewhat ponderous phrase. In fact, it refers to the balling-up of the cementite part of pearlite mentioned above. This phenomenon is utilised in the softening of tool steels and some of the air-hardening alloy steels. When in this condition such steels can be drawn and will also machine relatively freely.

The spheroidised condition is produced by annealing the steel at a temperature between 650 and 700°C, that is, just *below* the lower critical temperature (A_1) , so that, again, the iron-carbon diagram is not involved in our study. Whilst no basic phase change takes place, surface tension causes the cementite to assume a globular form (Fig. 11.8) in a similar way to which droplets of mercury behave when mercury is spilled. If the layers of cementite are relatively coarse they take rather a long time to break up, and this would result in the formation of very large globules of cementite. This in turn would lead to tearing of the surface during machining. To obviate these effects it is better to give the steel some form of quenching treatment prior to annealing in order to refine the distribution of the cementite. It will then be spheroidised more quickly during annealing and will produce much smaller globules of cementite. These small globules will not only improve the surface finish during machining but will also be dissolved more quickly when the tool is ultimately heated for hardening.

11.53 Annealing of Castings As stated earlier (11.20), the cast structure of a large body of steel is extremely coarse. This is due mainly to the slow rates of solidification and subsequent cooling through the austenitic range. Thus, a 0.35% carbon steel will be completely solid in the region of 1450°C, but, if the casting is large, cooling, due to the lagging effect of the sand mould, will proceed very slowly down to the point (approximately 820°C) where transformation to ferrite and pearlite begins. By the time 820°C has been reached, therefore, the austenite crystals will be extremely large. Ferrite, which then begins to precipitate in accordance with the equilibrium diagram, deposits first at the grain boundaries of the austenite. thus revealing, in the final structure, the size of the original austenite grains. The remainder of the ferrite is then precipitated along certain crystallographic planes within the lattice of the austenite. This gives rise to a directional precipitation of the ferrite, as shown in Fig. 11.9 and Plate 11.1c, representing typically what is known as a Widmanstätten structure. This type of structure was first encountered by Widmanstätten in meteorites (10.10), which may be expected to exhibit a coarse structure in view of the extent to which they are overheated during their passage through the upper atmosphere. The mesh-like arrangement of ferrite in the Widmanstätten structure tends to isolate the stronger pearlite into separate patches, so that strength, and more particularly toughness, are impaired. The main characteristics of such a structure are, therefore, weakness and brittleness, and steps must be taken to remove it either by heat-treatment or by mechanical working. Hot-working will effectively break up this coarse as-cast structure and replace it by a fine-grained material, but in this instance we are concerned with retaining the actual shape of the casting. Heat-treatment must therefore be used to effect what limited refinement of grain is possible, but it should be noted that the crystal size after heat treatment will be greater than that achieved by hot-working.

11.54 The most suitable treatment for a large casting involves heating it slowly up to a temperature about 40°C above its upper critical (thus the annealing temperature depends upon the carbon content of the steel, as shown in Fig. 11.10), holding it at that temperature only just long enough for a uniform temperature to be attained throughout the casting and then allowing it to cool slowly in the furnace. This treatment not only introduces the improvements in mechanical properties associated with fine grain but also removes mechanical strains set up during solidification.

As the lower critical temperature (723°C) is reached on heating, the patches of pearlite transform to austenite but these new crystals of austenite are very small since each patch of pearlite gives rise to many new austenite crystals. It is upon this fact that the complete success of this type of annealing process depends. As the temperature rises, the Widmanstätten-type plates of ferrite are dissolved by the austenite until, when the upper critical temperature is reached, the structure consists entirely of fine-grained austenite. Cooling causes reprecipitation of the ferrite, but, since the new austenite crystals are small, the precipitated ferrite will also be distributed as small particles. Finally, as the lower critical temperature is



Fig. 11.9 Structural changes occurring during the annealing of a steel casting (approx 0.35% carbon). The as-cast Widmanstätten structure is reheated to some temperature above its upper critical and then allowed to cool in the furnace.

reached, the remaining small patches of austenite will transform to pearlite. The structural changes taking place during annealing are illustrated diagrammatically in Fig. 11.9.

11.55 Whilst the tensile strength is not greatly affected by this treatment, both toughness and ductility are improved as shown by the following values for a cast carbon steel:

Condition	Tensile strength	Percentage elongation	Bend test
Specimen 'as cast'.	470 N/mm ²	18	40 °
Specimen annealed.	476 N/mm ²	34	180° (without fracture)

11.56 Overheating during annealing, or heating for too long a period in the austenitic range, will obviously cause grain growth of the newly formed austenite crystals, leading to a structure almost as bad as the original Widmanstätten structure. For this reason the requisite annealing temperature should not be exceeded, and the casting should remain in the austenitic range only for as long as is necessary to make it completely austenitic. In fact, castings are sometimes air-cooled to about 650°C and then cooled more slowly to room temperature, by returning to a furnace to prevent stresses due to rapid cooling from being set up.

11.57 Excessive overheating will probably cause oxidation, or 'burning', of the surface, and the penetration by oxide films of the crystal boundaries following decarburisation of the surface. Such damage cannot be



Fig. 11.10 The heat-treatment temperature ranges of classes of carbon steels in relation to the equilibrium diagram.

repaired by heat-treatment, and the castings can only be scrapped. To prevent 'burning' some form of inert atmosphere must be used in the annealing furnace in order to limit contact between the castings and atmospheric oxygen.

11.58 If annealing is carried out at too low a temperature, remnants of the as-cast structure will be apparent in the form of undissolved skeletons of Widmanstätten ferrite. As the temperature falls on cooling, the ferrite which did dissolve tends to reprecipitate on the existing ferrite skeleton so that the final structure resembles the unannealed.

Normalising

11.60 Normalising resembles the 'full' annealing of castings described in 11.53 in that the maximum temperature attained is similar. It is in the method of cooling that the processes differ. Whilst, in annealing, cooling is retarded, in normalising the steel is removed from the furnace and allowed to cool in still air. This relatively rapid method of cooling limits grain growth in normalising, whilst the ferrite/cementite lamellae in pearlite will also be much finer. For both reasons the mechanical properties are somewhat better than in an annealed component. Moreover, the surface finish of a normalised article is often superior to that of an annealed one when machined, since the high ductility of the latter often gives rise to local tearing of the surface.

11.61 The type of structure obtained by normalising will depend largely upon the thickness of cross-section, as this will affect the rate of cooling. Thin sections will give a much finer grain than thick sections, the latter differing little in structure from an annealed section.

Exercises

- 1. Calculate the relative proportions by mass of ferrite and cementite in pearlite (Fig. 11.1 and Fig. 11.4).
- 2. By reference to Fig. 11.2 explain what happens as a steel containing 0.12% C cools slowly between 1550°C and 1450°C (11.20).
- 3. One particular plain carbon steel may be described as a 'binary alloy' of exact 'peritectic' composition and as being 'hypo-eutectoid' in nature.
 - (i) Define the three terms in inverted commas.
 - (ii) Sketch qualitatively the relevant portion of the equilibrium diagram and on it indicate clearly the composition of the steel.
 - (iii) Discuss the changes of structure that would occur if an alloy of this composition were cooled under equilibrium conditions from its molten state down to room temperature. (8.13, 7.57 and 11.20)
- 4. Fig. 11.11 shows part of the iron-carbon thermal equilibrium diagram.
 - (i) Make an accurate assessment of the upper critical temperature of a steel containing 0.45% C;
 - (ii) What proportions by mass of primary ferrite and pearlite will be present in a 0.45% C steel which has been normalised?



- (iii) Between what temperatures would primary cementite be deposited when a steel containing 1.3% C were cooled slowly from 1200°C to ambient temperature?
- (iv) What effects would such treatment be likely to have on the resultant mechanical properties of the steel in (iii)? (11.20 and 11.24)
- 5. By using Fig. 11.11 determine what phases are present, the compositions of each of these phases and the proportions in which they exist for a 0.15% C steel at (i) 900°C; (ii) 800°C and (iii) 700°C. Assume equilibrium in each case. (11.20)
- 6. Draw and describe a Widmanstätten structure and explain how such a structure arises in a hypo-eutectoid steel. (11.53)
- 7. Compare and contrast the objectives in the following heat-treatments:
 - (i) stress-relieving of cold-worked mild steel;
 - (ii) annealing of steel and castings;
 - (iii) spheroidising annealing of tool steel.
 - Show how the thermal treatment differs in each case. (11.50)
- 8. How does *normalising* differ from *annealing* as applied to steels? What are the advantages of the normalising process in respect of final properties? (11.60)

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