

## CHAPTER 8

# HEAT TREATMENT OF METALS AND ALLOYS

### 8.1 INTRODUCTION

Steel and other alloys have a large number of applications in engineering practice under varying conditions, requiring different properties in them. At one place they may be subjected to bending while at the other to twisting. They may be required to withstand various types of stresses and, as tool materials, they may be required to have hardness, specially red hardness, combined with toughness, alongwith a non-brittle cutting edge. They may be required to bear static or dynamic loads, revolve at extremely high speeds, operate in highly corrosive media, carry an extremely hard skin with a tough core, subjected to fatigue and creep, etc., etc. Such varying conditions of their applications require these materials to possess specific properties of the required order to successfully serve under these conditions. But, a material may lack in some or all of these properties either fully or partially. These deficiencies are made good through the process of *Heat Treatment*.

The process of *Heat Treatment* involves heating of solid metals to specified temperatures, holding them at that temperature, and then cooling them at suitable rates in order to enable the metals to acquire the desired properties to the required extents. All this takes place because of the changes in size, form, nature and the distribution of different constituents in the micro-structures of these metals. All **Heat Treatment Processes**, therefore, comprise of the following three stages or components :

1. Heating the metal to a predecided temperature.
2. Holding it at that temperature for sufficient time so that the structure of the metal becomes uniform throughout.

3. Cooling the metal at a predetermined rate in a suitable media so as to force the metal to acquire a desired internal structure and thus, obtain the desired properties to the required extent.

## 8.2 PURPOSE OF HEAT TREATMENT

Metals and Alloys are heat treated in order to achieve one or more of the following objectives :

1. To relieve *internal stresses* set up during other operations ; like casting, welding, hot and cold working, etc.
2. To improve *mechanical properties* ; like hardness, toughness, strength, ductility, etc.
3. To improve *machinability*.
4. To change the *internal structure* to improve their resistance to heat, wear and corrosion.
5. To effect a change in their *grain size*.
6. To *soften* them to make suitable for operations like cold rolling and wire drawing.
7. To improve their *electrical* and *magnetic* properties.
7. To make their structure *homogenous* so as to remove *coring* and *segregation*.
9. To drive out *trapped gases*.

In order to understand the complete mechanism of heat treatment it is essential to know the internal structure, phase transformations, etc. fully. They have already been discussed in detail in chapter 5. However, a brief review of relevant topics will follow in the following articles.

## 8.3 STRUCTURE OF STEEL

*Pure iron* consists of only *ferrite* which is a very soft and ductile material having crystalline structure. This structure is considerably affected by the addition of carbon. This carbon forms a chemical combination with ferrite, known as **Cementite**, which is a very hard and brittle substance and white in colour. The whitish structure of the white cast iron is due to the formation of this *cementite* only. More the carbon content present in chemically combined form, higher will be the amount of cementite formed and so harder will be the metal. This formation is not visible by naked eye and can be seen only through *microstructures* in a precision optical instrument called *microscope*, since cementite is present in a typical form known as **Pearlite**. **Pearlite** is the term used for combination of cementite and ferrite and can be observed in the form of black patches, distributed throughout the structure, when the metal structure is seen through the microscope.

So, we can say that with the increase of chemically combined carbon the pearlite increases and the free ferrite decreases, as is clear from Fig. 8.1. (a), (b) and (c). This change in proportion continues till the carbon percentage reaches 0.83 per cent. At this stage steel consists of fully *pearlitic structure* having no free ferrite [Fig. 8.1 (d)]. With further increase in the carbon content the pearlitic structure is gradually reduced to a combination of free cementite and pearlite, [Fig. 8.1 (e)]. Above 0.83 percent carbon, higher the carbon content higher will be the proportion of free cementite with a simultaneous reduction in pearlite. These changes have an important effect on the characteristics of steel. With the increase in pearlite the strength increases and with its reduction the strength decreases. With the result, steel becomes stronger with the increase in carbon content upto 0.83 percent but, with further increase in carbon, the strength will be gradually reduced. Since the formation of cementite hardens the steel, its hardness will continue increasing as the carbon content increases. Presence of *free ferrite* renders the metal soft and ductile. With the result, as the carbon content is increased a simultaneous reduction in free ferrite, due to increase in the formation of pearlite, will reduce the *ductility* of the metal. *In other words we can say that hardness varies directly and ductility inversely as the increase in carbon content in steel.*

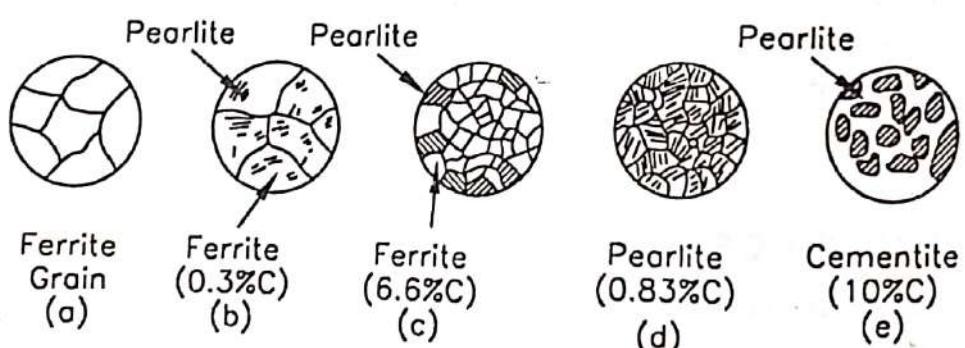


Fig. 8.1. Micro Structures of Steel.

The microspecimens for studying the microstructures are prepared by preparing a *flat mirror surface* on a small piece of metal through rubbing by sand papers, polishing and buffing etc. followed by etching with a chemical solution. This solution reacts with different constituents in varying degrees to reveal the *crystal structure* of the metal clearly when viewed through a powerful microscope.

#### 8.4 CHANGES IN STEEL STRUCTURE DURING HEATING AND COOLING

It is very important to have a clear conception of the changes that take place in the structure and state of steel, when it is heated and then cooled, since these changes only form the basis of different heat

treatments of steel employed for developing the desired characteristics in the same.

As an example, let us consider a piece of steel having 0.4 percent carbon. Now suppose we heat this piece, by some suitable means, by supplying heat at a uniform rate *i.e.* same amount of heat per unit of time and record the different temperatures attained by the metal piece at regular intervals of time, or to say against each unit of heat supplied to it. If these readings are plotted on a graph, to a suitable scale, with the different temperature readings along the ordinate and the time along the abscissa, we will obtain a common curve as shown in Fig. 8.2. Note that the temperature of the metal piece varies directly as the time and it rises at a uniform rate until its reading reaches  $723^{\circ}\text{C}$ , see point A on the curve. As soon as this temperature is attained, it would be observed that a sudden check is applied to further rise of temperature. For some time, inspite of the additional heat supplied, the temperature will not rise. It would further be observed that for a certain period of time, inspite of keeping the rate of supply of heat same as from O to A, the temperature of the piece rises at a much slower rate till it reaches point B, about  $780^{\circ}\text{C}$ . After this point the curve again adopts a straight line path, parallel to OA, which shows that the rise in temperature is again uniform as it was before point A. Let us continue supplying heat to the metal piece at the same uniform rate till its temperature rises to about  $1100^{\circ}\text{C}$ , we will observe that temperature rise continues at the same uniform rate.

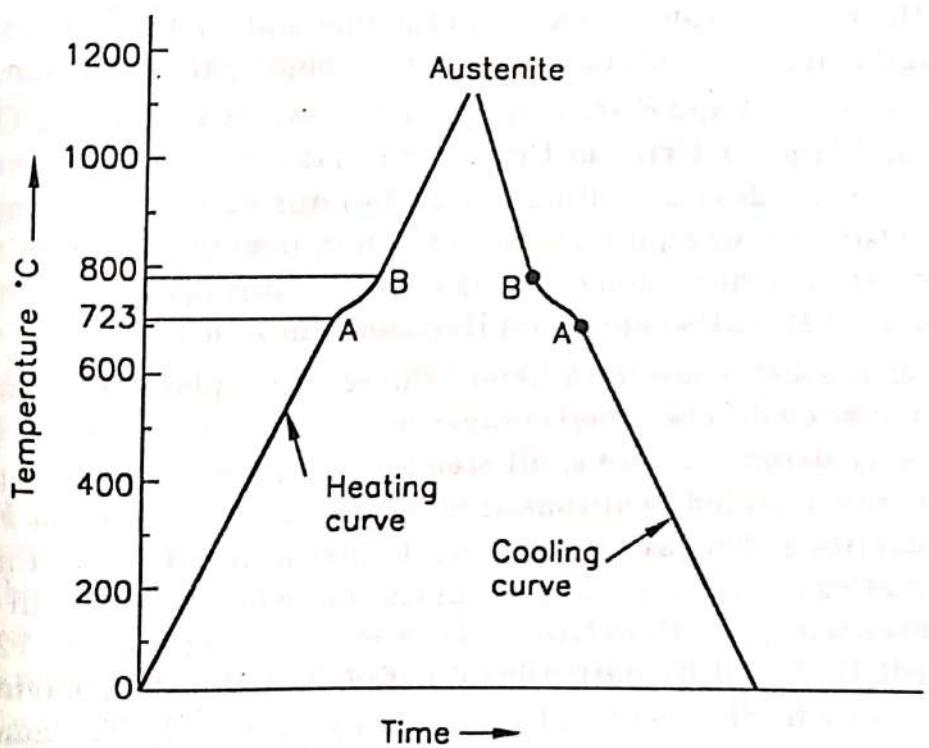


Fig. 8.2. Heating and cooling curves for steel.

Now, if we allow the piece to cool down from the highest temperature it has attained, it will be seen that its brightness diminishes and temperature falls to a little below point *B* at nearly the same uniform rate at which it had risen from point *B* during heating. After this, the rate of fall in temperature is slowed down till the temperature falls to point *A*. After this, the rate of fall in temperature will again be uniform and will follow the same path as it followed during the temperature rise from *O* to *A*. From all these discussions we conclude that during heating and then cooling of a steel piece, the rise and fall in temperature take place in nearly the same way.

Now the question arises that for what reason the uniform rise and fall of temperature during heating and cooling respectively, of the metal piece are checked between the points *A* and *B*; and where goes the amount of heat supplied during this period. It happens so for the reason that internal changes take place in the structure and state of the metal and the amount of heat supplied during this period is consumed in this *transformation*. With the result, the total heat supplied from point *A* to *B* is not entirely utilised in raising the temperature and, hence, the rise is slower. After this transformation has taken place completely, the further heat supplied again starts being consumed entirely for raising the temperature, and hence we obtain a similar straight line above the point *B* as was below the point *A*, showing that the temperature has again started rising at the same uniform rate. During cooling also the uniform fall of temperature is checked, as described above, and here again the reverse transformation in the internal structure takes place, slowing down the rate of cooling till the complete transformation is over.

The points *A* and *B* are respectively known as the **Lower Critical Point** and **Higher Critical Point**, and that particular moment when there is no rise during heating and no fall during cooling of the metal temperature, i.e. when it remains stationary inspite of consuming heat energy during heating and evolving the same during cooling, are called the points of **Decalescence** and **Recalescence** respectively.

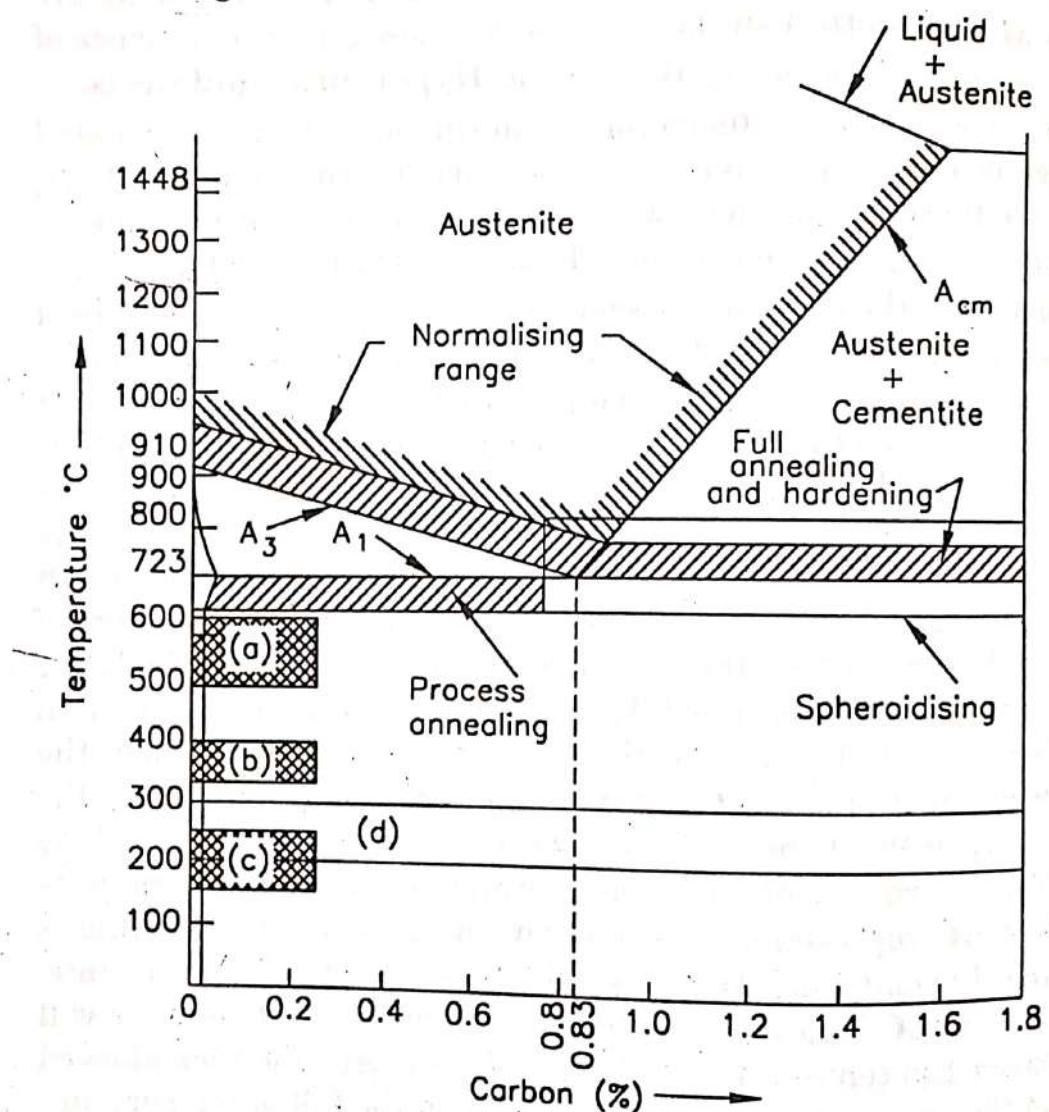
Fig. 8.3 shows how the different changes take place in the structure of steel, having different percentages of carbon, when they are heated. As already described above, all steels having less than 0.83 percent carbon, when heated, will consist of a structure composed of **Ferrite** and **Pearlite** so long as they attain a temperature of 723°C. Similarly steels having more than 0.83 percent carbon, when heated, will consist of **Cementite** plus **Pearlite** so long as the temperature 723°C is attained. It should be particularly noted that the steel having 0.83 percent carbon will have a fully *pearlitic structure* only. The amount of these constituents depends upon the carbon percentage. For steels having less than 0.83 percent carbon **pearlite** increases and **ferrite**

decreases, during heating, as the percentage of carbon content increases. This continues so long as the carbon content in steel becomes 0.83 percent, when it is fully composed of *Pearlite* only having no free ferrite. When the carbon increases beyond this, pearlite decreases and free cementite increases. The temperature of  $723^{\circ}\text{C}$ , called the **Lower Critical Point ( $\text{Ac}_1$ )**, is common for all steels irrespective of their carbon percentage. On the other hand, the **Higher Critical Point ( $\text{Ac}_3$ )** for different steels varies according to the carbon percentage. It is higher when the carbon content is low and lower when carbon percentage is high for steels having less than 0.83 percent carbon, same as the lower critical point for steel having exactly 0.83 percent carbon and varies directly as the carbon percentage for steels having more than 0.83 percent carbon. The range of temperature between these two critical points is known as the **Critical Range**. Steels having less than 0.83 percent carbon, i.e., having the structure composed of Ferrite and Pearlite are called **Hypo-eutectoid** steels, while those whose structure consists of Pearlite and free Cementite are known as **Hyper-eutectoid** steels.

The transformation temperatures during heating are designated as *Ac* points and those during cooling as *Ar* points. The points  $A_1, A_2, A_3$  and  $A_4$  are those points which will carry, the suffix *c* or *r* according to whether the temperature is recorded during heating or cooling.

Further to the above discussions, let us now study the structure of steel as it is heated above  $723^{\circ}\text{C}$ . We have seen above that as soon as this temperature is attained the temperature becomes almost constant for a little while and then starts rising at a much slower rate than before. The heat supplied during this period is partly utilised in changing the steel structure and partly in raising its temperature, and it is only due to this reason that the temperature rise slows down. The change which takes place during this period is the formation of **solid solution** of carbon with iron wherein the former completely dissolves in the latter to form a new substance called **Austenite**. When this transformation has taken place fully, i.e., the *Higher Critical Point* is reached, the temperature again rises at the same uniform rate as before. Above the Higher Critical Point the steel consists wholly of austenite only. Line *AE* in Fig. 8.3 represents the temperatures at which steel begins to melt. Line *AC* represents the temperatures at which the melting is completed. Beyond Line *AC* the steel is in completely molten State. Note that line *AC* is not horizontal, i.e., the melting temperature will vary with carbon content. If steel is heated above  $\text{Ac}_3$  and then allowed to cool at the same rate at which it was heated the fall in temperature will also be checked when its structure will be transformed from *Austenite* to *Ferrite* plus *Pearlite* (if it is a *Hypo-eutectoid* steel) and to cementite

plus pearlite, if it is a *Hyper-eutectoid* steel. After this, the temperature will continue to fall at a uniform rate. If, however, the rate of cooling is faster, the final structure after solidification will become **Sorbite** (*finely dispersed* pearlite). A still faster rate of cooling will lead to **Troostite** or **Bainite** structure, which carries finely decomposed *austenite*. Both **Sorbite** and **Troostite** are harder than coarse pearlite because they contain cementite in a finely divided form. But if the rate of cooling is increased to such an extent that the time allowed is too short for the above changes to take place, *Austenite*, instead of changing to any one of the above constituents, will be converted into a new substance known as **Martensite**, which is a very hard substance; the property which forms the basis of hardening the steel. The two critical points are the same ( $723^{\circ}\text{C}$ ) for steel having exactly 0.83 percent carbon as the transformation occurs fully at the same temperature. Some more microstructures are shown in Fig. 8.4.



**Fig. 8.3.** A portion of simplified iron-carbon equilibrium diagram showing structural changes and temperature ranges for heat treatments.

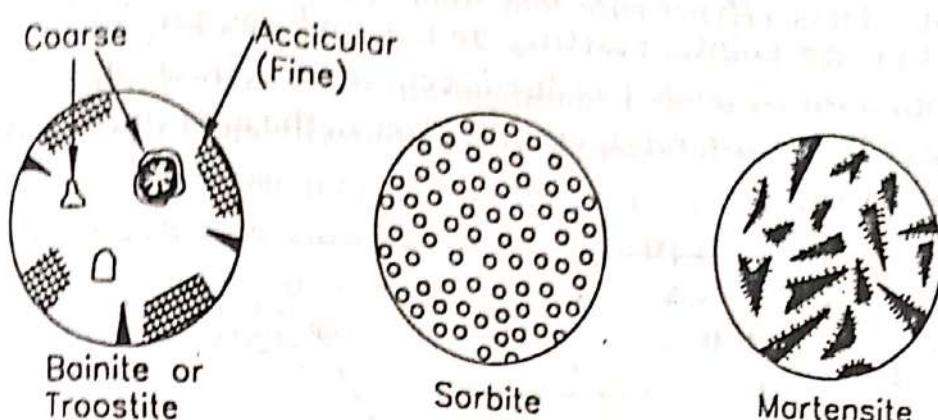


Fig. 8.4. Microstructures of steel.

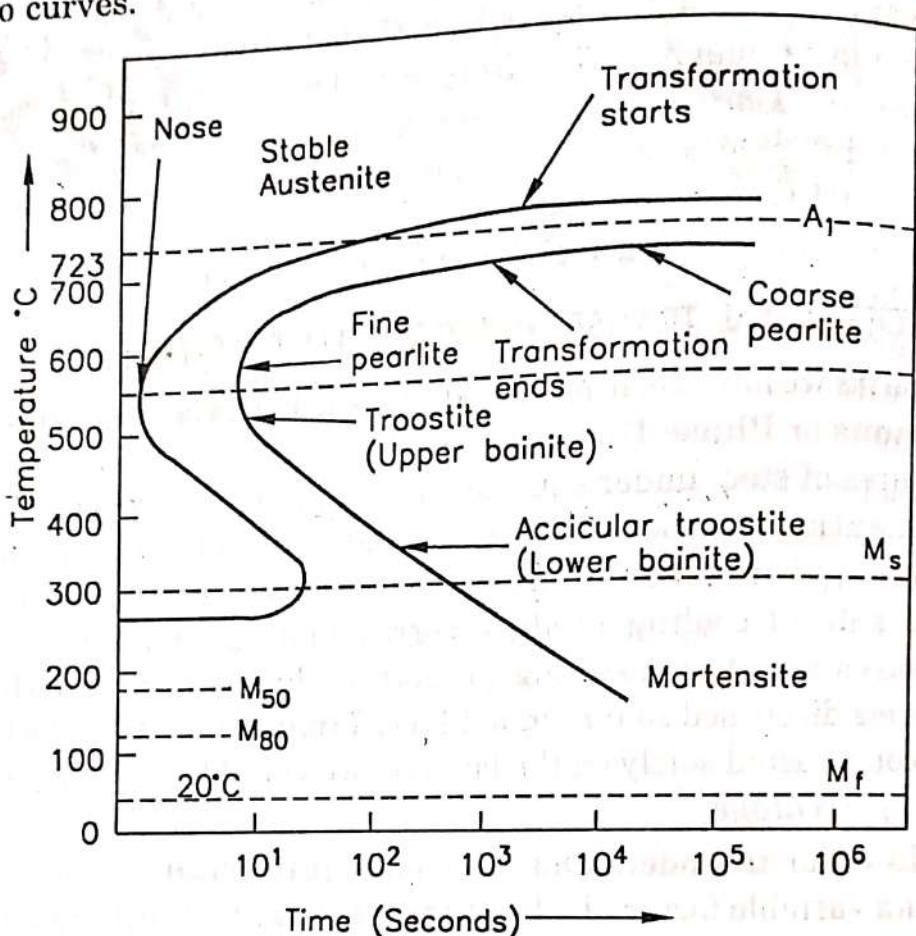
### 8.5 ISOTHERMAL TRANSFORMATIONS-TTT DIAGRAMS

So far we have been acquainted with the **Iron-Carbon Equilibrium Diagrams** or **Phase Diagrams** which revealed the changes in microstructures of steel under equilibrium conditions. However, most of the heat treatment processes are carried out under non-equilibrium conditions, where time is a variable factor and, accordingly, the variations in the rate of cooling produce corresponding variations in microstructures and the resulting properties. Remember that the *Phase diagrams* discussed so far did not have **Time** as a variable factor. They were constructed solely on the basis of two variables – *temperature* and *carbon percentage*.

In order to understand the **Non-Equilibrium** processes, where time is a variable factor, the **Isothermal Transformations Diagrams** are made. These diagrams are known as **Time-Temperature - Transformation (TTT) Diagrams** or **S - Curves** or **Isothermal C-Curves** or **Bain's Curves**. They reveal the decomposition of *austenite* into various forms during cooling. To construct these diagrams a number of thin specimens of a given metal are heated to a temperature where they all form a uniform *single phase* stable austenite. From there, they are suddenly quenched to bring them down to such temperatures where austenite will not be in a stable phase, held *isothermally* at those temperatures for different periods of time to allow austenite to decompose completely, and then their micro-structures are studied.

The *transformations* can be best understood by taking a concrete example. Let us consider the case of a plain carbon steel with 0.78% carbon. The **TTT Diagram** obtained for it is shown in Fig. 8.5. A logarithmic time scale is used in the diagram, so as to cover the vast variation in the time consumed in decomposition of austenite, which may vary from fraction of a second to several hours. By plotting and

joining the end points, starting points and completion points, of decomposition of austenite two distinct curves are obtained, as shown in the Fig. 8.5. The *transformations* take place in the area covered between these two curves.



**Fig. 8.5.** Isothermal Transformations (TTT) diagram of a hypoeutectoid steel.

Above the temperature line  $A_1$  ( $723^\circ\text{C}$ ) austenite is stable, but below that temperature it is unstable, i.e., depending upon the rate of cooling and the time allowed for decomposition, it can transform into either pearlite or bainite or martensite. As the cooling rate increases the stability of austenite decreases at a fast rate and reaches the minimum value at around  $550^\circ\text{C}$ . Below this temperature it again starts increasing. The point at which this turn takes place at the extreme left of the curve is called **Nose**. If the transformation occurs between temperature  $A_1$  and the temperature line passing through the nose of the curve, the deviation from the equilibrium condition is not very large. Consequently, austenite is again transformed back to a mixture of ferrite and cementite, i.e., **Pearlite**. Due to the fact that diffusion capabilities are higher at higher temperatures the pearlite formed near  $A_1$  temperature is **Coarse Pearlite** and that formed nearer to the nose line is **Fine Pearlite**. This transformation of austenite, on account of its decomposition into pearlite, from  $A_1$  temperature to the temperature corresponding to nose

point ( $550^{\circ}\text{C}$ ), consisting of ferrite and cementite, carries a *lamellar* structure and is known as **Sorbite**.

There is a temperature line denoted as **Ms** which corresponds to the temperature where *Martensite* formation will start. If the metal is quenched below this temperature, a different transformation takes place. The metal does tend to change from **FCC** to **BCC** structure but it fails to drive out enough carbon from it to form ferrite. Because of *non-equilibrium conditions* instantaneous structural changes occur in it without diffusion. Consequently, the structure is distorted and a new *distorted BCC structure* is produced which is called **Martensite**. Higher the amount of carbon trapped in the metal, larger will be the distortion and, therefore, higher the amount of *martensite* formed. This new substance (*Martensite*) is extremely hard, strong and brittle. The strength and hardness of the metal with this structure will depend on the carbon content.

Below the temperature line **Ms** there is a line marked **M<sub>50</sub>**, which indicates that the structure at that temperature consists of 50% *martensite* and 50% untransformed *austenite*. Below that there is another line marked **M<sub>80</sub>**, indicating the structure as 80% *martensite* and 20% untransformed *austenite*. If the metal is not cooled further the untransformed austenite remains within the metal structure and can lead to cracking, brittleness and reduction of strength and hardness. There is another line marked **Mf**, corresponding to  $20^{\circ}\text{C}$  temperature, showing that 100% *martensite* structure is obtained at  $20^{\circ}\text{C}$ . But this is not the case always. In common practice the metal is usually cooled down to room temperature (*i.e.*, around  $20^{\circ}\text{C}$ ) whereas the **Mf** (*martensite finish*) temperature may actually lie much below that. In such cases, the untransformed austenite present in the structure will always create problems. Such metals may, therefore, have to be quenched to the required (**Mf**) temperature through a suitable media, like liquid nitrogen, in order to allow full transformation of austenite into *martensite* and, thus, obtain full hardness in the metal. This is known as **Sub-Zero Treatment**.

## 8.6 CLASSIFICATION OF HEAT TREATMENT PROCESSES

Various heat treatment processes can be classified as :

1. Annealing.
2. Normalising.
3. Hardening.
4. Tempering.

5. Case hardening.
6. Surface hardening.
7. Diffusion coating.

### 8.7 ANNEALING

Annealing is indeed one of the most important heat treatment processes. The internal structure of the metal gets stabilized through this process. This heat treatment is given to the metal so as to achieve one or more of the following objectives :

1. To refine the grains and provide homogenous structure.
2. To relieve internal stresses set up during earlier operations.
3. To soften the metal and, thus, improve its machinability.
4. To effect changes in some mechanical, electrical and magnetic properties.
5. To prepare steel for further treatment or processing.
6. To drive out gases trapped during casting.
7. To produce desired microstructure.

Different types of *Annealing Processes* can be classified as follows :

1. Full annealing.
2. Process annealing.
3. Spheroidise annealing.
4. Diffusion annealing.
5. Isothermal annealing.

These annealing processes will now be dealt with in detail in the following articles.

### 8.8 FULL ANNEALING

It is also known as **High Temperature Annealing**. In this process complete phase recrystallisation takes place and, therefore, all imperfections of the previous structure are wiped out. The main objectives of this type of annealing are to soften the metal, relieve its stresses and refine its grain structure.

This involves heating of steel to a temperature of about  $30^{\circ}\text{C}$  to  $50^{\circ}\text{C}$  above the *Higher Critical Point* for **Hypoeutectoid Steels** (as shown in Fig. 8.3), and by the same amount above the *Lower Critical Point* for **Hypereutectoid Steels**, holding it at that temperature for sufficient time to allow the internal changes to take place and then cooling slowly. When steel is heated to the annealing temperature, its structure is converted into homogenous single phase austenitic form and then slow cooling enables the transformation of austenite into pearlite plus ferrite

or pearlite plus cementite, depending upon the percentage of carbon content. These constituents are comparatively softer and hence the steel gets softened by this process, together with an appreciable amount of increase in its ductility and toughness.

The approximate *annealing temperatures*, for **High Temperature Annealing** of various grades for carbon steel are given in Table 8.1.

**Table 8.1. Annealing temperatures for carbon steels**

Material	Annealing Temp. °C
Dead mild steel (< 0.15% C)	870 – 930
Mild steel (0.15 to 0.3% C)	840 – 870
Medium carbon steel (0.3 to 0.8% C)	780 – 840
High carbon steel (0.8 to 1.5% C)	760 – 780

A common rule for rate of cooling is to allow approximately 3 to 4 minutes time at elevated temperatures per mm thickness of the largest section. Cooling from high temperature is usually done in the furnace itself by allowing a fall of temperature at the rate of 10 to 30°C per hour. This fall of temperature is allowed to continue till the metal temperature comes down to about 30°C below the Lower Critical Temperature ( $A_1$ ). The metal piece is then air cooled down to the room temperature. This process results in a *coarse pearlitic structure* which is quite soft and ductile. In Hypereutectoid Steels the resulting structure is *coarse pearlite plus spheroidal cementite*.

An alternate way of cooling the metal after soaking is to embed it in a non-conducting material like sand, lime, mica, ash, etc.

## 8.9 PROCESS ANNEALING

It is also known as **Low Temperature Annealing** or **Sub-Critical Annealing** or **Commercial Annealing**. Often a metal gets severely *strain-hardened* during cold working operations like cold-rolling, wire drawing, etc. The purpose of this process is to remove the ill effects of cold working and soften the metal so that its ductility is restored and it can be again plastically deformed or put to service without any danger of its failure due to fracture. For this, the metal is heated to a temperature slightly below the  $A_1$  temperature (Fig. 8.3), generally between 550°C to 650°C, held there for sufficient time to allow *recrystallisation* of cold worked metal and, thus, softening to take place and then cooled at a slower rate (normally in air). The exact temperature to which the metal should be heated will depend upon the amount of cold working, composition of metal, grain size, etc. The process is schematically shown in Fig. 8.6.

This process is extremely useful for mild steels and low carbon steels and is a bit cheaper and quicker than full annealing. Also, less scale is produced during this process. The main results of this process are increased ductility and plasticity, improved shock resistance, reduced hardness, improved machinability and removal of internal stresses.

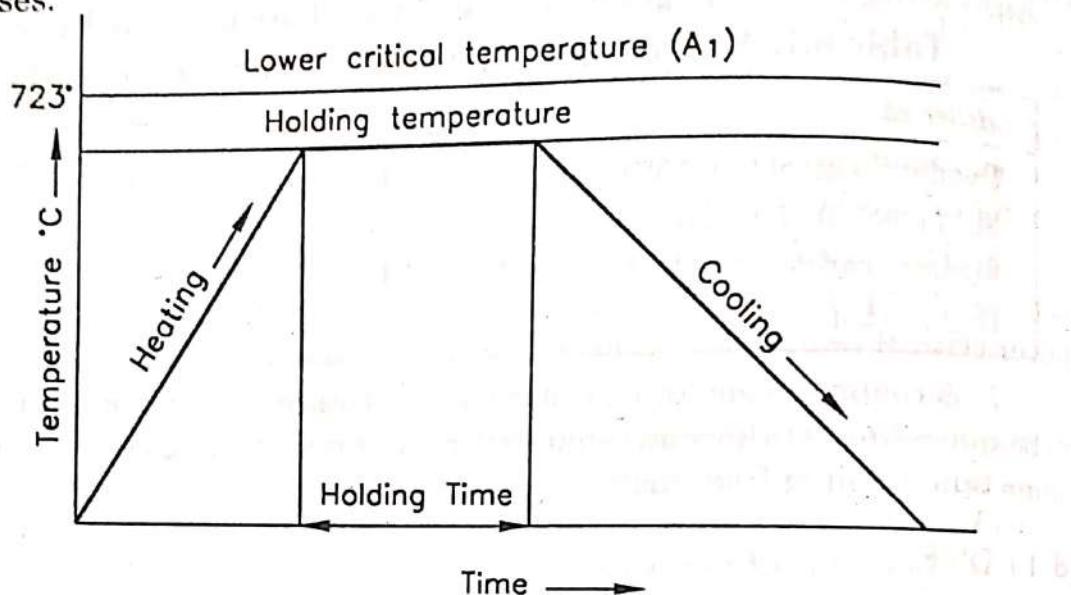


Fig. 8.6. The Process annealing or Low temperature annealing process.

### 8.10 SPHEROIDISE ANNEALING

The main objective in this process of annealing is to produce a structure of steel which consists of **Globules** or well dispersed **Spheroids** of cementite in ferrite matrix. Following are the main methods through which the above objective can be attained :

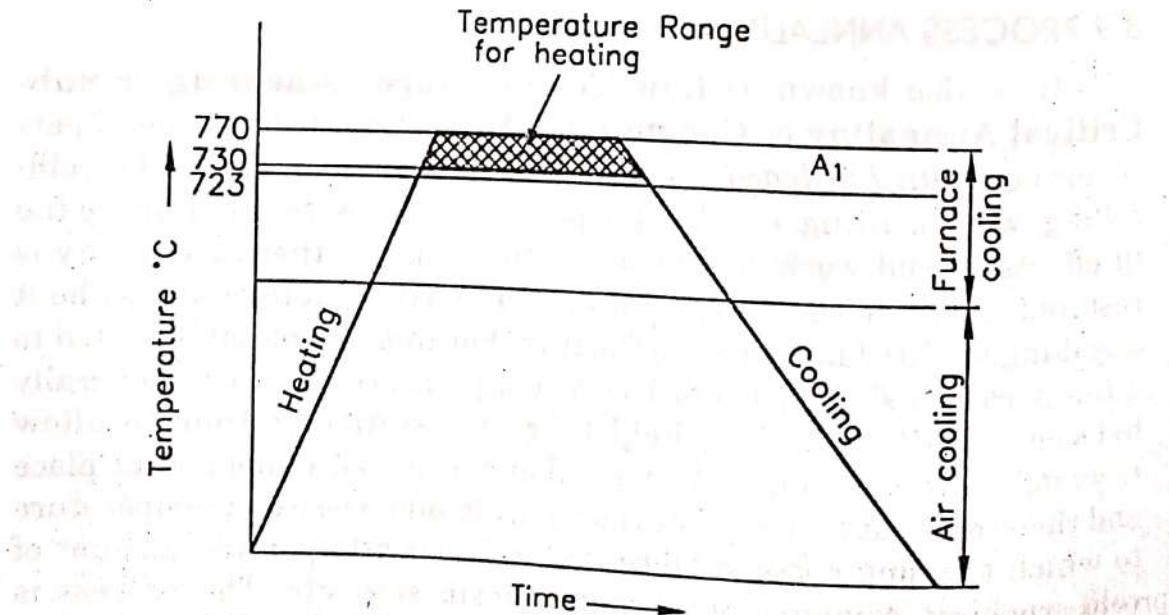


Fig. 8.7. Schematic diagram showing the process of Spheroidise annealing for high carbon steel.

1. The method which is mainly used for high carbon steels, to improve their machinability, consists of heating the steel to a temperature slightly above the Lower critical point  $A_1$  (say between  $730^{\circ}\text{C}$  to  $770^{\circ}\text{C}$ , depending upon the carbon percentage), holding it at that temperature for sufficient time and then cooling it in the furnace to a temperature of  $600^{\circ}\text{C}$  to  $550^{\circ}\text{C}$ , followed by slowly cooling it down to room temperature in still air, as shown schematically in Fig. 8.7.

2. Another method, which is largely applicable to *Tool steels* and *High-alloy steels*, consists of heating to a temperature of  $750^{\circ}\text{C}$  to  $800^{\circ}\text{C}$ , or even higher, holding at that temperature for several hours and then cooling the metal slowly.

3. The third technique involves prolonged heating alternately between temperatures that are slightly above and slightly below the lower critical temperature followed by slow cooling.

*Low carbon steels*, though normally not needed, may be required to be *spheroidised* to improve some properties, say strength, before giving some other heat treatment.

## 8.11 DIFFUSION ANNEALING

This process is mainly used for steel castings before applying full annealing. The purpose of this treatment is to remove the heterogeneity in the chemical composition of steel ingots and heavy castings. The

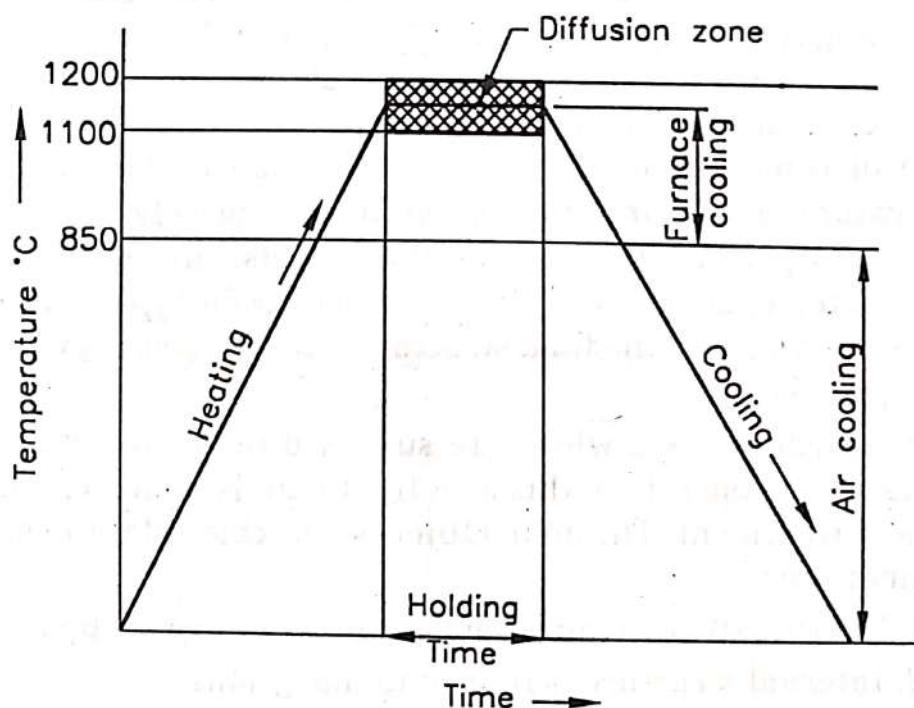


Fig. 8.8. The Diffusion annealing process.

process consists of heating the metal to a temperature between  $1100^{\circ}\text{C}$  to  $1200^{\circ}\text{C}$ , where *diffusion* occurs and austenite grains are homogenised. The article being treated is held at the diffusion temperature for a short

period to allow completion of diffusion and then cooled down to between 800°C to 850°C by allowing it to remain inside the shut off furnace for a period of about 6 to 8 hours. Then it is removed from the furnace and cooled in air down to the room temperature. This process is followed by *full annealing* in order to provide a fine-grained structure to the metal. The process is schematically shown in Fig. 8.8.

### 8.12 ISOTHERMAL ANNEALING

The main advantage of this process is that the total annealing time is considerably reduced. The process consists of heating steel to austenite state and then cooling it down to a temperature of about 630°C to 680°C at a relatively faster rate. It is followed by holding it at this temperature *isothermally* (*i.e.*, at constant temperature) for some time and then cooling it down to the room temperature at a rapid rate. During the *isothermal holding* full decomposition to pearlite structure takes place and that is why the process is known as *isothermal annealing*. Because of the two rapid coolings the total annealing time is considerably reduced. This, obviously, is a big advantage, specially in case of alloy steels, which otherwise will consume a lot of time through slow cooling for attaining a pearlitic structure with a view to soften them.

### 8.13 NORMALISING

This process is similar to annealing in sequence but differs a lot in the heating temperature range, holding time and the rate of cooling. In this process steel is heated to a temperature 40°C to 50°C above the *Higher Critical Point*, held at that temperature for a relatively shorter period of time (about 15 minutes) and then cooled down to room temperature in still air. Thus, austenite is ultimately transformed into ferrite plus pearlite for *hypoeutectoid* steels, into total pearlite for *eutectoid* steels and into pearlite plus cementite for *hypereutectoid* steels. In case of *alloy steels* the final structure after the process will consist of *sorbite* plus *ferrite*.

For such articles, which are supposed to be subjected to higher stresses during operation, this heat treatment is commonly used as the final heat treatment. The main **Objectives** achieved through this heat treatment are :

1. Internal stresses caused during previous operations are removed.
2. Internal structure is refined to fine grains.
3. Mechanical properties of steel are improved.

This process also improves the impact strength, yield point and ultimate tensile strength of steels. As compared to the *annealed* steels of the same composition the *normalised* steels will be less ductile but

stronger and harder. From the above discussions, therefore, it can be easily concluded that where the main aim of heat treatment is to improve the mechanical properties Normalising Process should be preferred and where the main aims are to attain better machinability, softening and greater removal of internal stresses Annealing Process should be employed.

### 8.14 HARDENING

It is the process of heating steel to a temperature within the hardening range (refer to Fig. 8.3), which is 30°C to 50°C above the higher critical point for hypoeutectoid steels and by the same amount above the lower critical point for hypereutectoid steels, holding it at that temperature for sufficient time to allow it to attain austenitic structure and then cooling it rapidly by quenching in a suitable medium like water, oil or salt both. This process is widely applied to all cutting tools, all machine parts made from alloy steels, dies and some selected machine parts subjected to heavy duty work.

In our foregoing discussions we have seen that during cooling, through normal rate, from austenitic condition the structure changes from austenite to either pearlite plus ferrite or pearlite plus cementite, depending upon the carbon percentage in the steel. This transformation takes place during the *critical range* and is finally completed at 723°C, the *lower critical point*. What we do in the process of hardening the steel is to develop such controlled conditions, by rapid quenching, that the above transformation is disallowed at the lower critical point and by doing so we force the change to take place at a much lower temperature than this. By rapid cooling the time allowed to the metal to change from austenite to the above constituents is too short and hence this transformation is not able to occur at the lower critical temperature. With the result, by effecting the change at a lower temperature than this, the metal is forced to be transformed from austenite to a new structure which is known as Martensite. This is a very hard substance and renders the steel hard and brittle.

It is evident, from the above discussion, that faster the rate of cooling, harder will be the metal. Efficient quenching, therefore, plays a vital role in hardening of steel. It should, however, be noted that efficient quenching is not the only factor which ultimately effects the *hardening*. The percentage of carbon present in the steel effects the result to a still greater extent. Higher the carbon percentage denser will be the solid solution of carbon with iron and therefore higher will be the amount

of martensite formed. It is only for this reason that, inspite of taking all precautions in quenching, low carbon steels cannot be hardened to any appreciable and practically useful degree of hardness through this normal process. By hardening the steel we increase its resistance to wear, ability to cut other metals, toughness, ductility and strength but some extra brittleness is automatically imparted to it. Fig. 8.9 shows the effect of carbon percentage on the hardness of the metal after the heat treatment.

Another important feature to be marked is that the critical rate of cooling required for steel for complete transformation to the martensitic structure depends entirely on the amount of carbon present in the metal. It varies inversely to the percentage of carbon present, i.e., lower the percentage of carbon higher will be the required *critical cooling rate* and vice versa (see Fig. 8.10). Various factors by which the *decomposition* of eutectoid and, hence, the process and results of hardening are effected can be summarised as follows :

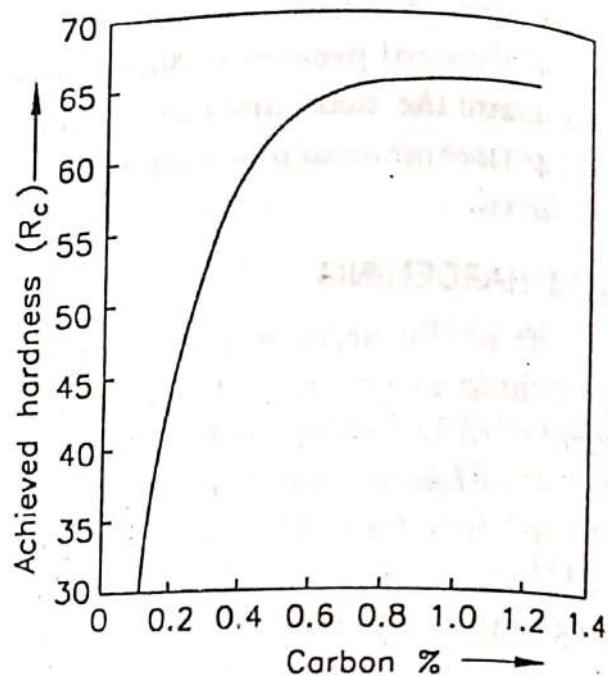


Fig. 8.9. Effect of the carbon content on the hardness of steel.

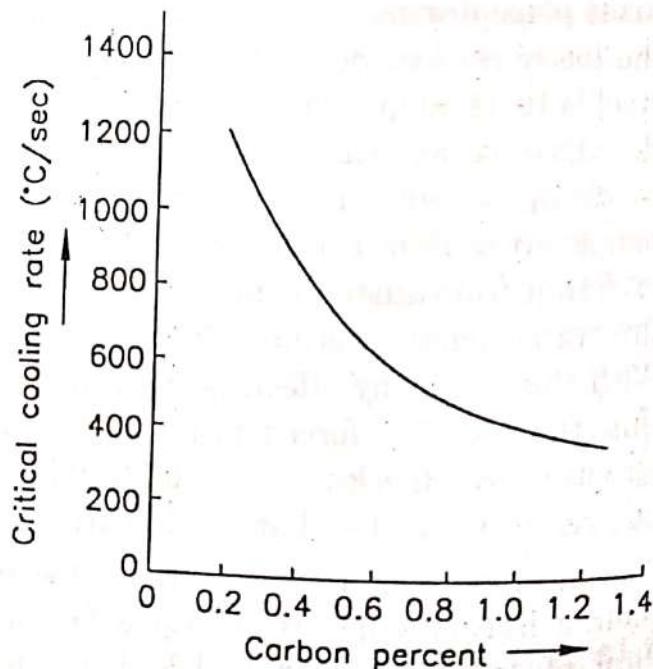


Fig. 8.10. Curve showing the relationship between the amount of carbon content and the required critical cooling rate for hardening of steel.

1. Amount of carbon content in steel.
2. Proportions of alloying elements, if an alloy steel.
3. Homogeneity/heterogeneity of austenite.
4. Decomposition of austenite.
5. Quenching medium.
6. Heating rate and duration.
7. Cooling rate.
8. Size of the component.
9. Surface conditions.

Due to super cooling of *austenite* to *martensite* form, the hardened steel becomes very brittle and stressed. It is, therefore not suitable for practical use. This is specially true with cutting tools. The hardening process should, therefore, be followed by tempering, in order to remove extra brittleness, relieve stresses and obtain better mechanical properties.

### 8.15 HARDENABILITY

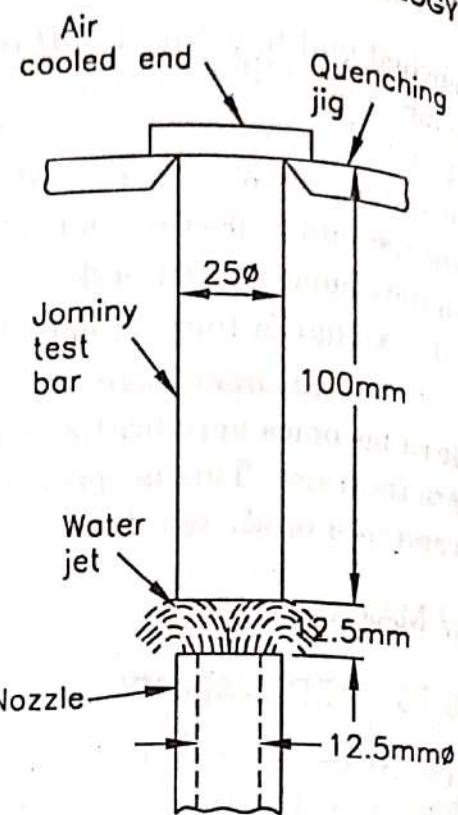
It can be described as the measure of the response of steel to the hardening process. It determines the depth and distribution of hardness in the metal due to quenching. It, however, should not be misunderstood with *hardness*. This, in fact, indicates the ability of the metal to attain uniform hardness throughout its mass or a varying hardness to some depth, usually considered upto *semi-martensitic* region where the structure consists of half martensite and half pearlite. Because of the varying hardness, there will be noticed a corresponding variation in the properties of steel at different depths of its cross-section. A *fully hardened* (or *uniformly hardened*) steel piece will exhibit uniform properties throughout its cross-section.

It is difficult to make thicker sections of *carbon steels* fully hardened. As a rough guide, carbon steel sections only upto 25 mm diameter or thickness can be full hardened. However, on account of larger stability of *Supercooled Austenite* and *Lower Critical Cooling Rate* the *alloy steels* can be effectively hardened to much larger depths than plain carbon steels. Also, for the same reasons the required hardness in them can be obtained by quenching them in oil instead of water. Thus, this is also clear that addition of alloying elements to carbon steels will increase their hardenability.

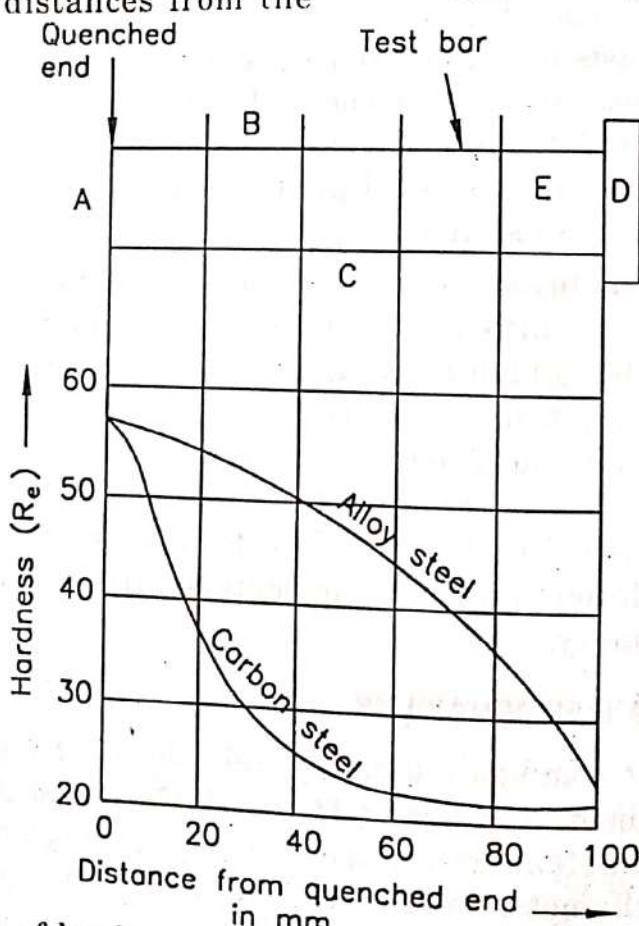
### 8.16 TESTING HARDENABILITY

The most commonly used and reliable test for determining the hardenability is the **Jominy End Quench Hardenability Test**, shown in Fig. 8.11. The standard test specimen used in this test is a cylindrical bar of 25 mm diameter and 100 mm effective length. One end of the bar carries a flange.

For conducting the test, the **Jominy Test Bar** is first heated to the austenitic temperature and held at that temperature for sufficiently long period so that the metal attains a uniform *austenitic* structure. It is then held in a jig and is quenched from its one end by throwing a jet of water through a *nozzle* on to the end continuously, maintaining a constant distance of 12.5 mm between the bar end being quenched and the end of the nozzle, as shown in the diagram. After the complete *test bar* has cooled down to room temperature a flat surface is ground on one side along the entire length and **Rockwell Hardness ( $R_c$ )** of the bar material is tested at every 1.5 mm from the quenched end. The readings (*hardness values*) so obtained are then plotted on a graph against the corresponding distances from the



**Fig. 8.11.** Setup for end-quenching of a heated Jominy test bar for hardenability test.



**Fig. 8.12.** Graph of hardness values of two Jominy test bars in Jominy hardenability tests conducted on test bars made of carbon steel and alloy steel.

quenched end to obtain the **Hardenability Curve**. Two such *curves*, one for *carbon steel* and the other for an *alloy steel*, are shown in Fig. 8.12. It will be evident from this diagram that the hardness is *maximum* near the quenched end, *continues decreasing* as the distance from the quenched end increases and is *minimum* at a point which is farthest from the quenched end. A clear correlation, therefore, appears between the degree of hardness produced and the corresponding cooling rate.

The main advantage of this test is that we are able to obtain a wide range of cooling rates, starting from very rapid near the quenched end to the very slow (*air quenching*) at the other end, in the same test bar and in a single set up.

### 8.17 MARTEMPERING

It is a misnomer, since it is not a *tempering* process but a *hardening* process. It is also known as **Stepped Quenching on Interrupted Quenching** process. It is employed for producing *martensite*. The process involves heating of steel to the *hardening range* and then quenching in a *salt bath*, which is maintained at a temperature slightly above the temperature at which *martensite formation* starts (i.e., between 150°C to 300°C). The component is soaked in the *bath* till its temperature comes down to the *bath temperature*, but it is not allowed to be immersed for a longer period, lest the *austenite* starts decomposing. It is then removed from the *bath* and cooled further, down to room temperature, in air or oil. During the second part of cooling in air or oil, the *austenite* is transformed into *martensite*. Because of the two different steps of cooling the process leads to the final structure of *martensite* with retained austenite in the steel. Thus, it enables formation of *martensite* without the formation of *bainite*. The main advantages of this process are :

1. Because of the simultaneous and uniform transformation occurring throughout the metal the chances of warping are very less.
2. The chances of setting up of residual stresses are minimised and, hence, of usual quenching cracks.
3. Since less amount of austenite is retained in the structure the volume changes are minimal.

### 8.18 AUSTEMPERING

It is a process which combines the good effects of both hardening and tempering, and is mainly employed for articles of high carbon steel

having thin sections, which need good resistance to impact. It is also known as **Isothermal Quenching**. The process consists of heating the steel to the usual hardening range, holding it there for sufficient time, to allow its structure to change to austenite, followed by *quenching* in a *salt bath* maintained at a temperature between 300°C to 350°C. The time allowed in the bath will depend upon the size and weight of the component. This enables the isothermal transformation of *Austenite* into **Accicular Troostite or Bainite**. After that, it is removed from the bath and allowed to cool down to room temperature in natural course. It is a faster process than both hardening and tempering. As a result of this treatment, strength and ductility of steel are increased and the chances of distortion are minimised.

Remember that the basis of this heat treatment is the **Isothermal (constant temperature) Transformation** of austenite. Usually no tempering is required after this treatment.

### 8.19 AUSFORMING

It should not be confused with **Austempering** since it is an altogether different process. It combines *heat treatment* with *plastic deformation* to give the desired results, and that is why it is also known as **Thermo-Mechanical Processing**. In this process, the metal is heated to the austenite temperature to acquire austenitic structure and then cooled by quenching to a temperature which lies between the temperature ranges for pearlite formation and bainite formation. The metal so cooled is capable of retaining its *austenitic structure* for some time. In this state itself the metal is subjected to *plastic deformation* and then cooled down to room temperature either in air or by quenching. In the former case a *bainitic* structure will result and in the latter case a *martensitic* structure will be obtained after cooling. If martensitic structure is obtained, it can be then tempered.

The metal after the above treatment exhibits very high ductility and strength, high creep resistance and toughness and longer fatigue life.

### 8.20 TEMPERING

A hardened steel piece, due to *martensitic structure*, is extremely hard and brittle, due to which it is found unsuitable for most practical purposes. So a subsequent treatment is required to obtain a desired degree of toughness at the cost of some strength and hardness to make

it suitable for use. It is specially true in case of the *Tools*. This is exactly what is mainly aimed at through **Tempering** of steel. This process enables transformation of some *martensite* into *ferrite and cementite*. The exact amount of martensite transformed into ferrite plus cementite will depend upon the temperature to which the metal is reheated and the time allowed for the transformation.

The process involves reheating the hardened steel to a temperature below the *lower critical temperature*, holding it at that temperature for sufficient time and then cooling it slowly down to the room temperature.

When the hardened steel is reheated to a temperature between 100°C to 200°C, some of the *interstitial carbon* is precipitated out from martensite to form a carbide called **Epsilon ( $\epsilon$ ) Carbide**. This leads to the restoration of **BCC** structure in the matrix. Further heating to between 200°C to 400°C enables the structure to transform to *ferrite plus cementite*. Further heating to between 400°C and 550°C leads to the *nucleation and growth of a new ferrite structure*, rendering the metal weaker but more ductile. If steel is heated above 550°C the cementite becomes *spheroidised*, and if heating is continued even beyond  $A_1$  line the structure will revert back to the *stable martensite*. As such, if a good impact strength is desired reheating should not extend beyond 300°C to 350°C. The section thicknesses of the components being treated also have a decisive effect on the results. Heavy components and thicker sections require longer tempering times than the lighter and thinner ones.

## 8.21 TYPES OF TEMPERING

The tempering procedures are classified as follows on the basis of the *ranges of temperatures* to which the components are reheated for tempering :

**1. Low Temperature Tempering.** The heating range for this type of tempering is from 150°C to 250°C. This treatment results in reduction of internal stresses and improvement in toughness and ductility without any appreciable loss in hardness. The main *applications* of this process are in *tempering* of carbon tool steels, low alloy tool steels, case carburised and surface hardened parts, measuring tools, etc. The different *colours* appearing on the surface of the metal are indicative of the approximate temperature attained by it. Such approximate temperatures, corresponding colours and the tools for whose tempering they are used are given in Table 8.2. For *temperature ranges* suitable for tempering of tools refer back to Fig. 8.3.

Table 8.2. Approximate tempering temperatures and temper colours for tools.

Colour	Temperature in °C	Use
Light yellow	220 – 225	Surgical instruments and turning tools for brass, Hacksaw blades.
Pale straw	225 – 230	Turning, planing and shaping tools, hammer faces and screw cutting dies for non-ferrous alloys.
Dark straw	230 – 240	Milling cutters, blades for iron jack planes, wood working tools, drills.
Brown	240 – 250	Shear blades, thread chasers, taps and dies for steel, reamers, boring tools.
Brownish purple	250 – 260	Brace bits for wood, guages, punches, snaps for rivet heads.
Purple	260 – 270	Axes, twist drills, punches and dies for power press work, scissors for sheet metal work.
Dark purple	270 – 280	Cold sets for steel, chisels for chipping work, smith's tools.
Light blue	280 – 290	Screw drivers, cold chisels for wrought iron.
Dark blue	290 – 300	Springs, blades for wood cutting saws.

**2. Medium Temperature Tempering.** This method of tempering is used to increase the toughness of steel at the cost of reduction in hardness. Simultaneously, it is accompanied by an increase in ductility and reduction in strength. It is mainly used for articles which are required to be subjected to *Impact Loading*, like coils and springs, hammers, chisels, etc., where a high yield strength, coupled with toughness, is a major requirement. The process involves reheating the component to a temperature between 350°C to 450°C, holding at that temperature for sufficient time and then cooling it to room temperature. This enables *transformation* of *martensite* and *austenite* (if present) to **Secondary Troostite**, resulting in the required change in properties.

**3. High Temperature Tempering.** This process enables the steel structure being finally transformed into **Sorbite**, which results in the material attaining high ductility while retaining enough hardness. The

process involves reheating the hardened steel to a temperature between 500°C to 650°C, holding it there for a certain time and then cooling it down to the room temperature. This results in complete elimination of internal stresses and providing a micro-structure which carries a useful combination of good strength and toughness. Crankshafts, connecting rods and gears, are a few examples of the type of parts usually treated through this process.

## 8.22 TEMPERING BATHS

Mainly three types of baths are used for tempering of steel parts and cutting tools :

1. Lead bath.
2. Oil bath.
3. Salt bath.

**Lead or Lead Alloy** bath may be used for tempering steel parts. The parts are preheated and then immersed in the bath, which is already heated to the tempering temperature. Once the parts reach the tempering temperature they are taken out and cooled to attain the required temper. **Oil baths** can be employed for various temperature ranges. **Light Oil Baths** are used for temperatures upto 230°C only. **Heavy Oil Baths** can be used for heating range from 343°C to 370°C. **Mineral oils** are commonly used for these baths. For *Oil Heating*, the bath temperature is first raised to the required tempering range and then partially heated component is immersed in it. If the temperature of both falls below the required level, both the bath and the immersed component can be heated together to the tempering temperature. After the component has reached the required temperature, it is removed and immersed in a tank of caustic soda, followed by *quenching* in a *hot water* bath. **Salt baths**, carrying liquid nitrates or nitrates plus nitrites, are used for higher temperatures. They can be used for temperature range from 540°C to 600°C. From efficiency and economy points of view their use below 173°C is not recommended. The salts used for these baths are generally *chlorides* and *fluorides*. These baths are very widely used for tempering of **High Speed Steels**. In this case, the part and the bath are heated together to the required temperature.

Many a times the **High Speed Steel Tools** are *double tempered* to ensure that no martensite remains untempered in the tool material. For this, the **HSS tool**, once primarily tempered as above, is reheated to the tempering temperature, held there for a required period of time and again cooled to the room temperature. In this manner, if any

*martensite* portion had remained *untempered* during the original tempering it will be tempered, internal strains, if any, in the material will be removed and it will truly exhibit the expected mechanical properties. This is called **Double Tempering**.

### 8.23 CASE HARDENING

It is the process through which a hard, wear resistant and shock resistant surface is produced on steel, having a tough core inside. The main theory behind this process is to heat the steel to red heat and then force the carbon content into its surface structure, so that a certain depth all along its surface becomes rich in carbon. It is then hardened as usual. For the above reason only this process is also frequently known as **Carburising or Carbonising**. The *carbon* is *infused* into the surface of steel by *diffusion* from *carbon monoxide* gas at elevated temperatures of the order of  $870^{\circ}\text{C}$  to  $950^{\circ}\text{C}$ . It is chiefly employed for wrought iron and mild steel, the metals which have a comparatively low carbon content. The use of these case hardened metals has three distinct advantages :

1. Because of the low carbon content in these metals hardness is imparted only to a relatively small depth below the outer skin and the soft and tough core is almost automatically obtained.
2. On account of the above transformation their outer surface gives as good service against wear, shock and abrasion as a hardened piece of high carbon steel, at the same time having an added advantage in having a soft and ductile core, which is quite tough against a comparatively brittle structure of fully hardened steel.
3. For similar service, they are comparatively cheaper than high carbon steel.

The process of *Case Hardening* is carried out in two stages : (i) *Carburising i.e.*, adding carbon to the outer skin to make it rich in carbon content so that it can be hardened, (ii) *Hardening* this skin and refining the structure of the core to make it tough.

There are three common methods of carburising :

1. Pack carburising.
2. Liquid carburising.
3. Gas carburising.

### 8.24 PACK CARBURISING

We have seen in the previous articles that iron has a definite affinity for carbon when it is at high temperature, particularly above the *critical range*. So what we do in the first stage is that we enclose the metal in a

cast iron or steel box, containing a material rich in carbon, such as small pieces of charcoal, wood, charred leather, tar, etc. and then heat it to a temperature slightly above the *critical range*, usually between 900°C to 950°C, and allow it to remain at that temperature for sufficient time so that the carbon is absorbed to the required depth. Thus, the outer skin is converted into high carbon steel, containing about 0.8 to 1.2 per cent carbon. The depth, to which this carbon enrichment takes place, depends upon the time allowed to the metal to remain at the elevated temperature, which may vary from 3 to 20 hours depending upon the size of the box carrying the articles for *Pack Carburizing*. The usual depth attained in 3 to 4 hours time varies from 0.8 mm to 1.6 mm. The metal is then allowed to cool slowly within the box and then removed.

The second stage consists of *reheating* the metal to about 900°C and then *quenching in oil* so that its structure is refined, brittleness removed and the core becomes soft and tough. The metal is then reheated to about 700°C and quenched in water, or oil, depending upon whether it is carbon steel or alloy steel, so that the outer casing, which had been rendered soft during the preceding operation, is again hardened.

## 8.25 LIQUID CARBURISING

**Liquid Carburising**, as the name suggests, is done in a liquid medium and no *carbonaceous* materials are required to be packed around the workpiece. For this process, liquid *salt baths* of cyanides, chlorides and carbonates (sometimes carbides too) are prepared and the parts to be case carburised immersed in them. Heating of the bath is done by means of *electrodes* immersed in the bath. Stirring of the bath is necessary to ensure uniform temperature. If the entire component is to be carburised then no additional treatment is necessary, but if only some selected portions of the component are to be carburised the remaining portions are covered by copper plating.

Temperatures for liquid carburising vary from 843°C to 927°C. However, it is observed that a 2 hours heating of components with the bath temperature at 900°C a *depth penetration* of about 0.5 mm can be achieved. Deeper the penetration desired, longer will be the heating time. After carburising is over, the components are removed from the bath and quenched in water, oil or brine, depending upon the operational requirements.

Some major advantages of this process are uniform heating, very little deformation of article, ease of carburising a wider range of parts, greater depth of penetration possible, selective carburising (if needed) and a faster process.

### 8.26 GAS CARBURISING

It is a relatively more recent process in which the components are heated in an atmosphere of *hydro-carbon rich* gases like natural gas (methane), propane, butane, hydrogen, etc. mixed with carbon monoxide or carbon-di-oxide. The components are either suspended in the gas furnace from hooks or are heated in a horizontal rotary type *Gas Carburiser*. The mixture of the gases is continuously fed into the furnace retort and a controlled atmosphere maintained inside. There is a provision for exhausting the spent gases into atmosphere.

After the parts have been *soaked* in the carburising chamber they are directly quenched without being exposed to atmospheric air. This enables a very superior surface finish, which cannot be attained by any other method. It is found that a 4 hours heating in a gas carburising temperature of about  $927^{\circ}\text{C}$  enables a depth penetration of about 0.5 mm to 0.75 mm.

The main advantages of this process are a superior surface finish on the component, controlled heating, accuracy of desired case depth, speedy process, requirement of less floor area and relatively more reliable results. Also, the process can be mechanised, if desired.

### 8.27 NITRIDING

This process, which is basically a **Surface Hardening Process**, is based on the absorption of *nitrogen* by the metal and no quenching is required. It can be used with equal advantage for both *Carbon-alloy steels* and other *alloy steels*. Also, it can be employed for both the complete hardening and selective hardening. Its specific application is in *complete* or *selective hardening* of such components which have been finish machined to their final shape and size and then they are required to obtain a hard surface without any distortion. Even heat treated parts can be skin hardened through this process. Alloys, carrying chromium, aluminium, molybdenum and vanadium as alloying elements, respond best to this process because all these elements are *nitride forming* elements.

This process can be performed both in gaseous atmosphere as well as in salt baths. In the former case it is known as **Gas Nitriding** and in the later case **Salt Bath Nitriding**. In both the cases, the parts are heated in a controlled atmosphere below the lower critical temperature.

In **Gas Nitriding** the parts are heated in an atmosphere of *Ammonia* to a temperature between  $480^{\circ}\text{C}$  to  $630^{\circ}\text{C}$  and held there for a fairly long period. During this period, nitrogen from ammonia gas decomposes and combines with the alloying elements in steel to form

*nitrides*. These nitrides, being very hard, render extreme hardness to the skin without quenching process. The degree of hardness obtained is higher than obtained through any other heat treatment. In addition, *nitriding* also increases fatigue and wear resistances, tool life of cutting tools and corrosive resistance against water, steam and atmosphere. However, this process is slower than other heat treatment processes, which is clear from the fact that a case depth of 0.5 mm may take 2 to 3 days in getting hardened through this process.

In **Salt Bath Nitriding** the liquid salt bath is first heated to a temperature range of 480°C to 590°C, depending upon the requirements of the parts. The parts to be treated are suspended in this bath and held there for a prolonged period for soaking. The bath temperature is maintained throughout within the above range. After soaking, the parts are removed but no quenching is done. This process is specially used for nitriding of cutting tools like drills, taps, reamers, milling cutters, hobs, dies, etc.

## 8.28 CYANIDING

It is a type of *case hardening process*, generally used for producing hard cases on low and medium carbon steel pieces. In this process, the metal absorbs carbon and nitrogen to acquire a hardened surface layer. Simultaneously the wear resistance and fatigue resistance of the skin are also improved. There is no *scaling* on the surface and heating is controlled and uniform. With the result, the surface finish of the component is not deteriorated and chances of cracks and distortions are minimised. The application of this process is generally limited to a maximum case depth of 0.5 mm, although higher depths upto 1.5 mm are possible.

The steel is heated in a molten *salt bath* to a temperature of about 800°C to 950°C. The types and proportions of cyanide salts used in preparing the molten salt bath depend upon the amount of carbon content needed in the surface of the metal. A *typical combination* can be a mixture of sodium cyanide, sodium chloride and sodium carbonate in equal proportions. In some cases *barium chloride* and *soda ash* can be added in suitable proportions. After soaking for the required period at proper temperature the steel piece is removed from the bath and quenched in water, brine or oil. The hardness induced in the case of the metal is due to the formation of compounds by nitrogen and carbon absorbed by the case. The soaking time required depends on the case

depth required and the soaking temperature. If tempering is needed, it can be done at lower temperatures between 120°C to 150°C.

### 8.29 CARBONITRIDING

It is a **Gas Process**, in which **Cyaniding** is carried out in a gaseous atmosphere, i.e., carbon and nitrogen are added to the surface layer of steel by a *dry gas* instead of a molten bath. This process is mainly used for producing a hard case on low carbon and tool steels. The surface skins produced through this process are harder and possess better wear resistance and hardenability than those produced through *carburisation*. This process is slower than *cyaniding*.

The process involves heating of parts in a controlled atmosphere of *natural gas* and *ammonia* at *critical temperature*, soaking there for the required period and then quenching. During the process, nitrogen released by *ammonia* and carbon from the *carburising (natural)* gas are absorbed by the metal surface. Various temperature ranges are used for heating and soaking, which depend upon the case depth required, composition of the component material being treated and the purpose for which it is to be used. For example, **High Speed Tools** can be carbonitrided at about 500°C and *machine parts* at 800°C. Carbonitrided parts and tools are normally tempered by quenching in oil in order to achieve maximum hardness and avoid distortion. Similarly, it is found that a *soaking temperature* of about 790°C enables a case depth upto 0.25 mm in about 90 minutes and *soaking* for about 5 hours at 870°C produces a case depth of about 0.75 mm. The process can, however, be accelerated by raising the heating and soaking temperature to about 900°C.

### 8.30 SURFACE HARDENING

Several times the operational requirements need the products to have hard surfaces, either throughout or at selected locations, with a tough core, as in *Case Hardening*. But, in case hardening, heating in a furnace or a liquid bath is required. There are methods of surface hardening in which the heating technique is different and these methods are grouped under **Surface Hardening**, otherwise the objective in both is the same. The common surface hardening techniques are the following :

1. Induction hardening.
2. Flame hardening.
3. Laser beam hardening.
4. Electron beam hardening.

### 8.31 INDUCTION HARDENING

In this process, the main controlling factor for degree of surface hardness is the carbon content present in the steel itself since no carbon or nitrogen is added from outside. So, the steel should contain enough carbon content to allow hardening to the required level through heating and quenching only. As such, low carbon steels with carburised cases, medium carbon steels and high carbon steels can be hardened through this process. In *Alloy steels* only a shallow hardening is possible because of the fear of cracking and high stressing due to rapid and intense quenching. Cast iron, carrying some amount of carbon in chemically combined form, can also be hardened through this process.

The steel piece to be hardened is placed inside an **Applicator Coil or Inductor**, quite close to it but without touching it. A high frequency (2000 cycles/sec) alternating current is passed through the coil which, in turn, induces *Eddy Currents* into the work surface. This, together with the *Hysteresis losses* in the surface metal raises the surface temperature to the hardening range within a few seconds. The component can be held in a fixed position, rotated or longitudinally moved through the coil. After the required temperature is attained by the surface, the component is quenched in water, oil or air. The duration and intensity of the heating cycle decides the depth to which hardness is induced. However, if deep hardening is needed or larger workpieces are to be induction hardened a prolonged low frequency heating should be employed.

Quenching, after **Induction Heating**, can be done in many ways. Small components, like drills, pins, etc., can be induction heated all over and quenched. Several components, like gears, may need selective and intermittent heating and quenching for induction hardening only on those portions (such as gear teeth) which are to be subjected to wear. Longer components like crankshafts, axles, camshafts, can also be provided required surface hardness either at selected locations or throughout, according to requirement. A water jet, an oil bath or air stream are the common quenching media used.

The main **Advantages** of this process are its fast speed (between 1 to 5 seconds), high efficiency, adaptability to special shapes, no oxidation, no scaling, no decarburisation, minimum chances of warpage or distortion, convenience in heat treating long parts, no dimensional changes in parts-enabling machine finish components to retain their dimensional accuracy after the treatment, easy control of hardness depth, possibility of selective hardening (if required), possibility of automation and economy in material cost because induction hardened medium carbon steel parts with high surface hardness, high fatigue

resistance, superior wear resistance and impact strength are capable of replacing costlier alloy steel parts in many cases. However, its Limitations are that it suits only to medium carbon and low alloy steels and its equipment is more costly.

### 8.32 FLAME HARDENING

In this process also hardening is only due to heating and quenching. As such, only medium and high carbon steels can be surface hardened through it. As a general rule, *any plain carbon steel carrying above 0.3 percent carbon can be flame hardened.*

In Flame Hardening, a high intensity *oxy-acetylene* flame is used to heat the surface or area to be hardened to above its critical range, so that austenite is formed, and then the hot surface is quenched to attain the desired hardness. This may be followed by tempering, if required. Because of the flame, the heating is very quick and is confined only to the surface and is localised to only a limited area. Also, the *water spray (quench)* immediately follows the flame. These two factors lead to a very slow and limited heat transfer to the remaining part of the component, leaving the latter free of any appreciable change. Depending upon the type of steel, if air quenching is required, a compressed air jet may replace the water spray. Also, if the desired surface properties require tempering, after flame hardening, a low temperature flame follows the quenching spray to reheat the surface to tempering temperature, followed by a tempering quench.

This process is quite flexible because the rate and depth of heating both can be varied according to the requirement. The hardening depth may vary from a very thin skin to more than 6 mm. Selective hardening or overall hardening, both are possible. The process can be performed manually or can be made *fully automatic*, including *computer controlled*.

### 8.33 LASER BEAM HARDENING

This process is also used for *surface hardening* of medium carbon and high carbon steels. It is similar to the above two surface hardening processes, except that the heat source is different. In this process, the job surface to be hardened, is first coated with an *absorptive media* as zinc or manganese phosphate. A **Laser Beam** is then used and the coated surface *scanned* with it. The beam size, the scanning speed and the intensity of beam are chosen according to the results desired. The *Absorptive Coating* applied on the surface helps in accelerating the conversion of light energy into heat. Soon after the scanning is over it is followed by water quenching or oil quenching. The depth of heating will depend upon the intensity of beam and the speed of scanning. A slow scanning speed with a beam of higher intensity will ensure a deeper

heating. Similarly, a faster scanning and lower beam intensity will lead to a shallower heating. Since there is no addition of carbon from outside the degree of hardness attained by the surface will mainly depend upon the carbon content of the material. For example, a medium carbon steel with 0.4% carbon can attain a **Surface Hardness** of the order of  $Rc\ 65$ .

The main **Advantages** of this process are its fast speed, facility of selective hardening, almost negligible distortion, can be made fully automatic and even computer controlled.

### 8.34 ELECTRON BEAM HARDENING

It is also a **Surface Hardening Process**, quite similar to *Laser Beam Hardening*, but its application is limited to only smaller and medium size components because of the constraints imposed by the size of vacuum chamber in which the component is to be housed. In operation, the process is almost similar to *laser beam* process except that here a **High-Energy Electrons Beam** replaces the *laser beam* as a heating source. *Electromagnetic controls* are employed for directing and focussing the charged electrons on to the surface to be hardened. The component is enclosed in a **High Vacuum Chamber** and has to be manipulated in the vacuum only. It is essential because the electrons cannot travel in a directed path in air. The size of this chamber, therefore, limits the size of the component that can be treated by this method. This process can be easily *automated*.

### 8.35 HEAT TREATMENT OF NON-FERROUS METALS

The major requirements of *Heat-treatments* in non-ferrous metals and alloys is of strengthening them. Single-phase metals can be strengthened by **Solid Solution Hardening** technique while ductile metals can be *strain hardened*. Similarly, **Dispersion hardening** can be employed for eutectic forming alloys. However, the most widely used and effective method for non-ferrous metals and alloys is **Precipitation hardening or Age hardening**.

#### Precipitation Hardening or Age Hardening

Most of the **Non-Ferrous Alloys** can be heated into a *single phase solid solution*. On account of their decreasing solid solubility, with lowering of temperature, their structure is transformed into two distinct phases at low temperatures. When they are cooled down at a faster rate, from the hot single phase state, the resulting structure is a **Supersaturated Solid Solution**, i.e., one of the materials, which was supposed to form the *second phase* of the structure, called **Solute**, gets trapped in the lattice of the other material called **Solvent**. When this alloy is further subjected to *ageing*, i.e., heating back to a predetermined temperature, the *solute atoms precipitate* out of the *super-saturated solid*.

solution and this phenomenon is responsible for hardening of the alloy. Hence, the name **Precipitation Hardening**.

The process will be more clear by considering a concrete example. Let us consider an **Aluminum-Copper Alloy** consisting of 96% aluminium and 4% copper and study its phase diagram shown in Fig. 8.13. It shows that a *solid solution* of aluminium with copper is formed in which the maximum solubility of copper at the *eutectic temperature* of  $548^{\circ}\text{C}$  is 5.7%. Now, if the *alloy* is cooled slowly from this stage the *second phase* ( $\theta$ ) precipitates out of the *solid solution* because the solubility of copper in aluminium reduces from 5.7% to about 0.2% at room temperature, as indicated by the *solubility curve*. If, however, this alloy was cooled from the liquid state at a faster rate, there will not be enough time for the transformation to usual two phase structure and the resulting structure will be a **Single Phase  $\alpha$**  in a *supersaturated form*, which is not a normal condition. Consequently, the *excess copper* will tend to precipitate out of this form and mix-up with the  $\theta$  phase. It is an unstable condition needing *diffusion*. To achieve that, it is reheated to between  $150^{\circ}\text{C}$  to  $200^{\circ}\text{C}$  and held there to allow precipitation of copper, resulting in a single phase structure consisting of  $\alpha$ -*solid solution* and the *precipitate*. This is known as **Ageing**, and if this is carried out under carefully controlled conditions the resulting structure (hence, the material) will be extremely hard and strong.

The phase diagram is almost identical for all the non-ferrous alloys which can be age hardened. The entire **Precipitation Hardening** process consists of the following three controlled stages :

**Stage I.** This stage consists of heating the metal to a temperature where it forms a single phase solid solution, soaking it there to allow formation of a uniform structure, followed by rapid cooling by quenching in water to disallow *diffusion* and enable formation of a *supersaturated solid solution*. The heating temperature should, however, not exceed the eutectic temperature otherwise melting may occur.

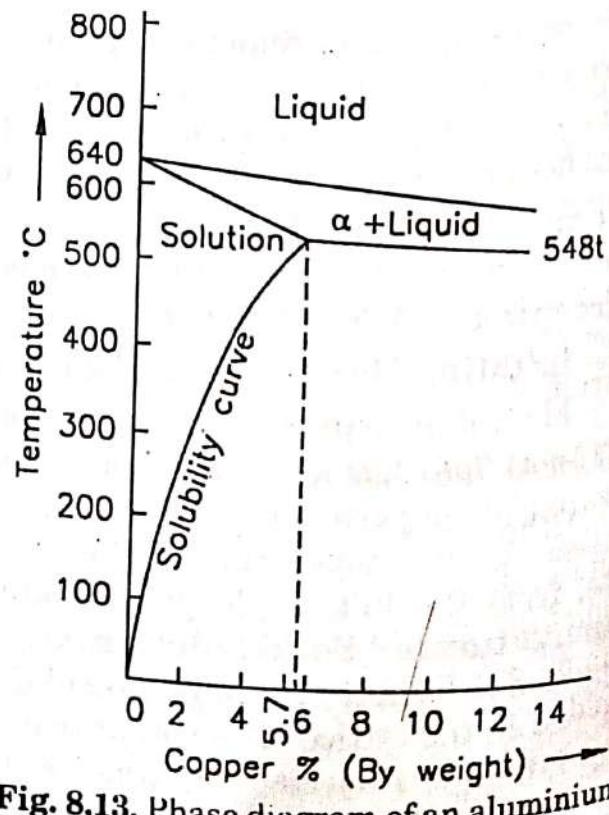


Fig. 8.13. Phase diagram of an aluminium-copper alloy.

**Stage II.** This stage comprises **Age Hardening**. Some metals and alloys get age hardened at room temperature itself. For them no reheating is required because *diffusion* occurs at this very temperature and the *supersaturated solution transforms* into a stable *two-phase* structure. Against this, some metals and alloys respond differently and need reheating and artificial ageing, as described earlier in this article.

**Stage III.** This stage consists of methods to control the properties. For this, the natural ageing type materials are subjected to refrigeration, while in case of artificial ageing type materials this control is exercised by properly adjusting the temperature and time of high temperature ageing.

### 8.36 SUB-ZERO TREATMENT OF STEEL

Whenever steel is hardened some amount of austenite is always retained by it. This results in the reduction of hardness, thermal conductivity and wear resistance and change in form or size, over a period of time, of the metal part. The **Sub-Zero Treatment** of hardened steel reduces the retained austenite. In this process, the hardened steel part is cooled to *sub-zero temperatures*. But, it is possible and useful in case of those steels only in which the *martensite finish (M<sub>f</sub>)* temperature is below 0°C. When these steels are cooled to their *M<sub>f</sub>* temperatures the retained austenite is transformed into martensite. Consequently, the hardness and wear resistance of the metal are increased and the form and size of the component become stable. An important point to be noted here is that cooling below the *M<sub>f</sub>* temperature will not be of any use because there is no chance of any more transformation of austenite into martensite below this temperature. Hence, this should not be done. For *Sub-zero treatment* the component is held for about an hour or a little more between – 30°C to – 120°C. High speed steel tools are generally subjected to this treatment since stable hardness is of paramount importance in them. Similar are the requirements of high wear resistance and good thermal conductivity in them. Other articles generally subjected to this treatment are carburised parts, measuring instruments, etc.

### 8.37 HEAT TREATMENT OF CUTTING TOOLS

Although several tool materials like sintered carbides, stellites, ceramics, diamonds, etc. are in use, specially in machining of *difficult to machine* materials and high speed machining, still in most of the common machining operations majority of the cutting tools are of solid forged type, made of *High carbon steels* or *High speed steel*. The latter are used in bit form also to save material cost without effecting the

cutting efficiency. Irrespective of whether they are in solid forged form or bit form all cutting tools, made of *high carbon steel* and *high speed steel*, need heat treatment in order to attain some specific properties needed in the *Metal cutting* or *Machining* operations performed by these tools. Some important properties required in these tools are high hardness, high wear resistance, good thermal conductivity and toughness and minimum brittleness, specially at the cutting edge.

Solid tools of plain carbon steels are forged in the temperature range of  $850^{\circ}\text{C}$  to  $950^{\circ}\text{C}$ . The actual forging temperature is determined by the carbon content of this class of steel. Higher the *carbon content* the higher is the *forging temperature*. During forging the metal should not be allowed to cool down below the *Lower critical temperature*. The forging temperatures for high speed steels range from  $1100^{\circ}\text{C}$  to  $1300^{\circ}\text{C}$ . The main heat treatments required for the forged tools are *annealing* or *normalising*, *hardening* and *tempering*.

**Annealing or normalising.** After forging to shape, the tools are *Annealed* or *Normalised*, depending upon whether the tools are made of *High Speed Steel* or *Plain Carbon Steel respectively*. The purpose of giving this treatment is to relieve internal stresses and refine grain structure. Of course, as usual, a little softening of material automatically takes place.

*High speed steel* tools are first preheated and then put in the furnace. If softening is desired, the tools are heated to a temperature of  $850^{\circ}\text{C}$  for a period of 3 to 4 hours and cooled slowly in the furnace. For annealing, the *HSS* tools are heated to a temperature of  $900^{\circ}\text{C}$  and allowed to cool in air. To ensure a perfectly uniform grain structure these tools are reheated to  $800^{\circ}\text{C}$  and then cooled in air. It is necessary to employ a furnace with protective atmosphere for heating in order to prevent oxidation. After *annealing*, the resulting structure will comprise *carbide globules* in a fine *pearlite matrix*.

For *Normalising*, the plain carbon steel tools are heated to a temperature range of  $760^{\circ}\text{C}$  to  $840^{\circ}\text{C}$ , depending upon the percentage of the carbon content in them. Upto the lower critical temperature, heating is slow and then it is accelerated. After holding them at the normalising temperature for a certain period of time the tools are removed from the furnace and cooled in air.

**Hardening.** For *Hardening* the *Plain Carbon Steel Tools*, they are heated to a suitable temperature within their *Hardening Range*, depending upon the percentage of carbon present in them. The common hardening temperature ranges are given in table 8.3 below :

**Table 8.3. Temperature ranges for hardening of plain carbon steel tools**

Carbon (%)	Hardening temperature ranges
0.70 to 0.80	780°C – 850°C
0.80 to 0.95	765°C – 790°C
0.95 to 1.10	750°C – 775°C
Above 1.10	750°C – 775°C

After heating to the required temperature and holding them at that temperature for a certain period of time they are removed and cooled by quenching in a *bath of water or brine solution*. Out of these two quenching media the latter is preferred because it ensures a more uniform cooling and, thus, minimises the chances of cracking.

The **Hardening of HSS tools** involves a relatively more complicated process. Although *austenite* formation takes place in these steels between 800°C to 850°C the carbon content is too low. If they are cooled from this temperature, the amount of *martensite* formed will also be low and, hence, too low will be the *Degree of hardness* produced. It is, therefore, necessary to heat these steels to much higher temperatures in order to force enough *carbon* and the *alloying elements* to dissolve in austenite. The complete process of hardening these tool steels consists of first preheating the tools to about 850°C in a preheating furnace, holding them at that temperature for a certain period of time and then heating them at a faster rate to 1190°C to 1340°C. *Preheating* of these steels helps in restricting the grain growth and oxidation. The *holding time* at the preheating temperature is usually 10 to 15 seconds per mm thickness of the cross-section of the tool being heat treated. Similarly, the *holding time* at the hardening temperature should be sufficient enough to allow *dissolution* of surplus *carbides* which could sneak into the solution at those elevated temperatures. After holding the tools at the hardening temperature for the required period the tools are quenched in oil to a temperature of around 420°C, held there for some time and then cooled in air to room temperature.

**Tempering.** **Tempering** of tools after hardening is essential in order to do away with some extra brittleness, specially at the cutting edge. It also helps in removing the internal stresses setup during the hardening process. *Tempering of Tools* involves reheating to specific temperatures, followed by cooling. *Plain carbon steel tools* are reheated to a temperature range from 150°C to 300°C for tempering; depending upon their applications. However, a temperature range from 200°C to 300°C is more commonly used, as shown in Table 8.2. **High Speed**

Steels are normally reheated to within the temperature range of 500°C to 600°C for tempering. Cobalt HSS tools are reheated to 650°C to 700°C for tempering. Salt baths are normally used for reheating the HSS tools for tempering. For cooling, oil quenching followed by air cooling gives best results. Cobalt HSS tools are usually cooled in dry still air, instead of quenching, to avoid internal strains. Prior to tempering and soon after hardening the HSS tools are normally subjected to sub-zero treatment in order to prevent the stabilisation of retained austenite after hardening, as explained in article 8.36.

### 8.38 POSSIBLE DEFECTS IN HEAT TREATMENTS, THEIR CAUSES AND REMEDIES

Due to several reasons there are possibilities of some defects occurring in the heat treated components. The possible common defects, their causes and remedies are summarised in Table 8.4.

**Table 8.4. Possible common defects in heat treatments, their causes and remedies**

Defects	Causes	Remedies
Oxidising	Oxidising atmosphere in heating furnace	Use carburising agents or controlled heating atmosphere.
Decarburisation	Prolonged heating in oxidising atmosphere at elevated temperatures	Use protective atmosphere for heating.
Cracks due to quenching	Defective design-presence of sharp corners in the part, high hardening temperature, delayed tempering	Change design avoiding sharp corners, heat to minimum hardening temperature and temper soon after quenching is over.
Soft spots	Heterogeneous initial structure, localised decarburisation and bubble formation during quenching	Ensure a homogeneous structure of steel before heat treating, prevent decarburisation and quench carefully in a suitable quench medium.
Coarse grained structure and fractures	Prolonged heating at elevated temperature	Use correct heating temperature and proper heating period. Annealing and normalising will all help minimise the defects.

Defects	Causes	Remedies
Too high or too low hardness in component after tempering	Improper tempering temperature, prolonged holding time or inadequate holding time	Employ proper tempering temperature and adequate holding time. Annealing after tempering can also help.
Warping	Non-uniform heating. Distortions caused during cooling due to improper quenching	Follow uniform heating for hardening, cool slowly and hold the part in proper position during quenching. Use of a proper quenching jig may also help.
Erosion and Corrosion	Employing highly oxidising or reducing heating atmosphere	Controlled heating, using proper salt compositions in baths, correct positioning of the component in relation to the heating electrodes and addition of deoxidising salts will help prevent these defects.
Circular Cracks	Non-uniform heating in hardening	Follow uniform heating during hardening.
Cavities and holes in component	Formation of bubbles during quenching	Use proper quench medium and perform quenching carefully.
Part undersized to clean up the decarburised portions	Insufficient allowance on the machined surfaces for grinding the effected portions	Take adequate care in design to provide enough machining allowance to clean up decarburised portions through grinding.

### 8.39 HEAT TREATMENT FURNACES

A Heat Treatment Furnace is normally a box like chamber carrying a refractory lining inside with *Temperature Controls and Indicating Devices* outside it. A door is always provided for accessibility. The basic requirements of a *Heat Treatment Furnace* are :

1. It should be so designed as to ensure uniform heating and cooling of components inside it.
2. It should carry means of easy and effective control of temperature.

3. It should not occupy a very large working area.
4. It should provide a controlled heating atmosphere inside, in order to avoid oxidation, scale formation, decarburisation, etc.
5. It should not take too long to heat up to the required temperature after being loaded.

The selection of a particular Furnace for heat treatment will depend upon :

1. The dimensions and shapes of the components to be heat treated.
2. The purpose for which it is to be used, i.e., hardening, annealing, tempering, nitriding, etc.
3. The amount of production of heat treated parts.
4. Whether to be used intermittently or continuously.
5. Cost considerations.
6. Ease in its operation and control.

#### 8.40 CLASSIFICATION OF HEAT TREATMENT FURNACES

Due to a very large variation in shapes and sizes of the components to be heat treated, in ranges of required temperatures, in types of heating environments needed, in volumes of production to be handled, in types of heat treatments to be given and many other similar requirements, it is not possible to carry out all types of heat treatments in the same type and size of furnaces. As such, a large number of *different types of furnaces* have been designed to meet such a variety of requirements. All these furnaces can be broadly classified as follows :

**1. According to the purpose.** Based on the purpose for which they are used, the furnaces are classified as *Annealing Furnaces*, *Tempering Furnaces*, *Carburising Furnaces*, *Nitriding Furnaces*, etc. Many of these furnaces are multi-purpose type, i.e., they can be used for more than one heat treatment process.

**2. According to the source of heat.** Based on this criterion, the furnaces are classified as *Oil Fired*, *Gas Fired*, *Coal Fired*, *Electric Furnaces*, etc. In modern practice, the **Coal Fired** furnaces are very rarely used because of their lower efficiency and hygienic considerations. **Oil Fired** furnaces are found to be quite efficient for high temperature heating, but for low temperatures they are found to be uneconomical. For this reason, they are preferred for use for temperatures above 1200°C.

The **Gas Fired** furnaces are found to be superior than both the coal fired and oil fired furnaces. They are more economical and their control is easier. By replacing different types of burners they can be adapted for both low temperature as well as high temperature heating.

In order to avoid the direct contact between the metal being heated and the *sulphur* or water *vapour* carried by the fired gas, it is preferred to use a **Muffle Type** furnace or a **Radiant Tube**. Gas fired furnaces can be effectively used for heating upto 1500°C temperature.

In this category, the most efficient and most widely used type of furnace is the **Electric Furnace**. They provide a uniform temperature throughout the heating chamber, are simple in construction and carry no chimney or gas chamber. Thus, they provide a very clean atmosphere. Also, they enable better temperature control and high thermal efficiency. In these furnaces, heat is transferred to the metal components by *radiation* or *convection* or *both*. These furnaces can be easily adopted for mass production in heat treatment work. These furnaces can be of **Resistance Type** or **Induction Type**, but resistance type were in wider use in heat treatment work earlier. In recent times, however, the use of **Induction type** furnaces has increased considerably.

**3. According to the type of work.** According to the type and bulk of the work they handle at a time, the heat treatment furnaces can be classified as **Batch Type**, **Semi-Continuous Type** and **Continuous Type**. In *Batch Type* furnaces a limited number (called *Batch*) of parts is heated at a time. Once that batch is ready it is removed and replaced by another batch. Like this, several batches one after the other can be heated. However, all the batches need not be similar in respect of the size and weight, type of steel and the type of heat treatment to be given. Different batches may have different requirements for heating. These furnaces can be further classified as follows :

**Table 8.5. Classification of Batch Type Furnaces**

According to heat source	According to position	Stationary type	Movable type
Oil fired	Vertical (Pit type)	Direct fuel fired	Car bottom type
Gas fired	Horizontal (box type)	Indirect fuel fired (muffle type)	Rotary type
Electric			

These furnaces are also known as **Hearth Furnaces**. In these furnaces, heat is obtained from burning oil, gas or electricity. In oil and gas fired furnaces the fuel is burnt and hot products of combustion are used to heat the metal parts either with direct contact or without it. In *electric furnaces*, which also look similar in appearance, the *Electric Resistance Heating Elements* are fitted in the heating chamber on the side walls and supported by the refractory lining provided inside the chamber. When the current is switched on, these heated elements

transfer the heat to the components, placed inside, directly by radiation. However, in low temperature furnaces the electrically heated air may be forced into the chamber which, while circulating in the chamber, transfers heat to the components.

A **Pit Type** furnace is used for heating bulky and long components. The components are held vertically in the furnace. Smaller components can, however, be kept in a suitable container (such as a crucible) and heated collectively. The **Box Type** batch furnace is preferred for heating batches of small components. The furnace carries a door, called *charging door*, through which the components are charged and removed manually. If the components are of large size and heavy they should preferably be loaded on the travelling car of a **Car Bottom Type** furnace. In these furnaces the *hearth* is movable and mounted on rollers. Thus, it can be rolled out of the furnace and after loading of components rolled back into the furnace for heating. The components are loaded with enough spacing amongst them to enable the *combustion products* to circulate freely through them to ensure uniform heating. A **Rotary Batch Type** furnace may either carry a rotary *horizontal hearth* or a *fixed hearth* with *rotary retort*. In either case the components are loaded on the hearth and the rotation, either of hearth or retort, is slow enough to ensure uniform heating of parts.

A **Muffle Furnace** is a *Stationary Indirect Fuel Fired Furnace*, i.e. the products of combustion do not come in direct contact with the components to be heated. It consists of a metallic outer shell provided with a refractory lining inside. A *Heating Chamber* or **Muffle** is incorporated inside with space all around it. Inlets for combustion products are provided in the empty area while the parts to be heated are loaded inside the heating chamber. Thus, the burning hot gases circulate all around the chamber but do not enter it. Heat is transferred to the components via the chamber. Thus, it provides a very clean heating atmosphere and there are no chances of any scaling, decarburisation, etc. It is very widely used for heat treatment of tools and dies in tool rooms.

In the **Semi-Continuous** variety the two popular furnaces are **Bell Lift Type** and the **Car Bottom Type**. The former is *movable* type, generally heated by radiant tubes or electric resistance. In either case it uses an indirect heating. The **Car Bottom Type** is a stationary type furnace using direct heating and carries a *roll out-roll in* type hearth as already described above.

A **Continuous** type furnace is also a stationary type furnace and is vastly employed in mass production of heat treated parts. These

furnaces may carry a conveyor, moving horizontally, on which the parts are loaded mechanically at one end, travelled through a horizontal heating chamber, quenched and delivered at the other end. Alternative arrangement may involve a rotary conveyor or hearth. In this also, the parts are loaded and unloaded at the same station. The common means of conveying the parts through the heating chamber, apart from the *chain conveyor*, are *rollers* and *push-pull type skids or cars*. The entire cycle of heat treatment, including loading, heating, quenching and delivery of heat treated parts, is a continuous cycle. These furnaces can be oil fired, gas fired or electrically heated. The heating atmosphere is well controlled and multi-stage heating is possible within the same furnace.

Almost all the above furnaces can be so designed as to facilitate controlled heating atmospheres to avoid scaling, disfiguring of surfaces or decarburisation or to provide carbon or nitrogen for surface hardening, according to the requirement.

**4. Bath furnaces.** Several *Liquid bath* furnaces are used in heat treatment processes. They include **Salt Bath Furnaces**, **Lead Bath Furnaces** and **Oil Bath Furnaces**. These furnaces carry a cylindrical outer casing made of steel sheet with refractory lining inside. A ceramic pot or metal container, called *Bath Pot*, is suspended from the top of the lining, leaving enough empty space between the pot body and the refractory lining. This empty space forms the *Heating Chamber* (See Fig. 8.14). The pot carries a salt or salts, lead or oil as the heating medium. The furnace can be *Oil fired*, *Gas fired* or *Electrically heated*. If it is *oil fired*, oil is forced under air pressure into the heating chamber through a nozzle and the air-oil mixture burnt. The flame produced circulates in the heating chamber around the pot and heats the salts, lead or oil contained in the pot. In the same way, in the *Gas fired furnace* the gas is forced into the gas chamber under pressure and burnt. The burning flame circulates around the pot and heats it and the material contained in it. In case of the *Electrically heated* furnace, it may either carry *electric resistance heating elements* fitted to the body and projecting into the heating chamber or two electrodes suspended into the pot. In the former case,

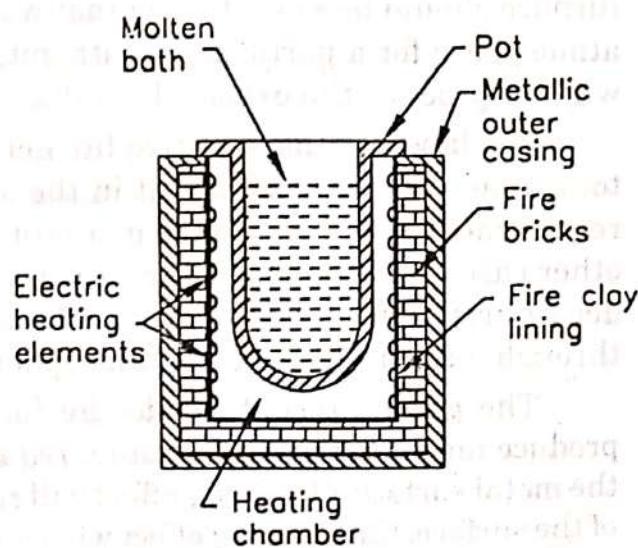


Fig. 8.14. Main Features of a Bath Furnace.

heating is *indirect* while in the later case it is *direct*. Obviously, there is no separate heating chamber in the second case and the pot just fits inside the refractory lining, or else the lining itself is made to form the container (pot). This directly heating type electric bath furnace is also known as *Electrolytically Heated* bath furnace.

The process involves filling the bath pot with salts or lead or oil and heating the same through a suitable heating source to the required temperature, depending upon the type of heat treatment being done. Once the molten bath is prepared and it attains the required temperature the parts can be quenched in the bath, soaked and cooled in the required manner to obtain the desired results. Normally the *oil baths* are used for heat treatment operations below 260°C, *lead baths* upto 327°C and *salt baths* from 160°C to 1330°C. The oil used is mineral oil, the lead used is the normal pig lead and the salts used are generally nitrates, chlorides, cyanides, carbonates, caustic soda, etc. Externally heated *bath furnaces* are normally used upto a maximum temperature of 700°C while the directly heating type electric bath furnaces are used for the heating range between 700°C and 1330°C. More details about different types of baths are given in article 8.22 earlier.

#### 8.41 ATMOSPHERE CONTROL IN THE FURNACE

Prevalence of a properly controlled atmosphere inside a heat treatment furnace is of great importance in order to meet the varying requirements of different heat treatment processes. Somewhere we need a chemically active atmosphere to effect some changes in the chemical composition of the surface metal whereas in many other cases a protective atmosphere is required so that undesirable changes do not take place. It is, therefore, essential that the atmosphere inside the furnace should be so controlled that we can get only the desired type of atmosphere for a particular treatment, otherwise the given treatment will not produce the expected results.

To elaborate the objective further, in **Gas Carburising** we need to increase the carbon content in the surface metal, in **Nitriding** the requirement is to infuse nitrogen into the surface metal and in many other cases we are required to prevent oxidation or scale formation or decarburisation at the surface. All these objectives can be achieved through a controlled heating atmosphere inside the furnace.

The gases present inside the furnace may chemically react to produce an *oxidising*, *carburising*, *reducing* or *decarburising* effect on the metal surface. *Oxidising* effect will result in scaling and discolouring of the surface. *Carburising* effect will result in addition of carbon content to the surface metal. *Reducing* effect will help in deoxidising and

preserving the metal surface of a clean metal. *Decarburising* will lead to reduction in carbon content of the surface metal. By controlling the various parameters, viz., supply, composition, distribution and concentration of the gases, it is possible to produce either a *chemically active atmosphere* or a *protective atmosphere*.

The *Active atmosphere* is needed when some chemical change is to be effected in the metal, either on the surface or throughout it, such as in carburising, nitriding, carbonitriding, etc. A *Protective atmosphere* is required when it is necessary to prevent oxidation, decarburisation, etc., of the metal surface in order to maintain a clean surface, free of scale and rust, discolouring and disfiguring and not to allow any chemical change in the surface metal. Such requirements are quite common in *bright annealing* and *normalising* of many ferrous and non-ferrous metals and alloys.

The above atmosphere controls are over and above the normal controls on heating temperatures, cooling temperatures and time. The supply, distribution and concentration of CO, CO<sub>2</sub> and methane can be quite effectively controlled by *Infrared Controllers*. The technique used for these controls is known as *Gas Chromatography*, but it does not, however, give the desired results if an automatic and continuous control is desired.

#### 8.42 HIGH TEMPERATURE MEASUREMENT OR PYROMETRY

It is quite evident from the above discussions in this chapter that an important activity in the heat treatment processes is the correct temperature measurement of the heat treatment furnaces, without which proper results cannot be obtained. Also, a simple *mercury thermometer* cannot be used for this purpose because mercury boils at 370°C while the temperatures involved in majority of heat treatment processes are of much higher order. As such, more improved temperature measuring devices, called **Pyrometers**, are used for this purpose and the process of measuring temperatures with these devices is known as **Pyrometry**. The most popular varieties of these pyrometers are described below :

**1. Thermo-couple Pyrometers.** They are also known as **Thermo-Electric Pyrometers**. They work on the principle that when two wires of dissimilar metals are joined together to form an electric circuit and their one junction is kept at higher temperature, in comparison to the other, an electron pressure is developed which causes an electric current to flow in the circuit. The circuit is shown in Fig. 8.15. The two wires are twisted together to form *Thermocouple*. One end of these wires is inserted in the hot metal and is known as *hot junction*.

*junction.* The other end is kept at a very low temperature by dipping it in ice water or by some other suitable method. A millivoltmeter is suitably incorporated in the circuit, which is calibrated in degrees of temperature, corresponding to the potential difference created, to give a direct reading. The temperature difference between hot and cold junction gives rise to the required P.D., leading to the flow of current. Compensating leads are to be provided between the two junctions as they are kept far apart from each other, but they should be so chosen that no P.D. is set up between them and the hot junction. The commonly used metal combinations for thermocouples are : *Copper/constantan* – upto  $500^{\circ}\text{C}$ , *Iron-constantan* – upto  $900^{\circ}\text{C}$ , *Chromel/alumel* – upto  $1150^{\circ}\text{C}$  and *Platinum/platinum rhodium* – upto  $1537^{\circ}\text{C}$ .

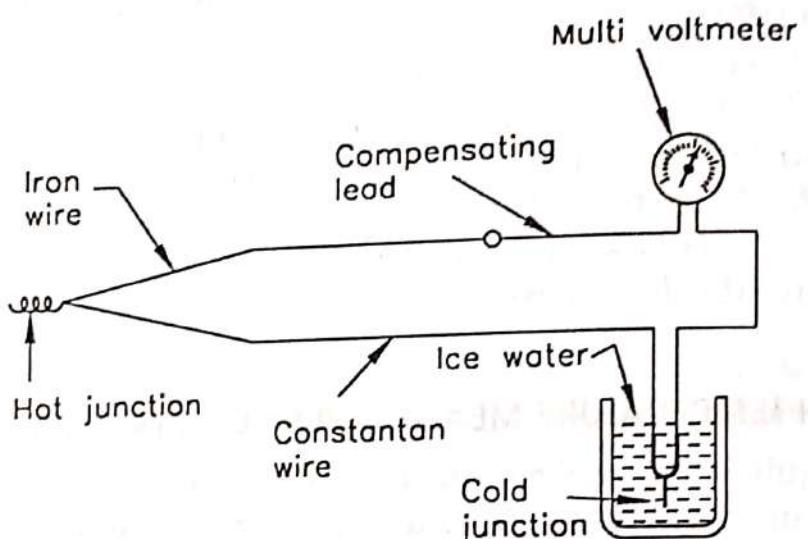


Fig. 8.15. Working principle of a thermocouple pyrometer.

**2. Electrical Resistance Pyrometers.** These *pyrometers* work on the principle of Wheatstone bridge circuit, shown in Fig. 8.16,  $R_1$  and  $R_2$  are known equal resistance.  $R_3$  is variable resistance and  $R_4$  is the unknown resistance. *Potential difference* between *A* and *B* is recorded on the galvanometer *G*: For a balanced bridge, the galvanometer reads zero, showing that :

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

For temperature measurement,  $R_4$  is replaced by a *platinum* resistance wire. The resistance of a particular metal varies with temperature according to a definite law. This wire is encased in a *porcelain sheath* and located in the furnace or the molten metal, as the case may be. With the rise in its temperature the resistance of the wire rises. It actuates the deflection of the galvanometer needle. By adjusting

the variable resistance  $R_3$ , the galvanometer needle is brought to zero reading. This change in  $R_3$  equals the change in resistance of the platinum wire and is used for calibration. For direct measurement of temperature the variable resistance is calibrated for two corresponding values. Two compensating leads of same length are provided and are enclosed in a porcelain sheath. As they are provided on both sides of the bridge, any change in their resistance is neutralised. These Pyrometers can be used to measure temperatures upto  $1400^{\circ}\text{C}$ .

### 3. Disappearing Filament Pyrometer

**Filament Pyrometer.** It is a *portable* instrument incorporating the principle of Wheatstone bridge in its electrical circuit. While using the instrument, it is sighted on to the hot metal and by adjusting the current supply to the lamp, the lamp filament is brought to the same brightness as that of the hot metal. At this stage, the lamp filament disappears against the background of the hot metal. It can be

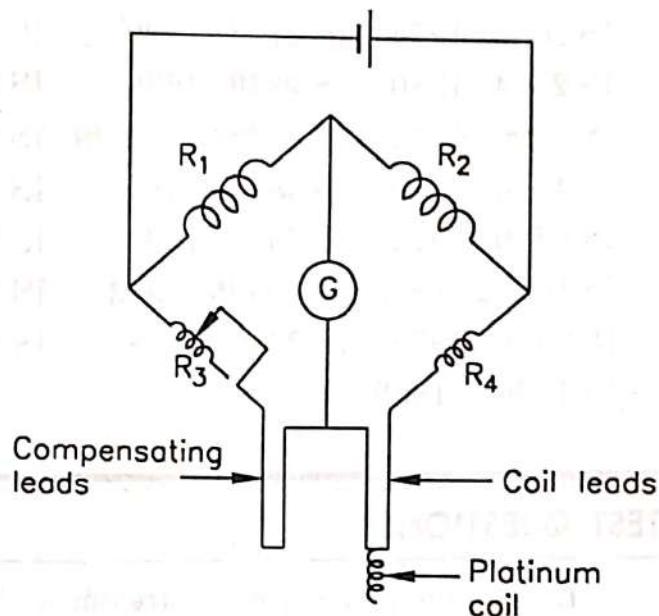


Fig. 8.16. A wheatstone bridge.

sighted through the eye-piece fitted in the instrument. A *milli-ammeter*, incorporated in the electrical circuit, is calibrated with the temperature scale which gives a direct reading in degrees of temperature corresponding to the *Out-of-Balance* current through the bridge.

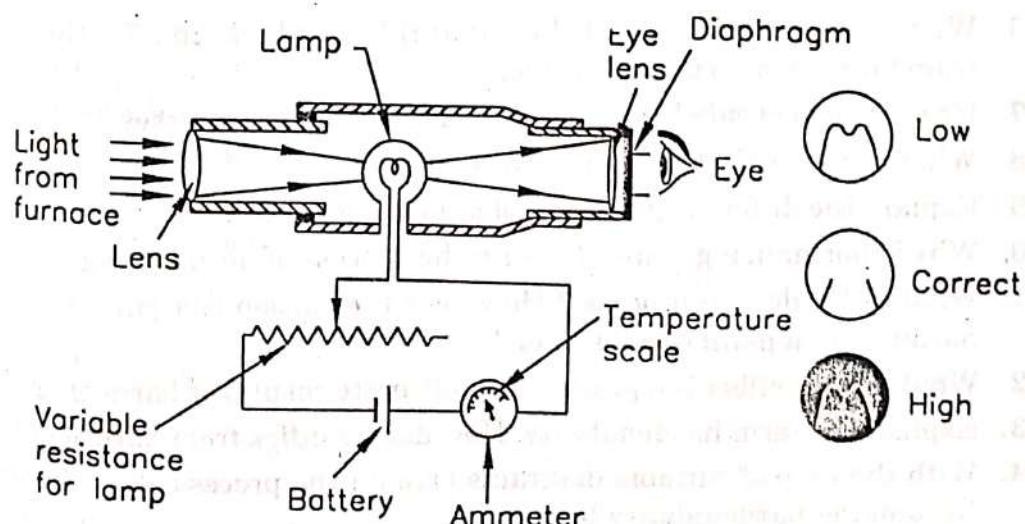


Fig. 8.17. Working principle of an Optical Pyrometer.

Since it is the intensity of light radiated from inside the furnace which forms the means of temperature measurement, these pyrometers are also known as **Optical Pyrometers**. These pyrometers can measure temperatures between 800°C to 4000°C. They are, therefore, used mainly for measuring the temperatures of such metals of which the melting points are very high, such as iron, steel and their alloys. The working principle of an **Optical Pyrometer** is shown in 8.17.

#### 8.43 SUGGESTED BIS CODES FOR FURTHER REFERENCE

IS 2053 : 1974	IS 2707 : 1989	IS 3930 : 1979	IS 6048 : 1970
IS 2664 : 1980	IS 2848 : 1986	IS 5032 : 1969	IS 6049 : 1971
IS 2806 : 1992	IS 3288 (5) : 1986	IS 5489 : 1975	IS 6050 : 1971
IS 4898 : 1989	IS 3848 : 1981	IS 5517 : 1978	IS 6416 : 1988
IS 6720 : 1972	IS 7358 : 1984	IS 9415 : 1980	IS 4432 : 1988
IS 10122 : 1982	IS 10625 : 1983	IS 10639 : 1983	IS 10801 : 1984
IS 8860 : 1978	IS 9029 : 1978	IS 12051 : 1987	IS 12145 : 1987
IS 12366 : 1988			

#### TEST QUESTIONS

1. Explain the need of heat treatment. What are the basic components of a heat treatment process ?
2. What is the purpose of heat treating a metal or alloy ?
3. How is the structure of a plain carbon steel effected with variation in its carbon content ?
4. With the help of heating and cooling curves explain the structural changes occurring in plain carbon steel.
5. What are TTT diagrams ? Why are these diagrams constructed ?
6. With the help of a suitable example explain the isothermal transformation occurring in steel.
7. How do you classify the different heat treatment processes ?
8. What are the objectives of annealing ?
9. Explain the different processes of annealing.
10. Why is normalising done ? Explain the process of normalising.
11. What is hardening process ? How does the carbon content effect the hardness of a plain carbon steel ?
12. What factors effect the process and ultimate results of hardening ?
13. Explain the term hardenability. How does it differ from hardness ?
14. With the help of suitable diagrams explain the process of conducting the Jominy hardenability test.

15. Briefly explain the following processes :
  - (a) Martempering
  - (b) Austempering
  - (c) Ausforming.
16. What is tempering ? Why is it done ?
17. Which different types of tempering do you know ? Describe them in brief.
18. What are tempering baths ? How many types of baths are used in tempering ? Explain, when and where are they used ?
19. What is case hardening and why is it done ?
20. Describe the different methods of carburising.
21. What is nitriding and how is it done ?
22. Write short notes on :
  - (a) Cyaniding
  - (b) Carbonitriding.
23. What is surface hardening ? How does it differ from case hardening ? What are the different methods of surface hardening ?
24. What is induction hardening ? Explain this process.
25. Describe the following processes of surface hardening :
  - (a) Flame hardening
  - (b) Laser beam hardening
  - (c) Electron beam hardening.
26. With the help of a suitable example describe the process and purpose of heat treatment of non-ferrous metals.
27. What is sub-zero treatment of steel and why is it done ?
28. Describe the various heat treatments given to cutting tools, clearly indicating the needs for these treatments.
29. What defects can occur in a heat treated component ? What are the possible causes of their occurrence and the possible remedies for them ?
30. What are the main requirements of the heat treatment furnaces ? What points should be considered while selecting a particular type of furnace for a heat treatment ?
31. How are heat treatment furnaces classified ?
32. Describe in brief the working and applications of the following types of heat treatment furnaces :
  - (a) Batch type furnaces
  - (b) Bath furnaces.
33. Why is atmosphere control necessary in a heat treatment furnace and how is it done ?
34. What is pyrometry ? Describe the principle of working, construction and use of the different types of pyrometers commonly used in high-temperature measurement.