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Department of Aerospace Engineering

Heat Treatment of Materials

HEAT TREATMENT OUTLINE	
♦ Introduction	♦ Process of Heat Treatment
♦ Objectives of Heat Treatment	♦ Heat Treatment Processes

5.1 Introduction

Heat treatment plays a very important role in various fabrication and manufacturing operations. Heat treatment may be defined as an operation involving the heating of a solid metal or an alloy to a specific temperature, followed by cooling at certain rates in order to obtain certain physical properties which are associated with changes in nature, form, size and distribution of micro constituents. The metals or alloys are heated in its solid state with the objective of changing the material characteristics in a desired manner.

5.2 Objectives of Heat Treatment

The purpose of heat treatment is to achieve the following objectives:

1. To relieve internal stress set up during cold working, casting, welding and hot working operations.
2. To improve machinability.
3. To improve mechanical properties, such as tensile strength, ductility, shock resistance, hardness, etc.
4. To refine grain size and crystal structure of the material.
5. To soften metal for further treatment, such as wire-drawing and cold rolling.
6. To modify various electrical and magnetic properties.
7. To produce hard surface and tough interior portion, and also increase wear resistance, corrosion and abrasion.

5.3 Process of Heat Treatment

Heat treatment is carried out in three stages:

1. Heating of a metal or alloy to a specific temperature;
2. Holding it at that temperature for a specific time; and
3. Cooling it in a suitable medium for a desired rate of cooling.

The theory of heat treatment is based on the principle, that when a metal or alloy has been heated above a certain temperature, it undergoes a structural adjustment or stabilisation when cooled to room temperature. In this operation, the cooling rate plays an important role in the structural modification of the metal or alloy. Since iron and steel play a much greater role than other metals in industrial applications, the heat treatment of ferrous metals achieve greater importance.

Steel is an alloy of iron and carbon, and the improvement in the strength of steel has a direct relation to the amount of carbon present in steel. As the carbon content increases, the steel becomes stronger. However, this may result in the loss of ductility. Therefore, heat treatment processes can be used to produce a material which possesses better hardness and strength along with other useful combinations of properties, such as ductility machinability, etc.

5.4 Heat Treatment Processes

In all the heat treatment processes, steel is slowly heated to a predetermined temperature and then cooled at different cooling rates. The structure of the resultant steel will solely depend upon the heating temperature and the rate of cooling. Figure 5.1 shows the iron-carbon diagram for steel and the various temperature ranges for different heat treatment processes. The following are the major heat treatment processes for ferrous alloys:

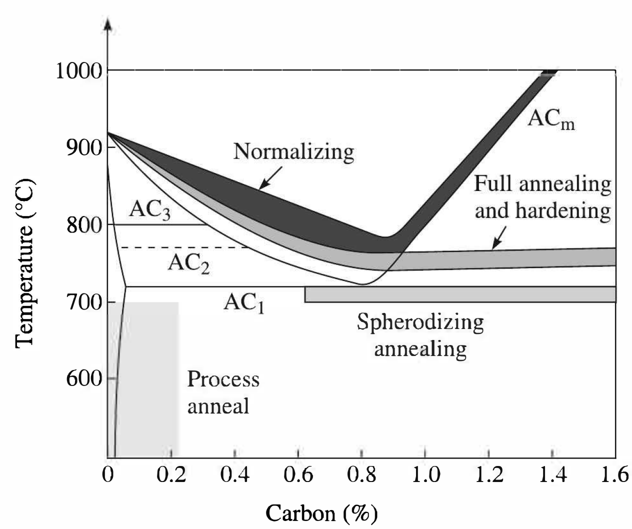

Figure 5.1 Heating temperature range for different heat treatment process.

5.4.1 Annealing

Annealing is done to soften the material. This process involves heating the metal slowly above critical temperature, then holding at that temperature for about 50–75 minutes and finally cooling it in the furnace at about 30°C to 15°C/hr (Figure 5.2).

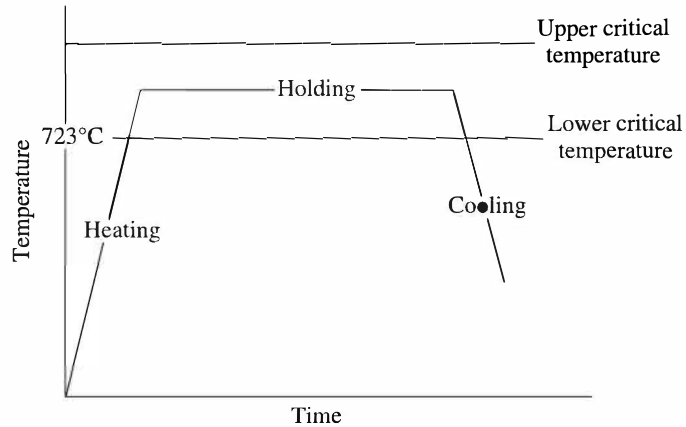

Figure 5.2 Annealing process.

Critical temperature of a metal is the temperature, above which the crystal structure of the metal begins to change. Table 5.1 gives the annealing temperature for plain carbon steels.

Table 5.1 Annealing temperatures

Plain carbon steel	*Carbon content*	*Annealing temperature (°)*
Dead mild steel	<0.15%	875–925
Mild steel	0.15–0.3%	840–970
Medium carbon steel	0.3–0.7%	780–840
High carbon steel	0.7–1.5%	760–780

Objectives of annealing

Annealing process is done to meet the following objectives:

1. Softens the metal to improve ductility, malleability and machinability.
2. Refines and removes structural in homogeneity.
3. Changes physical, as well as mechanical properties.
4. Relieves internal stress and produces the desired structure.
5. Prepares the steel for further treatment process.

Types of annealing process

Following are the types of annealing:

Full annealing: This removes all structural imperfection by complete re-crystallisation. The purpose of annealing is to soften the metal, relieve internal stress and refine the grain structure. It consists of the following processes (Figure 5.3):

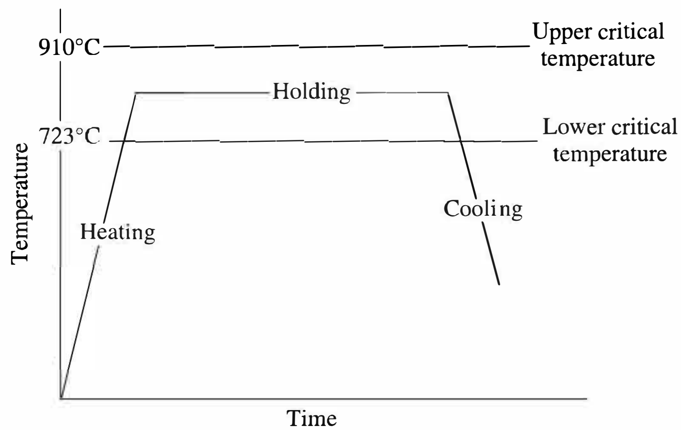

Figure 5.3 Full annealing process.

1. Heating the steel to about 50°C–70°C above the upper critical temperature for hypo-eutectoid steel, and by the same temperature above the lower critical temperature for hyper-eutectoid steel.
2. Holding it at this temperature for a sufficient time. The length of time depends upon the thickness of the workplace.
3. Slowly cooling the work piece in the furnace.

Process annealing: *Process annealing* is carried out by heating the cold worked steel below the lower critical temperature, holding it at this temperature for a desired period, followed by air cooling (Figure 5.4). This process is also called *subcritical annealing*.

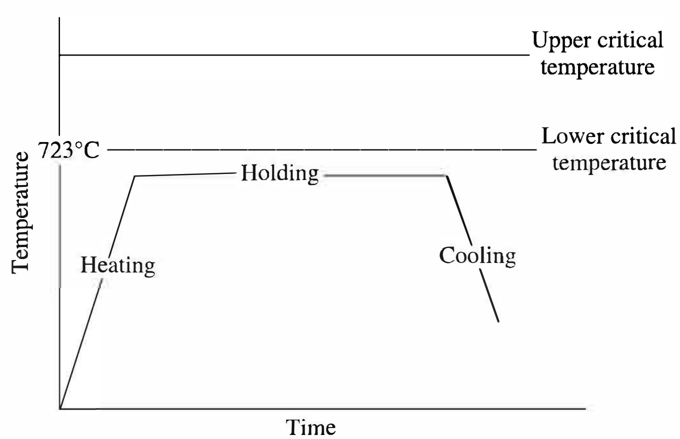

Figure 5.4 Process annealing.

It is carried out to remove the effects of cold working and to soften the steel to make it suitable for further cold treatment. The exact heating temperature depends upon the extent of cold working, grain size and composition of steel. This process is very useful for low carbon steels, such as dead mild steel and mild steel.

Spherodise annealing: In this process cementite is converted into a granular or spheroid form. This process is normally applied to high carbon steel by heating at about 680°C below the lower critical temperature, holding it at this temperature for a sufficient period of time, and then cooling it slowly (about 6°C/hour) to about 500°C–600°C (Figure 5.5). This process takes more time and is costly.

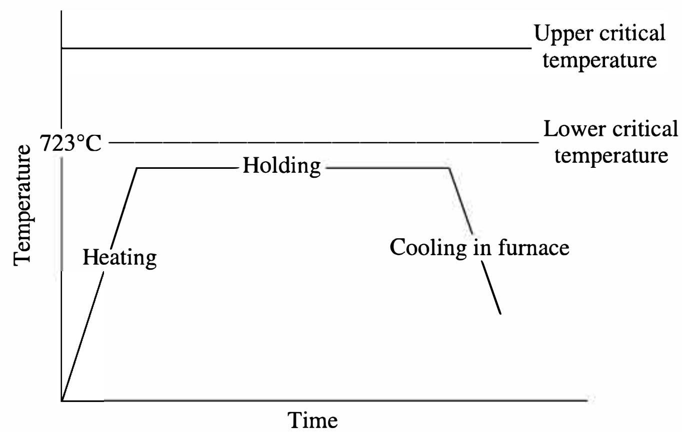

Figure5.5 Spheroidise annealing process.

Diffusion annealing: This annealing process is carried out in heavy casting to make austenic grains homogeneous. This process involves heating of workplace above upper critical temperature between 1000°C–1100°C (Figure 5.6).

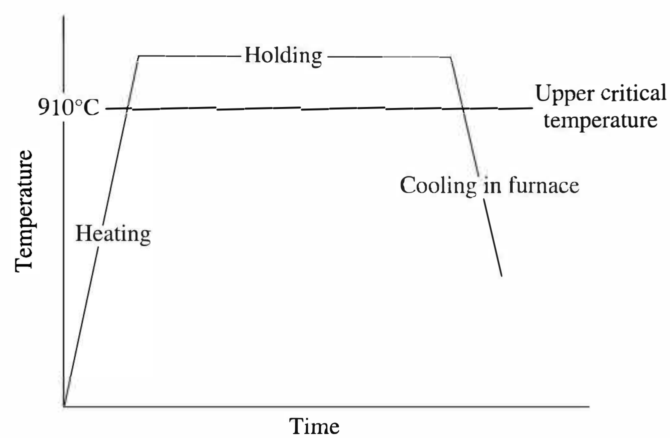

Figure 5.6 Diffusion annealing.

Metal is kept at this temperature for a very short period and then cooled in the furnace to 800°C–850°C. It is then further cooled in the air to room temperature.

5.4.2 Normalising

Normalising is frequently applied as a final heat treatment process to produce soft materials which are subjected to relatively high stress. This process consists of heating steel to 40°C–50°C above its upper critical temperature, holding at that temperature for a short duration (~15 minutes) and subsequently cooling in still air at room temperature (Figure 5.7). This process is also known as *Air Quenching*.

Objectives of normalising

Normalising is done for following purposes:

1. To refine grain structure of steel.
2. To remove internal stresses which are developed during previous operations, like welding, casting, hot working, cold working, etc.
3. To improve mechanical, as well as electrical properties.

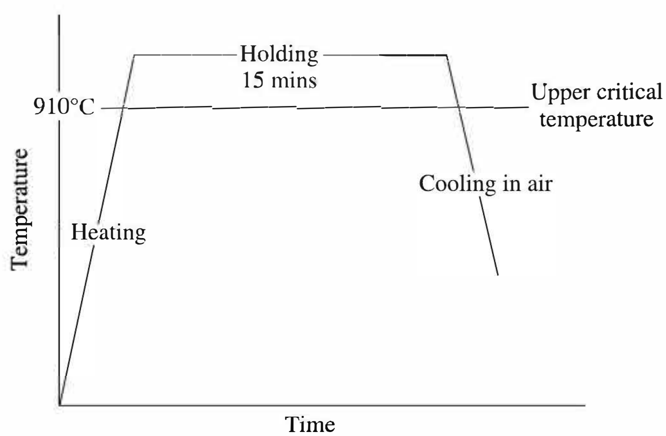

Figure 5.7 Normalising process.

Comparison between normalising and annealing

1. Mechanical properties are better than those produced by annealing.
2. Normalising requires a heating range which is slightly above 40°C of annealing temperatures.
3. Heat treatment process is of short duration due to increased rate of cooling of metal in air.

5.4.3 Hardening

Hardening is a process in which steel is heated to a temperature above the critical point temperature and then quenched in water, oil or a molten salt bath. It is applied to all tools and machine parts made from carbon steels and alloys steel. The process is carried out in the following three stages (Figure 5.8):

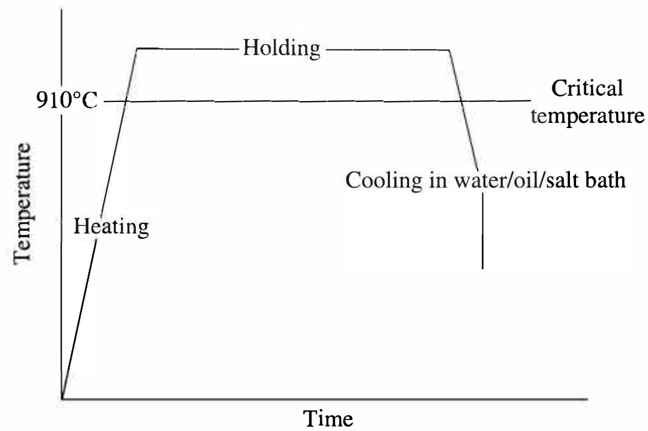

Figure 5.8 Hardening process.

1. Heating the work piece above the critical temperature;
2. Holding the work piece for a specific time at that temperature; and
3. Quenching in a suitable medium.

Objectives of hardening

The objectives of hardening are:

1. To improve the strength of steel.
2. To improve hardness, high wear resistance, abrasion resistance, etc.

Factors affecting hardness

1. Carbon content
2. Work piece size
3. Quenching rate and cooling rate
4. Quenching medium

5.4.4 Tempering

Quenching of high carbon steel causes formation of martensitic structures which are hard and strong, but they are brittle.

It is defined as a process in which hardened steel is heated to a temperature below the lower critical temperature to transform the hard and brittle martensite into ferrite and cementite. In this process ductility and toughness is achieved by sacrificing hardness and strength. On the basis of heating conditions it can be classified as follows:

1. Low temperature tempering (150°C–250°C)
2. Medium temperature tempering (350°C–425°C)
3. High temperature tempering (500°C–650°C)

Objectives of tempering

Tempering process serves the following objectives:

1. It reduces the brittleness of hardened steel.
2. It improves toughness and ductility.
3. It is used to relieve internal stress.

Classification of tempering process

1. Austempering
2. Martempering

Austempering: The process is also called *isothermal quenching*. It is an isothermal transformation process that converts austenite to hard structure. In this process, steel is heated to about 700°C and held at this temperature for some time. It is then quenched in molten salt, brought down to about 500°C, and held at this temperature for a prolonged period. The steel is finally quenched in water at room temperature (Figure 5.9). The steel thus produced is free from cracks, softer than martensite, and possesses good impact resistance.

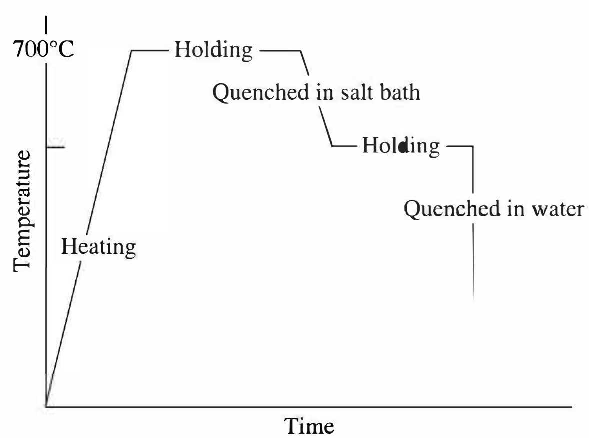

Figure 5.9 Austempering.

Objectives of Austempering: Steel becomes more tough and ductile.

1. Distortion and cracks developed during quenching are the minimum.
2. Martempering

Martempering: It is also known as *Stepped Quenching*. In this process, steel is heated to about 600°C and held for some time, and then quenched in a molten salt bath down to about 300°C. After holding it at this temperature until the steel reaches the temperature of the medium, the work piece is allowed to cool gradually in air or oil (Figure 5.10).

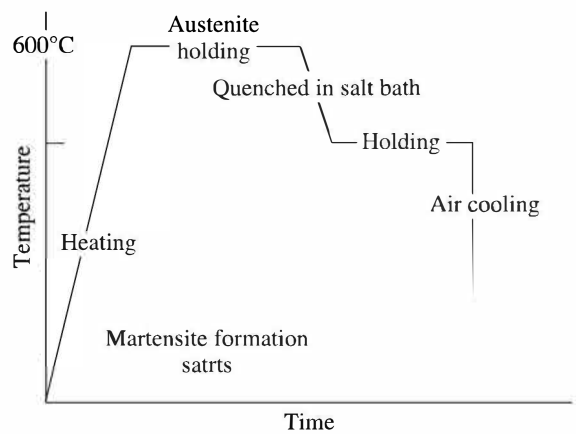

Figure 5.10 Martempering process.

Objectives of Martempering

1. To minimise distortion and cracking.
2. To relieve internal stress.

5.4.5 Surface Hardening

Many engineering applications require that the steel being used should have a hardened surface to resist wear and tear, while having a soft and tough core so that it can be able to absorb any shocks, etc. This is achieved by hardening of the outer surface of the steel.

Types of surface hardening

1. Induction hardening
2. Flame hardening

Induction hardening: In this process, we get a hard and wear resistant surface with a soft core in steel. The process involves induction heating whose schematic arrangement is shown in Figure 5.11. The work piece to be hardened is placed in an inductor coil that comprises several turns of copper tube; high frequency current of about 4000 cycles per second is passed through a copper block. This sets up an alternating magnetic field and induces an alternating current. This current produces a heating effect on the job's surface. The temperature produced is about 750°C–800°C. The heated surface is simultaneously quenched by a spray of water (Figure 3.11).

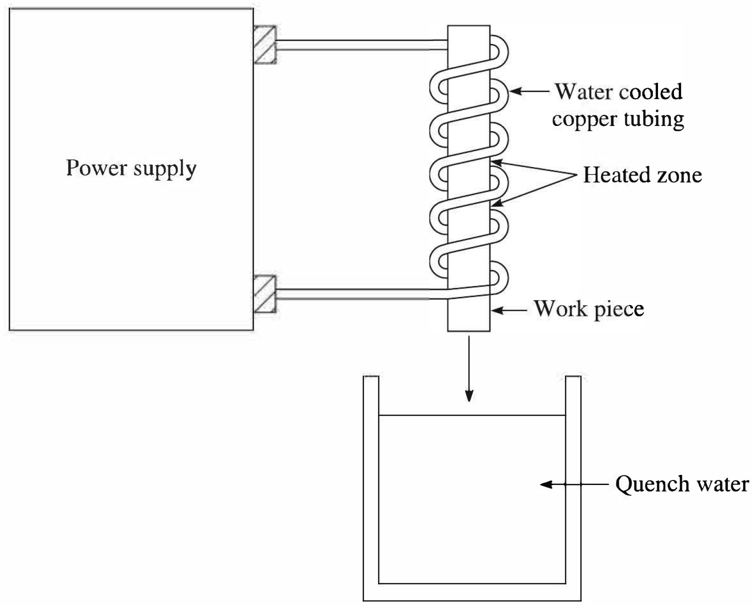

Figure 5.11 Induction hardening process.

Flame hardening: This hardening is used to harden the particular portion of job. The portion to be hardened is heated with an oxyacetylene flame above its critical temperature followed by quenching (spraying of water) (Figure 5.12). In flame hardening, stress is not developed due to localised heating, and chances of cracking and distortion are reduced.

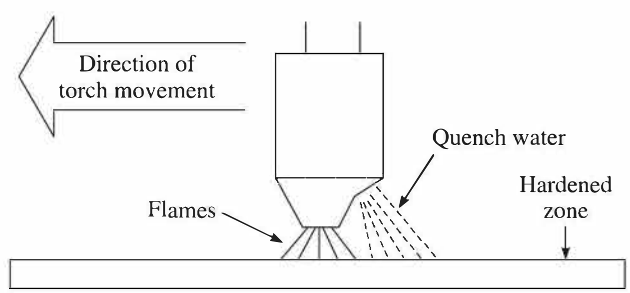

Figure 5.12 Flame hardening.

5.4.6 Case Hardening

This is the method of producing steel that has a tough inner core and hard outer surfaces. Articles such as gears, pins and pistons are hardened by this process.

This process involves heating of steel in contact with a carbon-rich substance above critical temperature for a prolonged duration (duration may vary from hours to days). Mild steel can be converted into high carbon steel with the addition of a desired amount of carbon.

Types of Case Hardening

1. **Pack carburizing:** In this process, the work piece to be carburized is placed in a carburizing box of a proper design made of a special heat resisting alloy, cast iron, or steel sheet along with charcoal, coke or other carbonaceous materials. This box is heated to the desired temperature for a long duration, due to which the carbonaceous material releases carbon monoxide gas. This gas in turn reacts with the work piece metal and releases carbon, which is then absorbed by the surface of steel (Figure 5.13).

   Advantage of pack carburizing

   (**a**) The process is very simple.
   (**b**) It requires less sophisticated equipment than the other two methods.

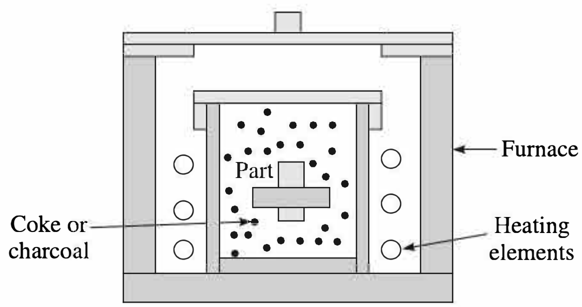

Figure 5.13 Pack or solid carburizing.

2. **Liquid carburizing:** This process is similar to pack carburizing, but in this process liquid is used in place of a carbonaceous material. The parts which are to be carburized are placed in liquid salt baths of molten salt containing sodium carbonate, sodium chloride and silicon carbide for a specific time (Figure 5.14). The temperature varies between 850°C–930°C.

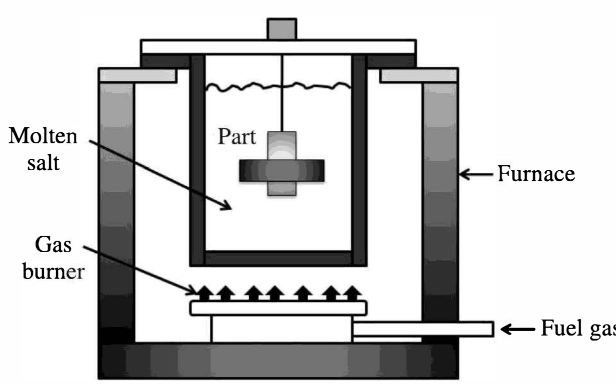

Figure 5.14 Liquid carburizing.

Advantage of liquid carburizing

(a) Large depth of penetration is possible.
(b) The heating rate is uniform.
(c) Easy to carburize in any part of the work piece.
(d) Very low deformation of component.

3. **Gas carburizing:** In this process, the component is heated in a furnace whose surrounding is filled with carbon-rich gas, such as methane, propane, etc., mixed with carbon monoxide or carbon dioxide (Figure 5.15). The operation is performed in a furnace at 900°C–960°C.

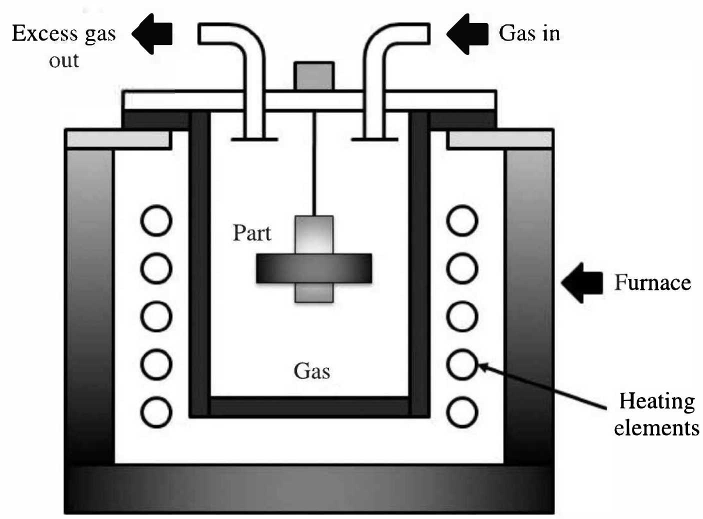

Figure 5.15 Gas carburising.

Advantages of gas carburizing

(a) Very high surface finish is obtained
(b) Used when better accuracy is desirable.
(c) Fast process as compared to pack and liquid carburizing.

5.4.7 Nitriding

This process involves heating of steel to about 650°C in the atmosphere of ammonia (NH_3) or other gases containing Nitrogen, and holding it for a prolonged period.

$$2NH_3 \longrightarrow N_2 + 3H_2$$

The nitrogen from ammonia penetrates into the surface of steel, and forms very hard nitrides on the surface.

Advantages

1. It improves corrosion resistance.
2. It provides very high hardness.
3. Economic for mass production, but costly for limited production.
4. Scaling or cracking doesn't occur because quenching is not required.

Applications

1. It is used in hardening of ball and roller bearing.
2. It is used in hardening of automobile engine parts, gears, clutches, mandrel, drawing dies, etc.

5.4.8 Cyaniding

This is a special case hardening process in which the mild steel absorbs carbon and nitrogen to obtain a hard surface. The component to be case hardened is immersed in a bath of sodium cyanide (NaCN) at a temperature above 400°C. It remains dipped in the bath until soaking takes place to a predetermine depth. The component is then quenched in oil or water to obtain a hard surface.

Short Answer Type Questions

1. What do you understand by heat treatment of steel?
2. Write a brief note on hot working of metals.
3. Explain different types of heat treatment processes.
4. What are the objectives of heat treatment?
5. What are the three basic steps of a heat treatment process?
6. Define the term recrystallisation.
7. What are the objectives of Annealing?
8. Briefly explain the process of Annealing.
9. Briefly discuss the different annealing temperatures.
10. What is Lower Critical and Upper Critical temperature?
11. Why is normalising done?
12. What are the objectives of tempering?
13. Explain the purpose of hardening of steels.
14. What are the factors affecting hardness of metals?
15. What is case hardening?
16. Write a short note on the tempering process.
17. Compare Austempering with Martempering.

18. Discuss Surface Hardening.
19. Explain the full annealing process with a neat sketch.
20. Compare Normalising with Annealing.

Long Answer Type Questions

1. What are the objectives of heat treatment processes? Explain various processes in brief. *(AmsubrA)*
2. What do you understand by heat treatment of carbon steels? Explain any one process in detail. *(AmsubrA)*
3. Explain the Annealing process. Discuss different types of annealing processes.
4. With neat diagrams explain Full Annealing and Process Annealing. *(AmsubrA)*
5. Briefly discuss the following:
   (a) Full Annealing
   (b) Process Annealing
   (c) Spheroidise Annealing
   (d) Diffusion Annealing
6. Describe the process of Normalising with the help of a neat sketch. What are its objectives? Compare Normalising with Annealing.
7. Describe the process of Steel Hardening. Why is steel required to be tempered after it has been hardened? *(AmsubrA)*
8. Compare the following:
   (a) Full Annealing and Process Annealing
   (b) Spheroidise Annealing and Diffusion Annealing
9. What do you mean by Case Hardening? Explain different methods of Case Hardening.
10. Discuss the process of Surface Hardening. Briefly explain Induction Hardening and Flame Hardening.
11. Define the tempering process. Why is tempering done? Briefly explain the Austempering and Martempering processes.
12. With a neat sketch explain the principle of Induction Hardening.
13. Compare Pack Carburizing with Liquid Carburizing processes.
14. Explain the process of Gas Carburizing. What are its advantages and objectives?
15. Define the following in detail:
    (a) Flame hardening
    (b) Cyaniding
    (c) Nitriding