## Heat treatment and its purpose

The properties of steel depend upon its composition and its structure. These properties can be changed to a considerable extent, by changing either its composition or its structure. The structure of steel can be changed by heating it to a particular temperature, and then, allowing it to cool at a definite rate. The process of changing the structure and thus changing the properties of steel, by heating and cooling, is known as 'heat treatment of steel'.

Structure of steel when heated (Fig 1)

If steel is heated, a change in its structure commences from 723°C. The new structure formed is called 'Austenite'. Austenite is non-magnetic. If the hot steel is cooled slowly, the old structure is retained and it will have fine grains which makes it easily machinable.

Fig 1
HEAT TREATMENT RANGES OF STEELS
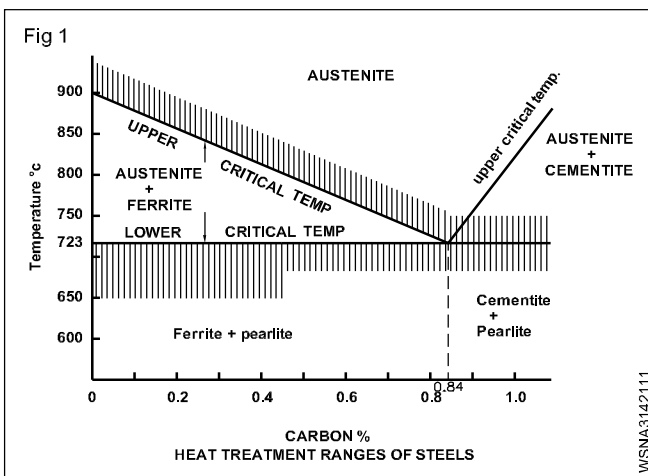
If the hot steel is cooled rapidly the austenite changes into a new structure called 'Martensite'. This structure is very fine grained, very hard and magnetic. It is extremely wear-resistant and can cut other metals.

Critical temperatures (Fig 2)

Fig 2
PERCENTAGE OF CARBON IN THE STEEL
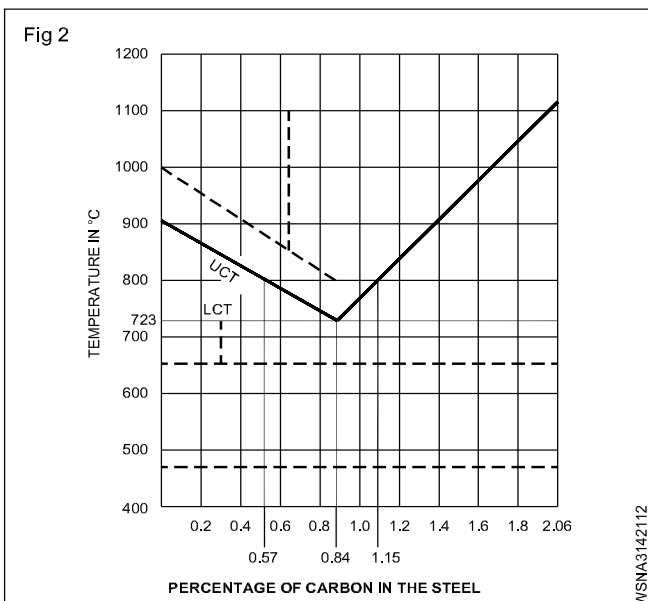
Lower critical temperature

The temperature, at which the change of structure to austenite starts - 723°C, is called the lower critical temperature for all plain carbon steels.

Upper critical temperature

The temperature at which the structure of steel completely changes to AUSTENITE is called the upper critical temperature. This varies depending on the percentage of carbon in the steel. (Fig 2)

Example

0.57% and 1.15% carbon steel: In these cases the lower critical temperature is 723°C and the upper critical temperature is 800°C.

For 0.84% carbon steel, both LCT and UCT are 723°C. This steel is called eutectoid steel.

Three stages of heat treatment

- Heating
- Soaking
- Quenching

When the steel on being heated reaches the required temperature, it is held in the same temperature for a period of time. This allows the heating to take place throughout the section uniformly. This process is called soaking.

Soaking time

This depends upon the cross-section of the steel, its chemical composition, the volume of the charge in the furnace and the arrangement of the charge in the furnace. A good general guide for soaking time in normal conditions is five minutes per 10 mm of thickness for carbon and low alloy steels, and 10 minutes per 10 mm of thickness for high alloy steels.

Heating steel

This depends on the selection of the furnace, the fuel used for heating, the time interval and the regulation in bringing the part up to the required temperature. The heating rate and the heating time also depend on the composition of the steel, its structure, the shape and size of the part to be heat-treated etc.

Preheating

Steel should be preheated at low temperatures up to 600°C as slowly as possible.

Quenching

Depending on the severity of the cooling required, different quenching media are used.

The most widely used quenching media are:
- brine solution
- water
- oil
- air

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Brine solution gives a faster rate of cooling while air cooling has the slowest rate of cooling.

Brine solution (Sodium chloride) gives severe quenching because it has a higher boiling point than pure water, and the salt content removes the scales formed on the metal surfaces due to heating. This provides a better contact with the quenching medium and the metal being heat-treated.

Water is very commonly used for plain carbon steels. While using water as a quenching medium, the work should be agitated. This can increase the rate of cooling.

The quenching oil used should be of a low viscosity. Ordinary lubricating oils should not be used for this purpose. Special quenching oils, which can give rapid and uniform cooling with less fuming and reduced fire risks, are commercially available. Oil is widely used for alloy steels where the cooling rate is slower than plain carbon steels.

Cold air is used for hardening some special alloy steels.

Advantages

The following are the advantages of this type of hardening.

- The hardening devices are brought to the workpiece.
- It is advantageous for large workpieces.
- Short hardening time.
- Great depth of hardening.
- Small distortion.
- Low fuel consumption.

Disadvantages

The following are the disadvantages.

- Not suitable for small workpieces because of the danger of hardening throughout.
- The workpieces must be stress-relieved before hardening.

Heat treatment - Different heat treatment process – Hardening, tempering, annealing, normalising, case hardening

Heat treatment processes and purpose

Because steel undergoes changes in structure on heating and cooling, its properties may be greatly altered by suitable heat treatment.

The following are the various heat treatments and their purposes.

|	
Hardening:	To add cutting ability.
	To increase wear resistance.
Tempering:	To remove extreme brittleness caused by hardening to an extent.
	To induce toughness and shock resistance.
Annealing:	To relieve strain and stress.
	To eliminate strain/hardness.
	To improve machinability.
	To soften the steel.
Normalising:	To refine the grain structure of the steel.

Annealing and normalising

The treatments that produce equilibrium conditions are annealing and normalising.

The treatments that produce non-equilibrium conditions are hardening and tempering (usually done in conjunction with each other).

Annealing

In this process, steel is heated to a suitable temperature depending upon its carbon content (Fig 3), and is held at that temperature for sufficient time, and then slowly cooled to room temperature.

ANNEALING TEMPERATURES FOR PLAIN CARBON STEELS
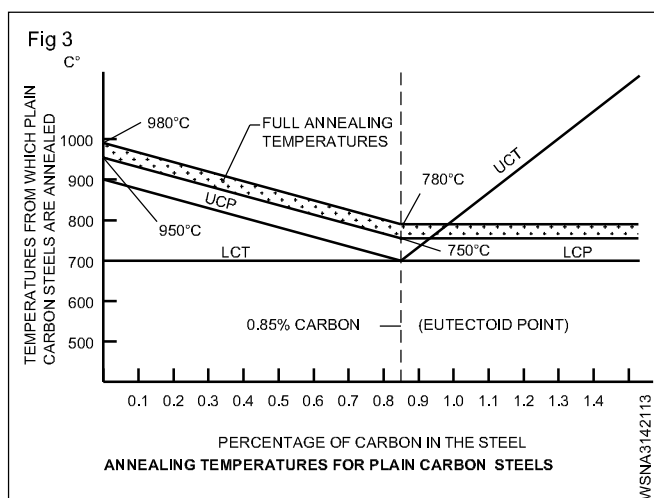
The heating, soaking (holding at that temperature) and slow cooling cause the grains to become large, and in the process, produce softness and ductility.

For annealing, the hypoeutectoid steel is heated to 30°C to 50°C above the upper critical temperature, and it is 50°C above the lower critical temperature for hypereutectoid steel. (Fig 3)

The soaking time at this temperature is 5 mts/10 mm of thickness for carbon steel.

The cooling rate for carbon steel is 100°C to 150°C/hour.

The cooling is done in the furnace itself by switching off the furnace or the steel is covered either in sand or dry lime and dry ash.

Purpose of annealing

Annealing is done:

* to obtain softness
* to improve machinability
* to increase ductility
* to relieve internal stresses
* to reduce or eliminate structural in homogeneity
* to refine grain size and to prepare the steel for subsequent heat treatment processes.

Annealing temperature

Carbon content %	Temperature °C
<0.12	875 to 925
0.12 to 0.25	840 to 970
0.25 to 0.50	815 to 840
0.50 to 0.90	780 to 810
0.90 to 1.3	760 to 780

Normalising

Due to continuous hammering or uneven cooling, strains and stresses are formed in the internal structure of steel. These should be removed from forgings or castings; as otherwise, they may fail at any time while in use.

Normalising is done to produce a fine grain for uniformity of the structure and for improved mechanical properties.

The normalising process

In this process, the steel is heated to a suitable temperature depending upon its carbon content, (Fig 4) and held at that temperature, and then, cooled freely in the air.

Normalising is usually done, before machining and before hardening, to put the steel in the best condition for these operations.

The steel is heated to a temperature (30 to 40°C above the upper critical temperature) at which only austenite is present even in the case of high carbon steel. This is because this process is the first step towards producing the final properties, and it is necessary to start with austenite to ensure uniformity.

Fig 4

NORMALISING TEMPERATURES FOR PLAIN CARBON STEELS

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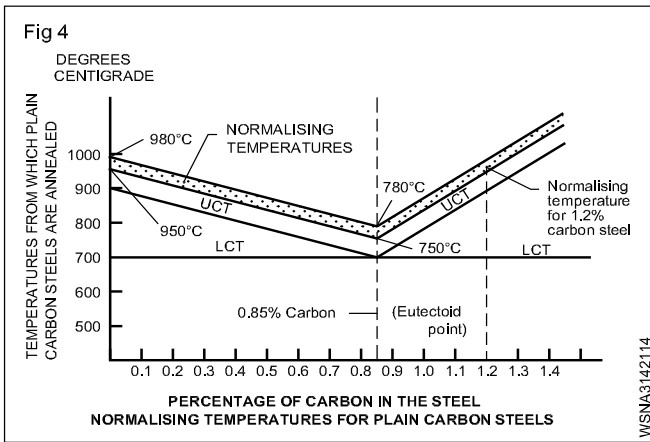
The heated piece for normalising should not be kept at any wet place, in wet air or kept in forced air as they will induce some hardness.

Hardening & tempering

If a piece of steel is heated to a sufficiently high temperature, all the carbon will be dissolved in the solid iron to form a solid solution, called austenite of the steel. When it is slowly cooled, the change in the arrangement of the iron atoms will cause a solid solution called ferrite to be produced. The solid solution can only contain up to 0.006% carbon, and so the excess carbon will be forced to leave the solid solution, and produce cementite. This will, with ferrite, form a laminated structure called pearlite.

The principle of hardening

If steel is cooled rapidly (quenched) the excess carbon will not have sufficient time to leave the solid solution with the result that it will be trapped in the iron, and so cause an internal distortion. This internal distortion is the cause for the increase in the hardness of steel with a corresponding reduction in its strength and ductility. This is the basis of the hardening process.

The mechanical properties produced as a result of this treatment will depend upon:

• the carbon content of the steel

• the temperature to which it is heated

• the duration of heating

• the temperature of the steel at the start of quenching

• the cooling rate produced by quenching.

The effect of carbon content upon the hardness produced by the hardening process is illustrated in Fig 5.

Fig 5

CARBON CONTENT AND HARDNESS (HV) OF STEEL

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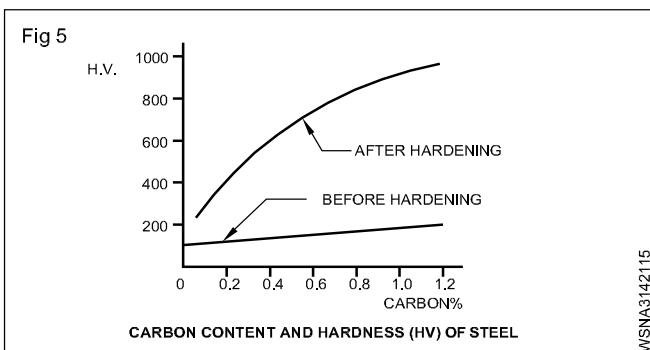
The increase in carbon content will result in an increase in the hardness produced by the treatment.

Steel with less than about 0.15% carbon will not respond to this treatment.

Process of hardening

In order to produce the desired effect, sufficient carbon must be put into the solid solution to cause internal distortion when it is trapped in the iron by quenching.

When the carbon content is less than 0.83%, the steel is heated to only just above its upper critical point (heating).

When its carbon content is more than 0.83% the steel is heated only to just above its lower critical point (heating).

Fig 6 illustrates the temperatures to which steels are heated before quenching, and the quenching temperature of steels with different carbon content.

Fig 6

HARDENING OF PLAIN CARBON STEELS

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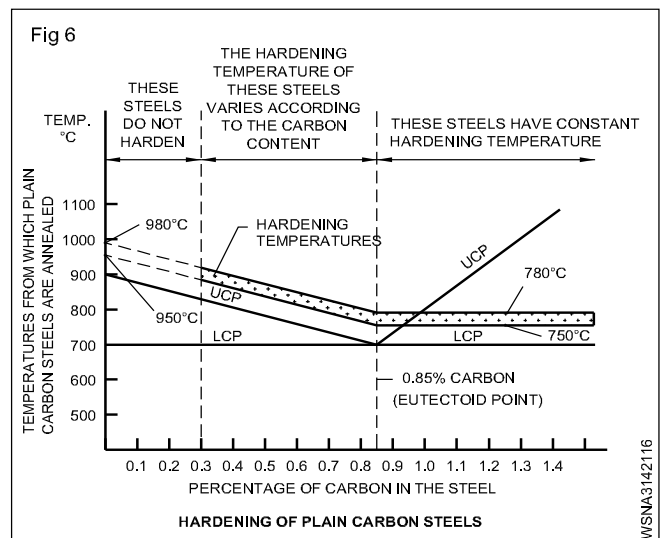
Soaking time

After heating, the steel is held at that temperature for some time. Normally 5 mts are allowed as soaking time for 10 mm thickness of steel.

Cooling

Then the steel is cooled in a suitable quenching medium at a certain minimum rate called the critical cooling rate. The critical cooling rate depends upon the composition of the steel. This cooling transforms all the austenite into a fine, needle-like structure called martensite, (the appearance of which is shown in Fig 7).

The structure of steel treated this way is very hard and strong, but very brittle.

The quenching medium

The quenching medium controls the rate of cooling.

For a rapid quenching a solution of salt or caustic soda in water is used.
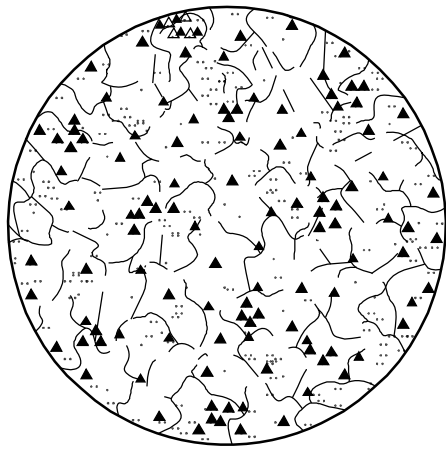
For very slow quenching a blast of air is sufficient.

Oil gives an intermediate quenching.

Water and oil are the most common quenching media used.

Air quenching is suitable only for certain special alloy steels.

Fig 7

THE MICROSTRUCTURE OF MARTENSITE

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Tempering

After hardening, steel is usually reheated to a suitable temperature below the lower critical point (heating) to improve its toughness and ductility but it is done at the expense of hardness and strength. It is done in order to make the steel more suitable for service requirements.

Purpose of tempering the steel

Steel, in its hardened condition, is generally too brittle and too severely strained. In this condition, steel cannot be used, and hence it has to be tempered.

The aims of tempering are:

• to relieve the steel from the internal stresses and strains

• to regulate the hardness and toughness

• to reduce the brittleness

• to restore some ductility.

Process of tempering

The tempering temperature depends upon the properties required, but it is between 180°C and 650°C. (Fig 8) The duration of heating depends upon the thickness of the material. Tools are usually tempered at a low temperature. The temperature itself is judged by the colour of the oxide film produced on the surface during heating. (Table 1)

Fig 8

TEMP °C

TEMPERING RANGE

CARBON IN%

TEMPERATURE FOR TEMPERING
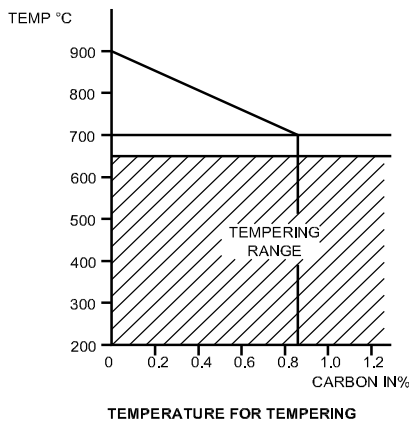
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This method is not, however, suitable for accurate temperature assessment.

In a manufacturing plant, when heat treating is done on a production basis, modern methods are used. Tempering is done in controlled-atmosphere furnaces with the temperatures controlled by modern instruments. Under such conditions, it is possible to obtain accurate and uniform results in any number of pieces.
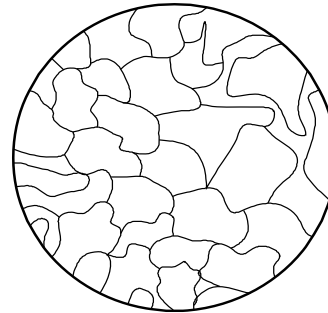
Table 1

Tempering temperature

Temper colour	Temperature in °C
Pale straw	230
Dark straw	240
Brown	250
Brownish purple	260
Purple	270
Dark purple	280
Blue	300

Fig 9 illustrates the appearance of the microstructure of hardened, and then tempered steel.

Fig 9

THE MICROSTRUCTURE OF HARDENED AND TEMPERED STEEL

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Generally, tempering in the lower temperature range for an increased time provides greater control in securing the desirable mechanical properties. Such heat treatment may not be feasible under all conditions. For precision work, where results justify the method, and for certain combination of mechanical properties, tempering for long periods of time in a lower temperature range provides a reliable method of getting the desired results.
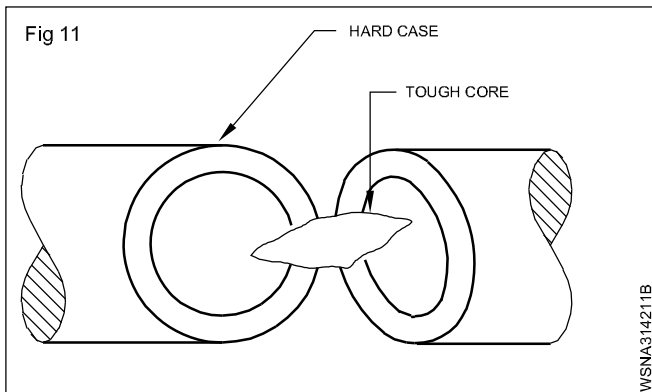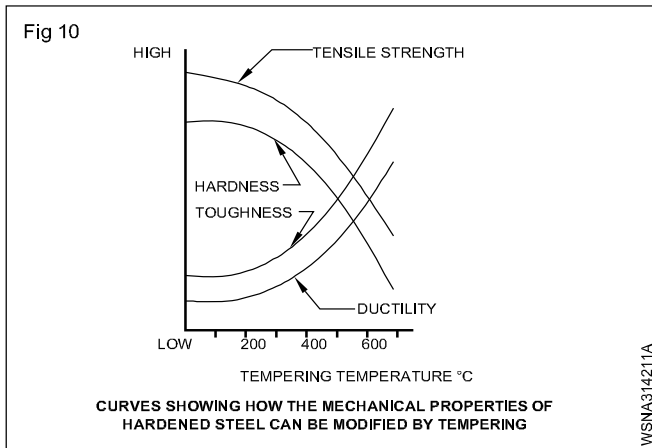
Fig 10 illustrates how the mechanical properties of hardened steel can be modified by tempering.

Surface Hardening of Steels

Most of the components must have a hard, wear-resisting surface supported by a tough, shock-resisting core for better service condition and longer life. This combination of different properties can be obtained in a single piece of steel by surface hardening. (Fig 11)

Types of surface hardening

• Case hardening

• Nitriding

• Flame hardening

• Induction hardening

Fig 10

CURVES SHOWING HOW THE MECHANICAL PROPERTIES OF HARDENED STEEL CAN BE MODIFIED BY TEMPERING

Fig 11

Fig 12

WORKPIECE HEATED IN CONTACT WITH THE CARBURISING COMPOUND

(a) CARBON-RICH COMPOUND — WORKPIECE OF LOW CARBON STEEL

(b) THE OUTER SURFACE ABSORBS CARBON AND BECOMES HIGH CARBON STEEL HIGH CARBON STEEL AS LOW CARBON STEEL

AFTER HEATING, THE WORKPIECE HAS HIGH CARBON CASE, WHICH CAN BE HARDENED

(c) HARDENED CASE SOFT AND TOUGH CORE

AFTER QUENCHING THE CASE BECOMES HARD AND THE CORE WHICH IS OF LOW CARBON STEEL REMAINS SOFT AND TOUGH

Case hardening

Parts to be hardened by this process are made from a steel with a carbon content of 0.15% so that they will not respond to direct hardening.

The steel is subjected to treatment in which the carbon content of the surface layer is increased to about 0.9%.

When the carburised steel is heated and quenched, only the surface layer will respond, and the core will remain soft and tough as required. (Fig 12)

The surface which must remain soft can be insulated against carburising by coating it with suitable paste or by plating it with copper.

Case hardening takes place in two stages.

*   Carburising in which the carbon content of the surface is increased.

*   Heat treatment in which the core is refined and the surface hardened.
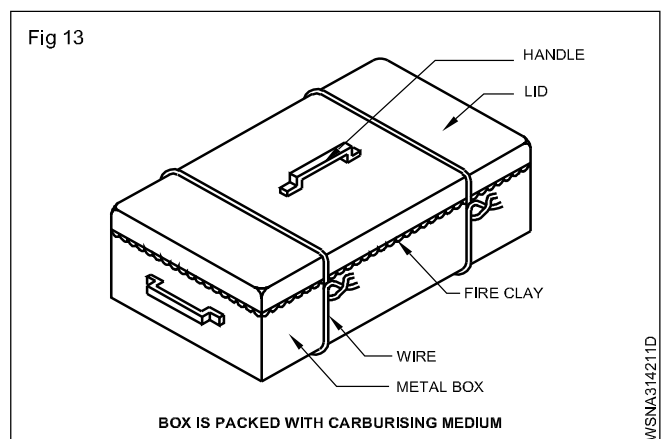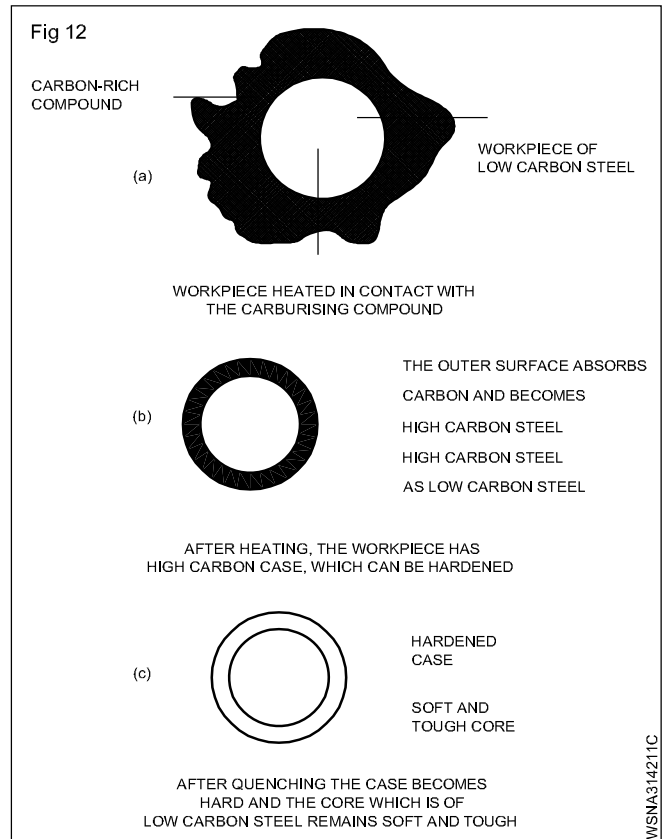
Carburising

In this operation, the steel is heated to a suitable temperature in a carbonaceous atmosphere, and kept at that temperature until the carbon has penetrated to the depth required.

The carbon can be supplied as a solid, liquid or gas.

In all cases, the carbonaceous gases coming from these materials penetrate (diffuse) into the surface of the workpiece at a temperature between 880° and 930°C.

Pack carburising (Fig 13)

The parts are packed into a suitable metal box in which they are surrounded by the carburising medium.

Fig 13

BOX IS PACKED WITH CARBURISING MEDIUM

The lid is fitted to the box and sealed with fireclay and tied with a piece of wire so that no carbon gas can escape and no air can enter the box to cause decarburisation.

The carburising medium can be wood, bone, leather or charcoal, but an energiser, such as barium carbonate, is added to speed up the process.

Liquid carburising

Carburising can be done in a heated salt-bath. (Sodium carbonate, sodium cyanide and barium chloride are typical carburising salts.) For a constant time and temperature of carburisation, the depth of the case depends on the cyanide content.

Salt-bath carburising is very rapid, and is not always suitable because it produces an abrupt change in the carbon content from the surface to the core. This produces a tendency for the case to flake.

This is suitable for a thin case, about 0.25 mm deep. Its advantage is that heating is rapid and distortion is minimised.
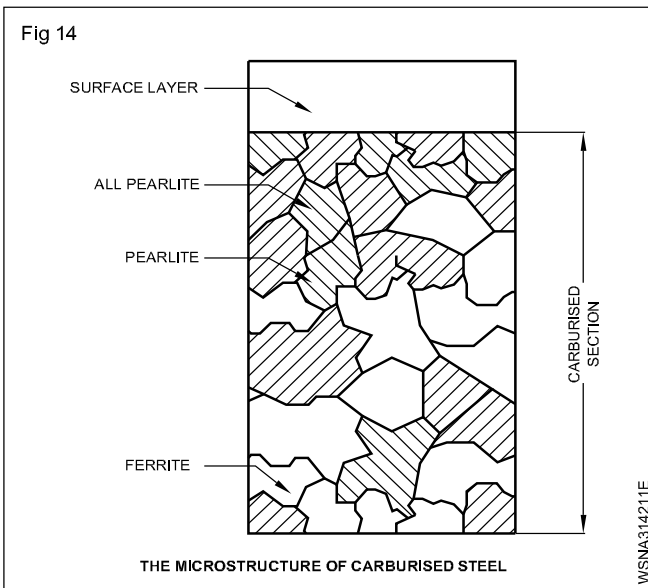
Gas carburising

The work is placed in a gas-tight container which can be heated in a suitable furnace, or the furnace itself may be the container.

The carburising gas is admitted to the container, and the exit gas in vented.

The gas such as methane or propane may be fed directly into the container in which the work is placed.

In a continuous gas carburising furnace, the carburising, quenching and tempering processes are carried out in sequence in the same closed furnace as they progress on a conveyer from one operation to the next.

Fig 14 illustrates the appearance of the structure across its section produced by carburising.

THE MICROSTRUCTURE OF CARBURISED STEEL

Heat treatment

After the carburising has been done, the case will contain about 0.9% carbon, and the core will still contain about 0.15% carbon. There will be a gradual transition of carbon content between the case and the core.

Owing to the prolonged heating, the core will be coarse, and in order to produce a reasonable toughness, it must be refined.

To refine the core, the carburised steel is reheated to about 870°C and held at that temperature long enough to produce a uniformity of structure, and is then cooled rapidly to prevent grain growth during cooling.

The temperature of this heating is much higher than that suitable for the case, and, therefore, an extremely brittle martensite will be produced.

The case and the outer layers of the core must now be refined.

The refining is done by reheating the steel to about 760°C, to suit the case, and quenching it.

Tempering

Finally the case is tempered at about 300°C to relieve the quenching stresses.

If the part is not required to resist shock, it is unnecessary to carry out the core refining operation; in these conditions, a coarse martensite at the surface may not cause trouble, and so this part may be quenched directly after carburising.

Fig 15 illustrates the appearance of the structure across its section produced by case hardening.

THE MICROSTRUCTURE OF CASE-HARDENED STEEL
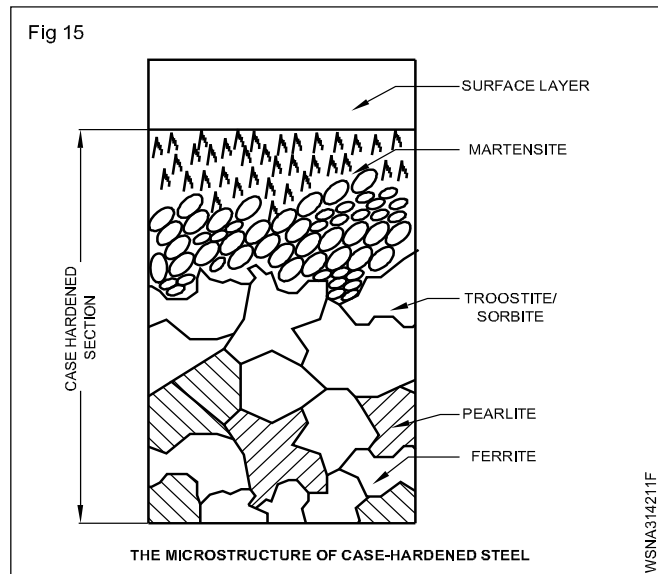
Nitriding

In the nitriding process, the surface is enriched not with carbon, but with nitrogen. There are two systems in common use, gas nitriding and salt bath nitriding.

Gas nitriding

The gas nitriding process consists of heating the parts at 500°C in a constant circulation of ammonia gas for up to 100 hours.

During the gas nitriding process the parts are in an externally heated gas-tight box, fitted with inlet and outlet bores for the ammonia gas which supplies the nitrogen. At the completion of the 'soaking' the ammonia is still circulated until the temperature of the steel has fallen to about 150°C, when the box is opened, and the cooling completed in air. Nitriding causes a film to be produced on the surface but this can be removed by light buffing operation.

Nitriding in salt-bath

Special nitriding baths are used for salt-bath nitriding. This process is suitable for all alloyed and unalloyed types of steel, annealed or not annealed, and also for cast iron.

Process

The completely stress-relieved workpieces are preheated (about 400°C) before being put in the salt-bath (about 520°C-570°C). A layer 0.01 to 0.02 mm thick is formed on the surface which consists of a carbon and nitrogen compound. The duration of nitriding (half an hour to three hours) depends on the cross-section of the workpiece. (It is much shorter than for gas nitriding.) After being taken out of the bath, the workpieces are quenched and washed in water, and dried.

Advantages

The parts can be finish-machined before nitriding because no quenching is done after nitriding, and, therefore, they will not suffer from quenching distortion.

In this process the parts are not heated above the critical temperature, and, hence warping or distortion does not occur.

The hardness and wear-resistance are exceptional. There is a slight improvement in corrosion-resistance as well.

Since the alloy steels used are inherently strong when properly heat treated, remarkable combinations of strength and wear-resistance are obtained.

Flame hardening

In this type of hardening, the heat is applied to the surface of the workpiece by specially constructed burners. The heat is applied to the surface very rapidly, and the work is quenched immediately by spraying it with water. (Figs16 and 17) The hardening temperature is generally about 50° C higher than that for full hardening.


Fig 16

Fig 17
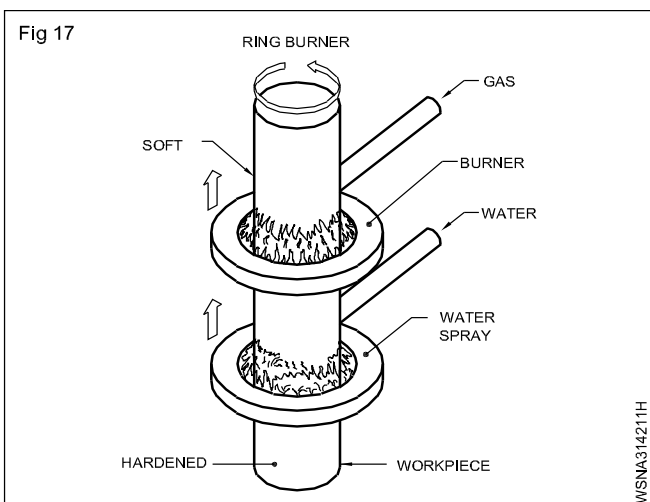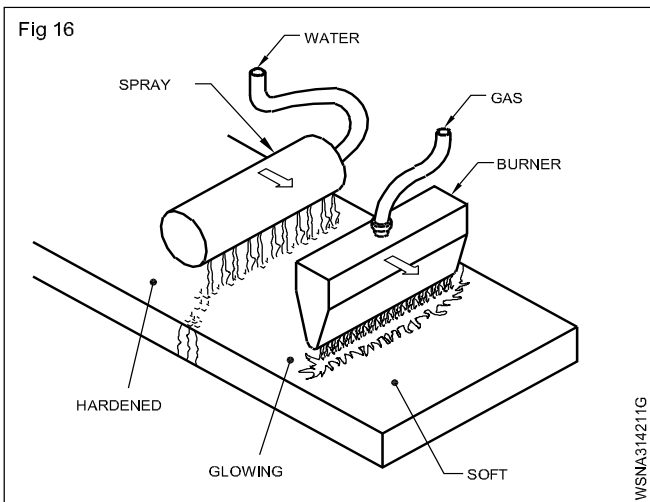
The workpiece is maintained at the hardening temperature for a very short period only, so that the heat is not conducted to more than the necessary depth into the workpiece.

Steels used for surface hardening by the flame hardening method will have a carbon content of 0.35% to 0.7%.

Induction hardening

This is a production method of surface hardening in which the part to be surface-hardened is placed within an induction coil through which a high frequency current is passed. (Fig 18) The depth of penetration by the heating becomes less, as the frequency increases.

Fig 18
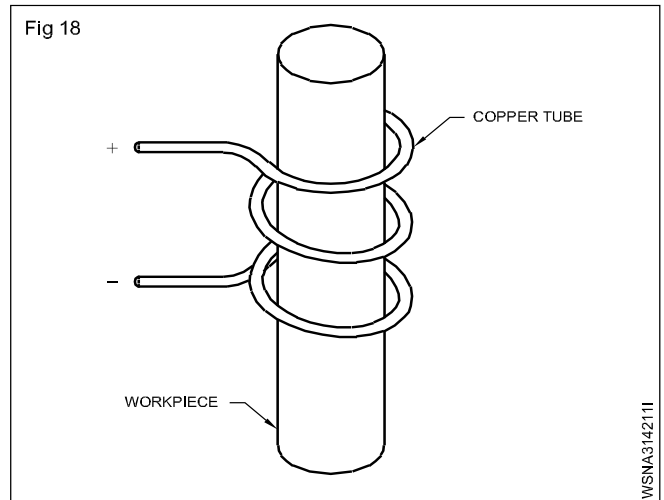
The depth of hardening for high frequency current is 0.7 to 1.0mm. The depth of hardening for medium frequency current is 1.5 to 2.0mm. Special steels and unalloyed steels with a carbon content of 0.35 to 0.7% are hardened.

After induction hardening of workpieces, stress-relieving is necessary.

Advantages

The following are the advantages of this type of hardening.

*   The depth of hardening, distribution in width and the temperature are easily controllable.

*   The time required and the distortion due to hardening are very small.

*   The surface remains free from scale.

*   This type of hardening can easily be incorporated in mass production.

Heat treatment of high speed steel

High speed steels get their name from the fact that they may be operated as cutting tools at much higher speeds than is possible with plain carbon tool steels. Since the maximum hardness of high speed steel is obtained on tempering at high temperatures, it can be operated as a cutting tool in the same temperature range without loss of hardness. That is, the rise in temperature due to friction will not reduce the temper of the tool point as it cuts into the steel. Tool steels are often annealed for softening before machining or forming, and also for obtaining grain refinement.

Annealing

Soak at 900°C for about four hours. Then cool slowly at not more than 20°C per hour to 600°C. It may then be cooled to room temperature in still air.

Hardening

Preheat to 850°C slowly to prevent cracking. Then heat rapidly in a salt-bath furnace approximately to 1250°C depending upon the alloy used. This rapid heating in a salt-bath furnace reduces grain growth and prevents oxidation of steel during heating. Quench in an air blast or oil depending on the mass of the component. When a salt bath furnace is not available, this can be minimised in a double chamber muffle furnace (Fig 19) by using the excess fuel to give a carburising atmosphere. However, this reduces the combustion efficiency, and there may be some difficulty in reaching the hardening temperature. With high temperature salts available, modern practice favours the use of the salt-bath furnace. (Figs 20 and 21)
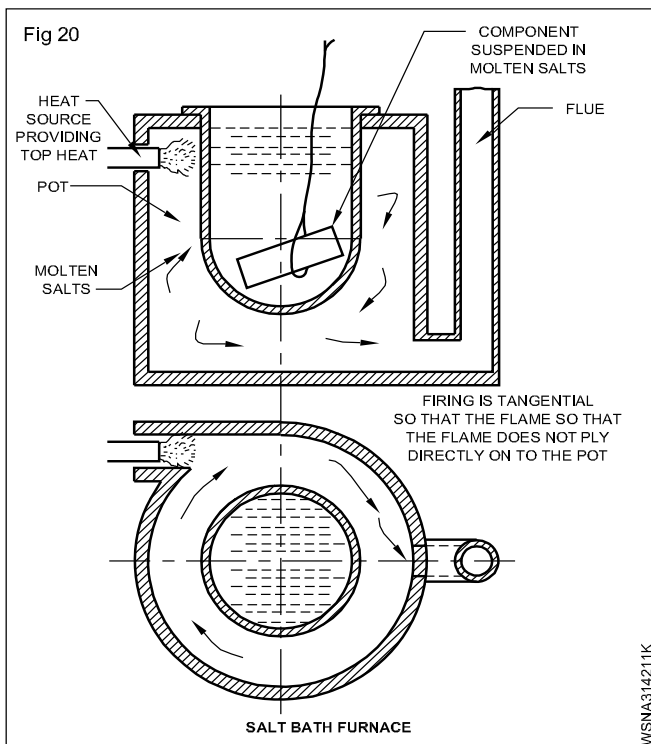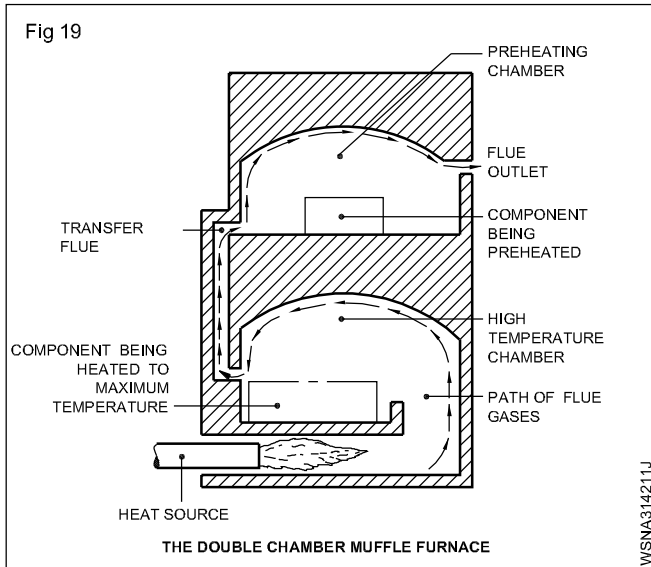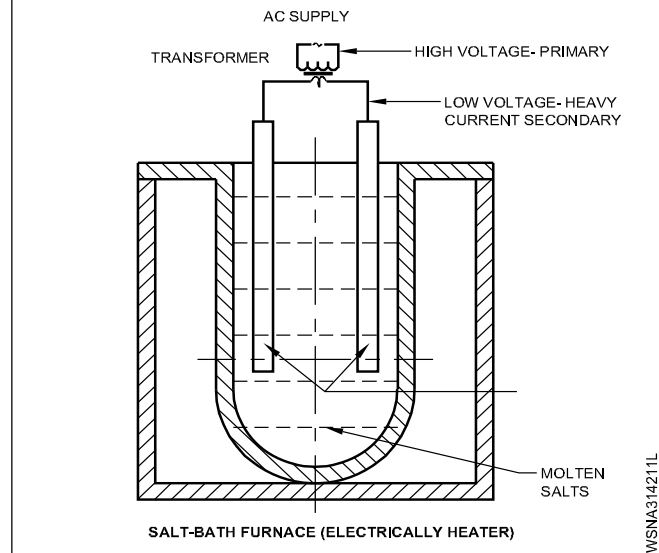

THE DOUBLE CHAMBER MUFFLE FURNACE

Fig 19

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SALT BATH FURNACE

Fig 20

WSNA314211K

SALT-BATH FURNACE (ELECTRICALLY HEATER)

Fig 21

WSNA314211L

Secondary hardening (Tempering)

This is sometimes called tempering. However, this term is not strictly true. Not only does secondary hardening increase the toughness of the steel, it also increases the hardness whereas tempering increases the toughness at the expense of hardness. The effect of secondary hardening helps these steels to work effectively at higher temperatures than plain carbon tool steels.

Heat treatment of non ferrous metals

Annealing

Like steel, non-ferrous metals can be softened by heating and allowing to cool. However, since they cannot be hardened by rapid cooling, the rate of cooling is comparatively unimportant. In fact, copper components are often quenched in water. This not only saves time but also cleans the black oxide film from the surface of the components because of the rapid contraction.

Hardening

Only a very few non-ferrous alloys can be hardened by heating and quenching like steel, and most non-ferrous metals are hardened by cold working. As anyone, who has worked as a coppersmith will know, the metal starts to work-harden as it is beaten to shape and it must be annealed from time to time to prevent it from cracking.

Assignment A

1 a What is two purpose of Hardening.

  b What is the purpose of normalising.

  c Write four annealing purposes.

  d What is the purpose of tempering.

  e What is the purpose of annealing.

  f Which cooling process is suitable for annealing.

  g Which cooling process is suitable for normalising.

  h What type of structure in the normalising process.

  i What reason the steel is reheated (after hardening) to a suitable temperature (180°C to 650°C).

  j Why steel is reheated.

2 i What is the heating method for nitriding?

    a Temperature controlled furnace

    b Electric induction coil heat

    c By use of Oxy-Acetylene torche

    d By Ammonia gas

  ii What is the heating method for flame hardening?

    a Temperature controlled furnace

    b Electric induction coil heat

    c By use of Oxy-Acetylene torche

    d By Ammonia gas1 Hardening Process

  iii What is the heating method for induction hardening?

    a Temperature controlled furnace

    b Electric induction coil heat

    c By use of Oxy-Acetylene torche

    d By Ammonia gas

  iv What is the heating method for normal hardening?

    a Temperature controlled furnace

    b Electric induction coil heat

    c By use of Oxy-Acetylene torche

    d By Ammonia gas

  v Which quenching medium for hardening of H.S Steel?

    a Water spray

    b Still air

    c Bath of water

    d Air blast or oil

  vi Which quenching medium for hardening of carbon steel?

    a Water spray

    b Still air

    c Bath of water

    d Air blast or oil

  vii Which quenching medium for normalising low carbon or medium carbon steel?

    a Water spray

    b Still air

    c Bath of water

    d Air blast or oil

  viii Which quenching medium for flame hardening?

    a Water spray

    b Still air

    c Bath of water

    d Air blast or oil

B MCQ

1 The process of changing the structure of a metal by heating and cooling is

  A Heat treatment   B Machining

  C Hot rolling   D Melting

2 The three stages of heat treatment is Heating, Soaking, and

  A Smelting   B Quenching

  C Hardening   D Tempering

3 The quenching oil viscosity should be.

  A normal   B medium

  C low   D high

4 Which relieves stress and strain.

  A Hardening   B Normalising

  C Tempering   D Annealing

5 Which process produce equilibrium conditions.

  A Annealing and Normalising

  B Hardening and Tempering

  C Annealing and Hardening

  D Normalising and Tempering

6 Which quenching medium is commonly used.

  A Water & Lead   B Water & Oil

  C Water & Brine solution D Lead & Brine solution

7 Which process is used to reduce the brittleness.

  A Annealing   B Normalising

  C Tempering   D Case hardening

8 What is the purpose of Nitriding process.

  A partial   B whole

  C case   D surface

9 Which temperature change structure to austenite.

  A lower   B upper

  C higher   D larger

10 Which temperature change structure of steel to austenite

  A lower   B upper

  C smaller   D lesser

Key Answers

A

1 a i   To add cutting ability

     ii To increase water resistance

  b To refine grain structure of the steel

  c i   To relieve strain and stress

     ii To eliminate strain/hardness

     iii To improve machinability

     iv To soften the steel

  d i   To remove extreme brittleness caused by hardening

     ii To reduce toughness and shock resistance

  e Ductility

  f Room temperature

  g Air

  h Grain

  i Ductility

  j Tempering

2 i d   ii c   iii b   iv a   v d   vi c   vii b   viii a

B MCQ

1 A   2 B   3 C   4 D   5 A

6 B   7 C   8 D   9 A   10 B