ME 3392 -ENGINEERING MATERIALS AND METALLURGY

UNIT- II

HEAT TREATMENT

Definition – Full annealing, stress relief, recrystallisation and spheroidising – normalising, hardening and Tempering of steel. Isothermal transformation diagrams – cooling curves superimposed on I.T. diagram CCR – Hardenability, Jominy end quench test - Austempering, martempering – case hardening, carburizing, Nitriding, cyaniding, carbonitriding – Flame and Induction hardening – Vacuum and Plasma hardening..

TWO MARKS:

1. What are the purposes of the processing heat treatment ?

- To relieve internal stresses
- To improve machinability
- To refine grain size
- To soften the metal
- To improve hardness of the metal surface
- To improve mechanical properties(like tensile strength,hardness,ductility,shock resistance,etc.,)

2. Difference between normalizing and full annealing.

S.NO.	Normalizing	full annealing
1.	Normalizing is more Economical then full Annealing(since no Furnace is required to Control the cooling rate)	Full annealing is costly
2.	Normalizing is less time consuming	Full annealing is more time consuming
3.	Normalizing temperature is higher than full annealing	Annealing temperature is lower than normalizing
4.	It provides a fine grain structure	It provides coarse grain structure

3.What does the term hardening refer ?what are the factors affecting the hardness?

- Hardening refers to the heat treatment of steel which increases its hardness by quenching
- The hardness obtained from the hardening process depends upon the following factors 1.carbon content,2.quenching medium,3.specimen size, and 4.other factors

4. Distinguish the work hardening with the age hardening process.

- Work hardening also known as strain hardening, is the process of hardening a metal, while working on it (under cold-working conditions).
- Age hardening, also known as precipitation hardening, is the process of hardening a metal when allowed to remain or age after heat treatment.

5. What is the significance of TTT diagram in the heat treatment of steel?

- The TTT diagram is most useful in giving an overall picture of the transformation behavior of austenite. This enable the metallurgist to interpret the response of a steel to any specified heat treatment.
- Using a TTT diagram, one can plan practical heat treatment operations to get desirable microconstituents, to control limited hardening or softening, and the time of soaking.

6. Define the term critical cooling rate. What are the factors affecting it?

- The slowest rate of cooling of austenite that will result in 100% martensite transformation is known as the critical cooling rate.
- Factors affecting the critical cooling rate are: 1. chemical composition of steel, 2. Hardening temperature, and 3. Metallurgical nature(i.e., purity) of steel.

7. What is significance of the critical cooling rate?

The critical cooling rate is most important in hardening. In order to obtain a 100% martensitic structure on hardening, the cooling must be must be higher than the criticalcooling rate.

8. What is the difference between hardness and harden ability?

- The term hardness the property of a material by virtue of which it is able to resist abrasion, indentation and scratching. It is a mechanical property related to strength and is a strong function of the carbon content of a metal.
- On the other hand, hardenability is the susceptibility of a material to get hardened. It is affected by the alloyed elements in the material and grain size.

9. What is martempering and austempering?

- ✓ Martempering, also known as marquenching, is a interrupted cooling procedure used for steels to minimize the stresses, distortion and cracking of steels that may develop during rapid quenching.
- ✓ The austempering is an isothermal heat treatment process, usually used to reduce quenching distortion and to make tough and strong steels.

10. What are the differences between surface hardening by diffusion methods and thermal methods?

- ❖ In diffusion surface-hardening method, the hardness of the surface is improved by diffusing interstitial elements like carbon, nitrogen, or both into the surface of steel components.
- ❖ In thermal method of surface hardening, only the surface of the steel components are heated to temperature above the upper critical temperature and is suddenly quenched to get martensite formation on the surface which gives higher hardness at the surface.

11. Differentiate between pack carburizing and gas carburizing.

- ✓ In pack carburizing, the components to be treated are packed into steel boxes, along with thecarburizing mixture, so that a space of roughly 50 mm exists between them.
- ✓ Gas carburizing overcomes the drawbacks difficulties of pack carburizing by replacing the solid carburizing mixture with a carbon-providing gas.

12. A low carbon steel in the normalized condition is stronger than the same steel in the annealed condition. Why?(May/June 2006)

Unlike full annealing, the rate of cooling in normalising is more rapid. Also normalizing process provides a homogeneous structure consisting of ferrite and pearlite for low carbon steel. That's why normalizing produces harder and stronger steels than full annealing.

13. Case carburizing heat treatment is not generally carried out for medium carbon steels. Why?(May/June 2006)

We know that carburizing process a diffusion treatment process. For diffusion to take place, the host metal must have a low concentration of the diffusion species and there must be a significantconcentration of the diffusing species at the surface in the host metal. Since the medium carbon steels lack the above-said criteria, they are not generally carburizing.

14. What is "critical cooling rate" in hardening of steels?(Nov/Dec2006)

The slowest rate of cooling of austenite that will result in 100% martensite transformation is known as the critical cooling rate.

15. What is the microstructure of an austempered steel? What is the advantage of austempering heat treatment?(Nov/Dec 2006)

- The resulting microstructure of the austempering process is bainite.
- The advantages of austempering are:
- Improvedductility.
- Increased impact strength and toughness.
- Decreased distortion of the quenched material.
- Less danger of quenching cracks.

16.What is the principle of surface hardening in induction hardening process?

The induction hardening is a process of selective hardening using resistance to induced eddy currents as the source of heat.

17. What is the need for providing a tempering treatment after quench hardening of steels?

The quench hardening develops maximum hardness, excellent wear resistance and high strength in the steel. But it lacks good ductility and toughness; also the internalresidual stresses are developed. The tempering is used to relieve the residual stresses and improve ductility and toughness of the hardened steel. That's why quench hardening is always followed by tempering treatment.

18. Define critical cooling rate.(Nov/Dec 2007)

The slowest rate of cooling of austenite that will result in 100% martensite transformation is known as the critical cooling rate.

19.Can mild steel be induction hardened?Substantiate.(Nov/Dec 2007)

No, mild steel cannot be induction hardened as it contains less than 0.25% c. during induction hardening, mild steel may conduct current instead of forming a magnetic field.

20.What are the principal advantage of austempering over conventional quench and tempermethod? (April /May 2008)

- ✓ Improved ductility.
- ✓ Increased impact strength and toughness.
- ✓ Decreased distortion of the quenched metal.
- ✓ Less danger of quenching cracks.

21. Mention few applications of induction hardening.(April /May 2008)

The induction hardening is employed for hardening the surfaces of gears, tool drivers, wrist pins, crank shaft bearing journals, cylinder liners, rail ends, machine tool ways and pump shafts.

22. Name and explain any one subcritical case hardening treatment.(May/June 2009)

- ✓ Nitriding is a subcritical case hardening treatment.
- ✓ Nitriding is a process of introducing nitrogen atoms, to obtain hard surface of steel components.

23. With heat treatment cycle, explain the conventional normalizing treatment for hyper eutectoid steel? (May/June 2009)

- ✓ In normalizing, the steel is heated to 50°C to 60°C above its upper critical temperature (i.e., above the A_{cm} line)for hyper eutectoid steels. It is held at this temperature for a short time and then allowed to cool in still air.
- ✓ The normalizing process provides a homogenous structure consisting of pearlite and cementite for hypereutectoid steels.

25. When is annealing process is preferred? (May/June 2013)

- ✓ It provides coarse grain structure.
- ✓ In full annealing, the furnace cooling ensures identical cooling conditions at all locations within the metal, which produces identical properties.

16 MARKS:

1. Draw Time-Temperature-Transformation (T-T-T) diagram and label all the phases. Also enumerate any four objectives of heat treatment of steel. (NOV 2013)

(T-T-T) Diagrams:

The time-temperature-transformation (TTT) diagram, which is also called the isothermal transformation (IT) diagram, is a tools used by heat treaters to predict quenching reactions in steels.

Because of the shape, the TTT diagrams are also called **S curves or C curves**. Sometimes TTT diagram is also known as **Bain's curve**.

The TTT diagram is a plot of temperature **Vs** the logarithm of time for a steel alloy of definite composition.

The TTT diagram assumes that the temperature is constant (i.e., isothermal) during the transformation.

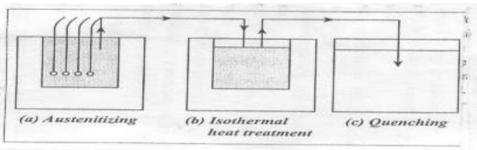
The TTT diagram is used to determine when transformations begin and end for an isothermal heat treatment of a previously austenitized alloy.

Construction of a TTT diagram:

The step by step procedure for constructing TTT diagram is as follows:

Step 1: Obtain a large number of relatively small specimens of same material.

Step 2: Austenitize the sample in a furnace at a temperature above the eutectoid temperature, as shown in fig.

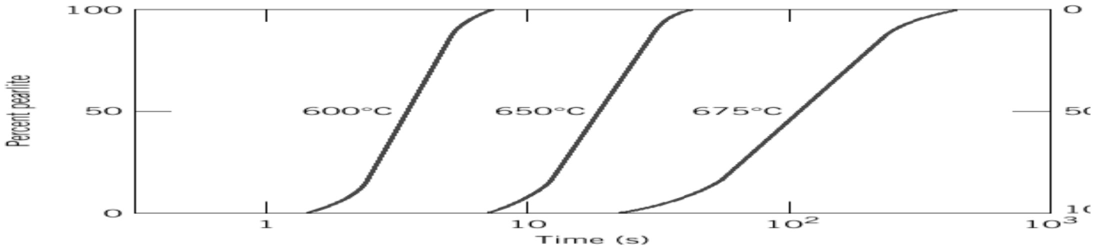


MICROSCOPIC CHANGES THAT OCCURS IN ISOTHERMAL TRANFORMAT

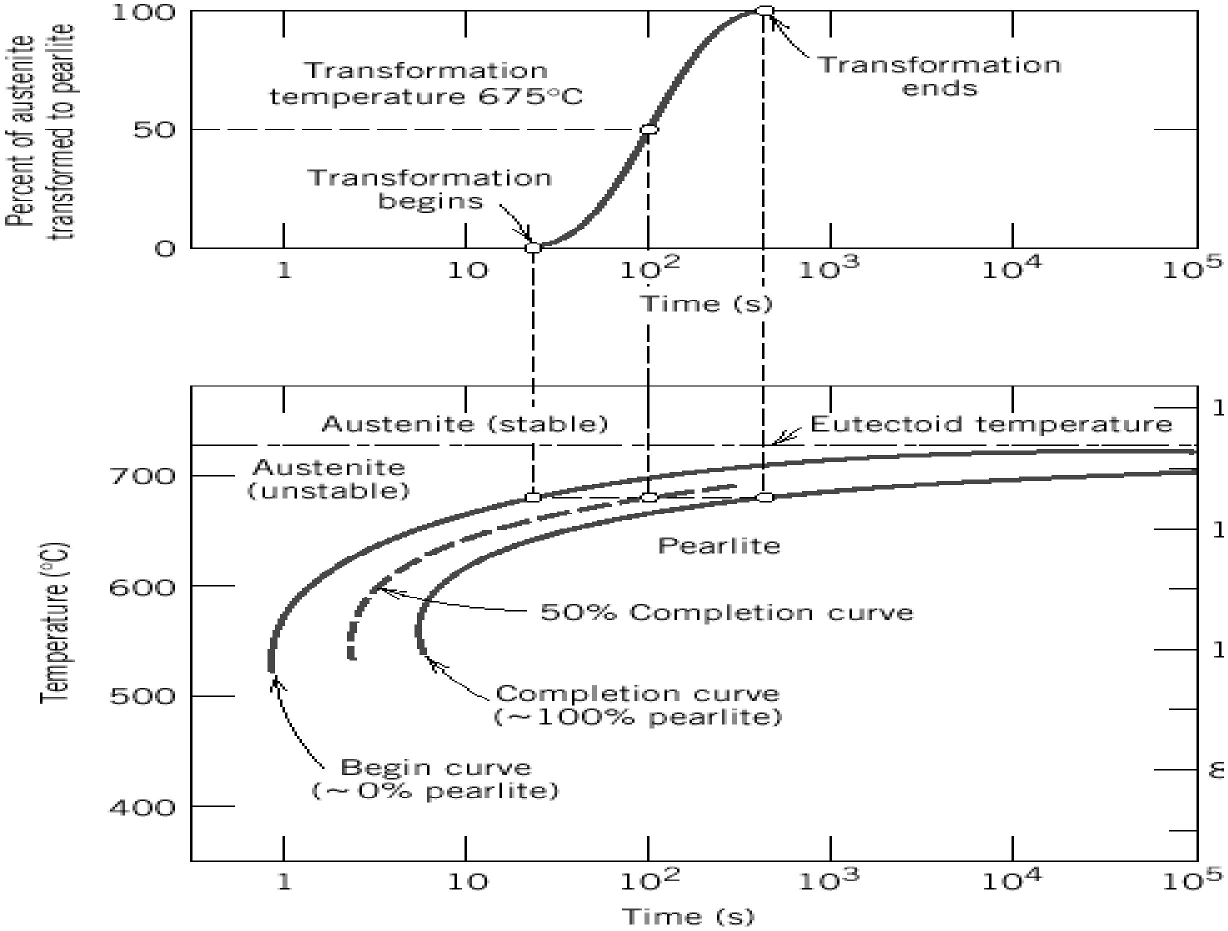
Step 3: Then quench i.e., rapidly cool the samples in a liquid salt bath at the desired temperature below the eutectoid temperature, as shown in fig.

Step 4: After various time intervals, remove the samples from the salt bath one at a time and quench into water at room temperature, as shown in fig. .

Step 5: Now, examine the microstructure after each transformation time at room temperature. The result obtained is the reaction curve as shown in fig .

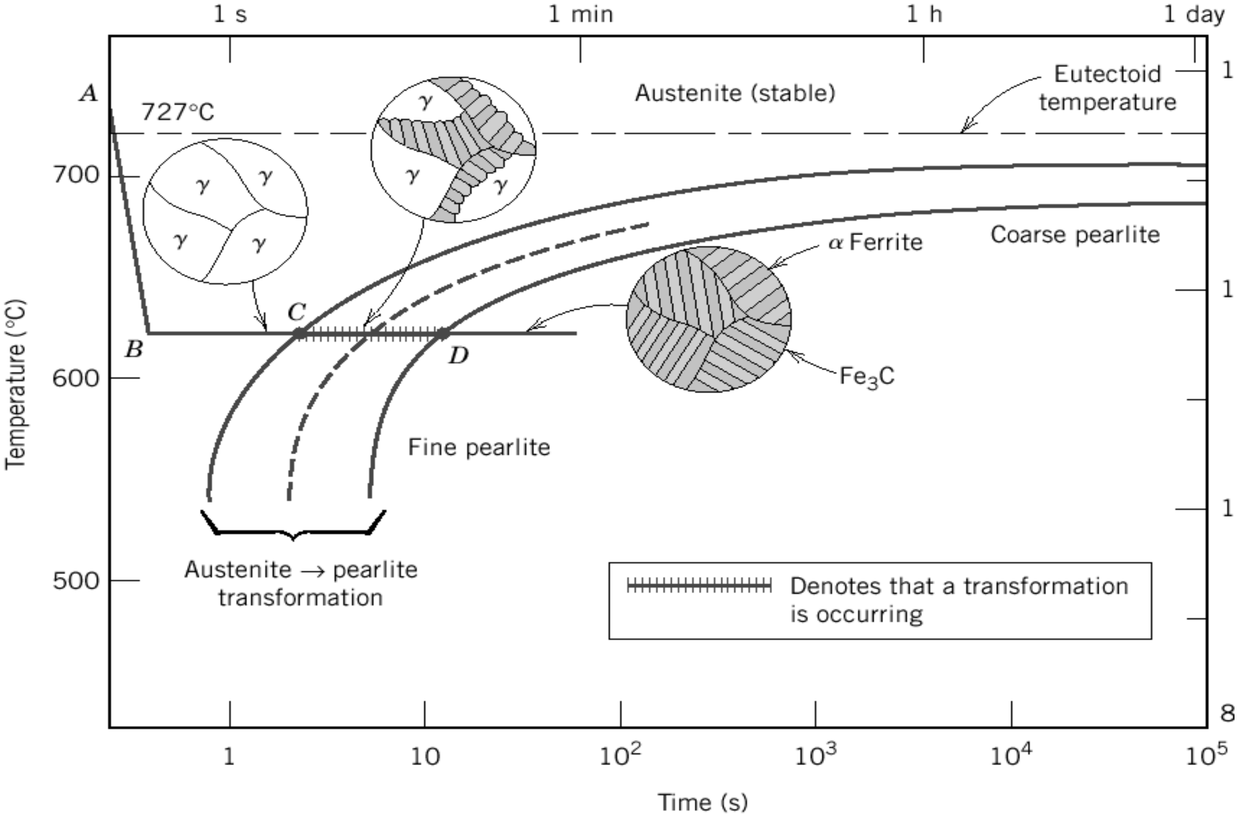


Step 6: Now repeat the above procedure for the isothermal transformation at progressively lower temperature. The data obtained from a series of isothermal reationcurves over the whole temperature range of aust enite instability for a given composition of steel, shown in fig.



TTT Diagram for a Eutectoid steel:

Fig depicts a simplified version of the TTT diagram for 0.8%(eutectoid) carbon steel.



The TTT diagram consists essentially of two C-shaped curves:

The left-hand C-shaped curve indicates the time necessary for the isothermal transformation of austenite to begin.

The right-hand C-shaped curve indicates the time required for the transformation to be completed.

Two parallel lines near the foot of the diagram are, strictly speaking, not part of the TTT diagram. But these two parallel lines indicate the temperature where austenite will start transform to martensite(M_s) and where this transformation will finish(M_f).

The TTT diagram of a eutectoid steel (which is the same as that fig.), but indicating various structures resulting from transformation at various temperature, is depicted in fig..

From the figs., the following interpretations can be made :

Isothermal transformations of eutectoid steels at temperature between 723⁰C and about 550⁰C procedure pearlitic microstructures.

As the transformation temperature is decreased in this range the pearlite changes from a coarse to a fine structure, as shown in fig.

Rapid quenching of a eutetoid steel from temperatures above 723⁰C, where it is in the austenitic condition, transforms the austenite into martensite.

If eutectoid steels in the austenitic condition are hot quenched to temperatures in the 550^{0}C to 250^{0}C range and are isothermally transformed, a structure intermediate between pearlite and martensite, called bainite, is produced.

Bainite in iron-carbon alloy can be defined as an austenitic decomposition product that has a non-lamerllar eutectoid structure of ɑ ferrite and cementite(Fe_3C).

For eutectoid carbon steels, a distinction is made between upper bainite and lower bainite.

Upper bainite is formed by isothermal transformation at temperatures between 550^{0}C and 350^{0}C. Upper bainite has large, rod like cementite regions.

Lower bainite is formed between about 350^{0}C and 250^{0}C. Lower bainite has much finer cementite particles.

As the transformation temperature is decreased, the carbon atoms cannot defuse as easily. Hence the lower bainite structure has smaller particles of cementite.

Significance of TTT Diagram in the Heat Treatment of Steel

The TTT diagram is most useful in giving an overall picture of the transformation behavior of austenite. This enable the metallurgist to interpret the response of a steel to any specified heat treatment.

Using a TTT diagram one can plan practical heat treatment operations to get desirable microconstituents, to control limited hardening or softening and the time of soaking.

2.Write short notes on the following surface heat treatment operations.

a) Carburising b) Nitriduing

c) Cyuniding d)Carbonitriding

CARBURISING

Carburising is the process in which carbon atoms are introduced onto the surface of low carbon steels to produce hard case of surface, while the interior or the core remains soft.

Steels for carburising should have carbon from 0.10 to 0.20%.

PROCESS OF CARBURISING

In Carburisation, when a piece of low-carbon steel is placed in a carbon saturated temperature, then the carbon will diffuse of penetrate into the steel and carurising it.

METHODS OF CARBURISING

The carburizing i.e, the process of adding carbon to a metal surface, can be accomplished by the following three methods.

Pack Carburising
Gas Carburising
Liquid Carburising(or cyaniding).

This Classification is based on the form of the Carburising medium used.

PACK(OR SOLID) CARBURISING

What is Pack Carburising?

In pack Carburising, the components to be treated are packed into steel boxes, along with the carburizing mixture, so that a space of roughly 50 mm exists between them.

The Carburising mixture essentially consists of some carbon-rich material, such as charcoal or charred leather, along with an energizer(upto 40% of the total composition).

The energizer is generally a mixture of sodium carbonate ('sodaash') and barium carbonate. Its function is to accelerate the Carburising process.

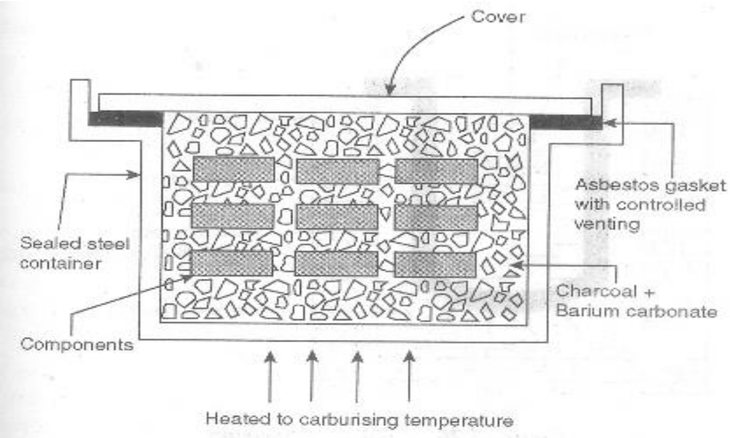


Figure 5.25 Pack carburising

Pack Carburising

Once the components to be heat treated and Carburising mixture are packed into steel boxes, then lids are fixed on the boxes. Then they are heat treated to the Carburising temperature (between 900^{0}C and 950^{0}C). They are maintained at this temperature for upto six hours according to the depth of case required (Fig.).

When Carburising is complete, the components are either quenched or allowed to cool slowly in the box.

The pack Carburising process is illustrated in Fig..

Fig. shows the relationship between time and temperature of the Carburising treatment and the depth of case produced. The Carburising times are estimated using the Fig..

Mechanism of Carburisation Process

During the process of Carburising, the following things happen:

During heat treatment, the charcoal is treated with barium carbonate (Carburising mixture) that promotes the formation of CO_2 gas.

$$BaCO_3 ========== BaO + CO_2$$

This CO_2 gas in turn reacts with the excess carbon in the charcoal to produce carbon monoxide(CO).

$$CO_2 + C ========= 2CO$$

This CO supplies the carbon that is necessary for diffusion.

$$2CO + 3Fe ======== Fe_3C + CO_2$$

Thus the formation of Fe_3C on the surface gives a very high hardness to them.

Drawbacks

There are several problems in pack Carburising process. They are :

Inefficient heating.
Temperature of a Carburising medium is not uniform throughout.
Difficulty in handling.
The process is not readily adoptable to continuous operation.

GAS CARBURISING:

Meaning:

Gas Carburising overcomes the drawbacks/difficulties of pack Carburising by replacing the solid Carburising mixture with a carbon-providing gas.
Gas Carburising can be done with any carbonaceous gas (i.e., gas containing an excess of CO). In general, natural gas, propane, or generated gas atmospheres are most frequently used.

Procedure

The gas- Carburising is carried out in both continuous or batch-type furnaces. In this process, the components are heated (at about 900^0C). In a furnace, in which the Carburising gas which is rich in carbon, such as methane, propane, or butane is circulated.

The horizontal rotary type of gas Carburising furnace has a muffle or retort which revolves slowly, so that the components are rotated in the stream of the gas. The Carburising gas contains CO and hydrocarbons which decompose at red heat and deposit the carbon on the component surfaces.

The thickness of the case formed depends upon the rate of flow of the gases and the temperature.

Mechanism/Reactions during Gas Carburising process

The major reactions that take place during the process of gas Carburising are given below:

$3Fe + 2\,CO==========Fe_3C + CO_2$

$Fe_3C + 2\,H_2========= 3Fe + CH_4$

$3Fe + CO + H_2============= Fe_3C + H_2O$

$CO_2 + CH_4 ========== CO + 2H_2$

$CO_4 + 3\,Fe============ Fe_3\,C + 2H_2$

Thus, like in pack Carburising, the formation of Fe_3C on the surface gives a very high hardness to them.

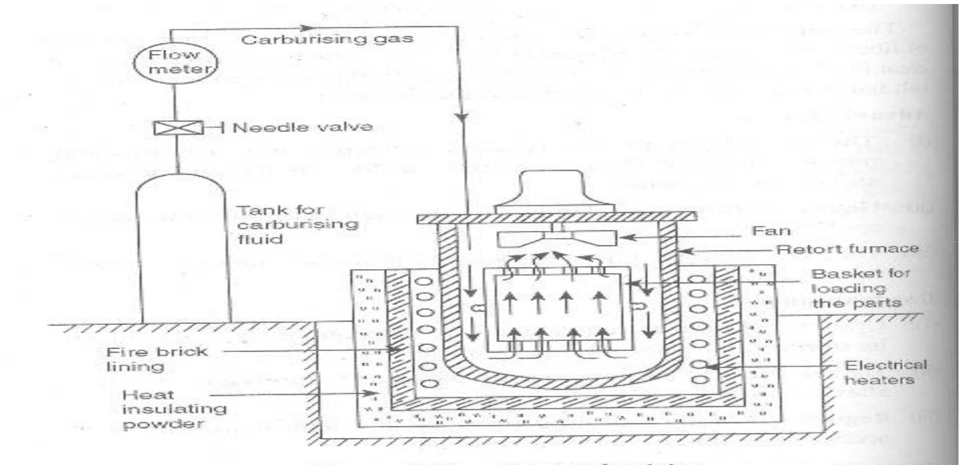


Figure 5.27 Gas carburising

<u>Application</u>

Gas Carburising is widely used for large-scale treatment, particularly for the mass production of thin cases.

<u>LIQUID CABURISING</u>

Meaning

Liquid Carburising, also known as ***salt Carburising***, is carried out in baths of molten salt which contains 20 to 50% sodium cyanide, 40% sodium carbonate, and varying quantities of sodium or barium chloride.

The cyanide-rich mixture is heated in iron pots to a temperature of 870 to 950^{0}C. The workpiece, which is carried in wire baskets, is immersed for periods of about five minutes upwards, according to the depth of case required.

<u>Mechanism</u>

Liquid Carburising takes place due to the decomposition of sodium cyanide at the surface of the steel. Atoms of both carbon and nitrogen are released, so liquid Carburising is due to the absorption of the nitrogen, as well as carbon,

The chemical reaction that occurs in liquid Carburising is

$2 NaCN + 2 O_2 ============ Na_2co_3 + 2N + Co$

Dissociation of CO at the steel surface then takes place, in the same manner as pack carburizing.

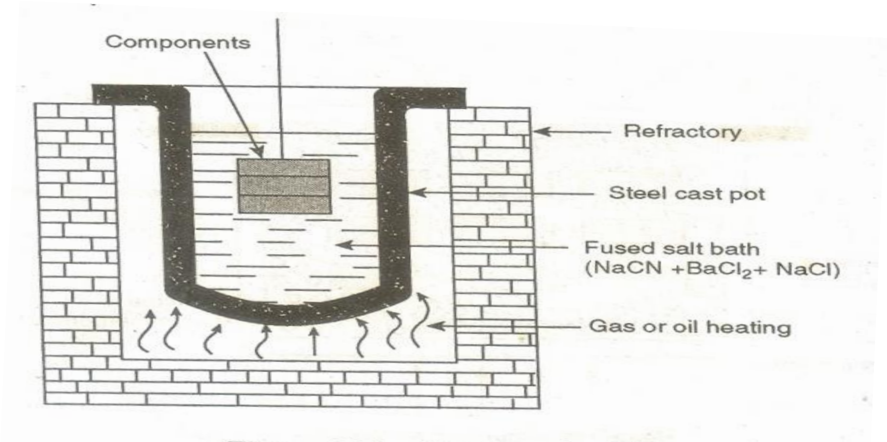


Figure 5.26 Liquid carburising

Suitability

The liquid carburizing process is suitable for producing shallow cases of 0.1 to 0.25 mm.

Advantages:

The temperature of a liquid salt bath is uniform throughout.
The temperature of the liquid salt bath can be controlled accurately by pyrometers.
The surface of the work remains clean.

Disadvantages:

Salt pots usually require batch processing.
The cost of carburizing salt is high.

NITRIDING

Nitriding is a process of introducing nitrogen atoms, to obtain hard surface of steel components. It is another process for the surface hardening of steel.

Nitriding Vs Case Hardening

In case-hardening, the medium contains carbons whereas in nitriding it contains gaseous nitrogen.

Special steels known as Nitralloy steels are necessary for the nitriding process, because hardening depends upon the formation of very hard compounds of nitrogen and metals such as aluminium , chromium and vanadium present in the steel.

Procedure:

Prior to begin nitrided, first the work pieces are heat-treated, to produce the required properties in the core.

In nitriding, the steels parts are heated and maintained at about 500^0C for between 40 and 100 hours. The treatment takes place in a gas-tight chamber through which ammonia gas is allowed to circulate. Some of the ammonia decomposes, releasing single atoms of nitrogen.

NH_3========== 3H + N (atom)

This atomic form of nitrogen (N) is absorbed on the surface of steel component.

A typical basic nitriding step is illustrated in fig..

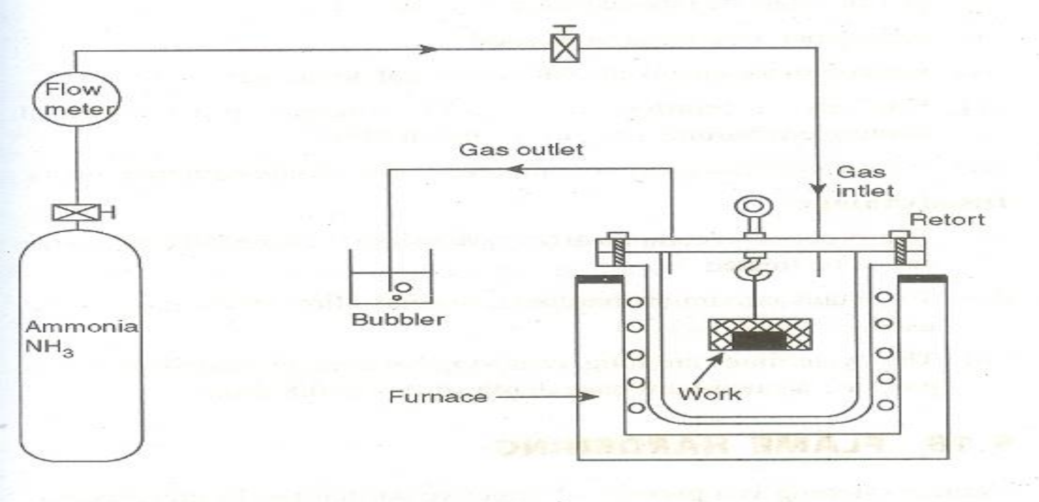


Figure 5.31 Nitriding process

Applications:

The nitriding process is used in the production of machine parts such as aircraft engine parts, aero engine cylinders, aero crankshaft, crank pins, journals, valve seats, gears, bushings,etc.

Advantages:

1. The extremely hard surface is formed.
2. No subsequent heat treatment is necessary.
3. It is cheap if large number of components are to treated.

Disadvantages:

1. Nitriding is more expensive than other case-hardening processes. However nitriding is economical is only when large number of components are to be treated.
2. If a nitrided component is accidentally over heated, the loss of surface hardness is permanent, unless the component can be nitrided again. Whereas a case hardened component would need only to be heated.

CYANIDING

- It is also known as liquid carburizing, is a process of introducing both nitrogen and carbon to obtain hard surface of the steel components .
- Cyaniding is done by immersing the work piece in a cyanide bath, as in liquid carburizing described in section
- Metals usually hardened by cyaniding process are plain carbon or alloy steels containing about 0.20% carbon.

Procedure

In cyaniding process, the steel components are heated in a bath of molten sodium cyanide and sodium carbonate at a temperature of about 950^{0}C. During this treatment both carbon and nitrogen diffuse into the surface of the steel. The formation of hard iron nitrides contributes to the surface of hardening of the material.

Reactions During Cyaniding Process.

The following reactions occur during the cyaniding process,

$$2\ NaCN + O_2(air) \text{ -------------> } 2\ NaCNO$$

$$2NaCNO + O_2\ (air) \text{ ----------------> } Na_2CO_3 + CO + 2N\ (atomic)$$

$$2CO \text{ ----------------- > } CO_2 + C\ (atomic\ )$$

The atomic nitrogen and carbon diffuse into steel. After cyaniding, the components require quenching to obtain harness. The case depths of 0.1 mm to 0.5 mm may be readily obtained by the process.

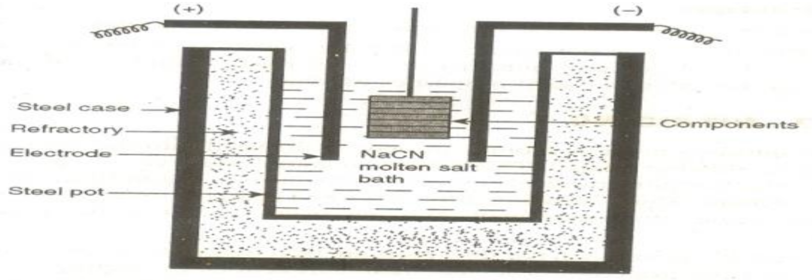


Figure 5.30 *Cyaniding process*

Differences Between Cyaniding and Liquid carburizing

The salt bath composition for cyaniding gives a case high in nitrogen, whereas liquid carburizing gives a case rich in carbon.

Applications

The cyaniding process is applied to produce automobile parts such as gears, shafts, pins, brakes, cams, sleeves, springs, steps, etc.

Advantages

It require less time and lower temperatures than carburizing.
Resistance to corrosion and wear is high.

Disadvantages

It is costly process.
Since **cyaniding** bath is toxic, workers require due protection.

CARBONITRIDING

Carbonitriding is also known as ***gas-cyaniding*** or ***dry-cyaniding,*** because it makes use of mixture of hydrocarbons and ammonia.

Suitability

Carbonitriding is an ideal process for hardening small components where great resistance to wear is necessary.The steels that are commonly carbonitrided are the low-carbon and low -carbon alloy steels.

Process

The carbonitriding process is carried out in a gas atmosphere furnace using a carburizing gas such as propane or methane mixed with the ammonia. The organic gas serves as the source of carbon and the ammonia gas serves as the source of nitrogen.

The work piece is heated to 850^0 C in the mixture of above gases for 2-10 hours. This is followed by quenching and then tempering is employed at 180^0C.

A typical carbonitriding system is illustrated in Fig

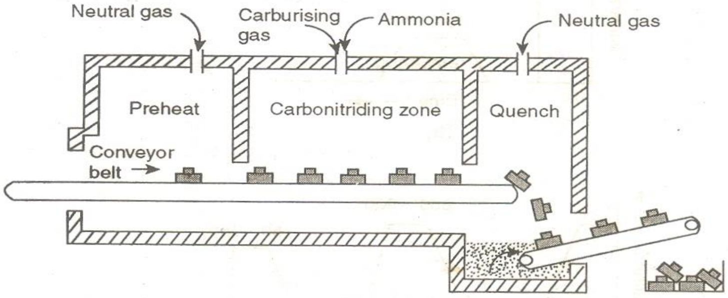


Figure 5.29 Carbonitriding process

Advantages

- ❖ It needs a less drastic quenching.
- ❖ It provides higher resistance to wear and corrosion.

The advantages of carbonitriding over nitriding is :

i. It can be used to get significant case depths (upto 0.25 mm) on plain carbon steels.

3. Write short notes on selective heating techniques employed for surface hardening.

a)Flame hardening **b) Induction hardening**

Thermal methods of surface hardening:

Selective hardening technique is by which different properties are obtained simply by varying the thermal histories of the various regions.

Two different thermal methods of surface-hardening widely used are:

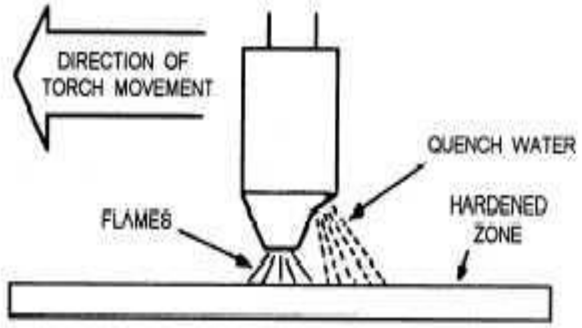
1. Flame hardening
2. Induction hardening

Flame hardening

- ✓ Flame hardening is the process of selective hardening with a combustible gas flame as the source of heat for austenitizing.

Principle of flame hardening

The surface to be hardened is to a temperature above its upper critical temperature, by means of a travelling oxy-acetylene torch, as shown in fig2.33. Then it is immediately quenched by a jet of water issuing from a supply built into the torch-assembly. Thus, the surface hardening results when the austenitized surface is quenched by the water spray that follows the flame.



Suitability

The flame hardening technique is suitable for the plain carbon steels with carbon contents ranging from 0.04% to 0.95% and low-alloy steels.

Applications

It is used to improve wear resistance and surface hardness of teeth of gears, wheels, sheaves, bushings, shafts, mill rolls, cams, spindles, hand tools , etc.

Advantages

1. It is more efficient
2. It is very economical for larger works.
3. Heating rate is high the surface of work remains clean.

Disadvantages

1. Very thin section may get distorted excessively.
2. Overheating may cause cracks.

INDUCTION HARDENING

The mechanism and purpose of induction hardening are the same as for flame hardening. The main difference is that is induction hardening the source of heat input is an induced electric current instead of using flame.

Suitability

The steels that can be hardened with this process are the same as those used in flame hardening.

Procedure

Induction heating is done by passing a high-frequency alternating current through a water-cooled coil or inductor around the work piece. The cyclic magnetic field that is generated induces alternating currents that heat the work piece, shown in fig..

Typical frequency is used are: 3000 Hz for depths of 3 to 6 mm; and 9600 Hz for depths of 2to 3 mm.

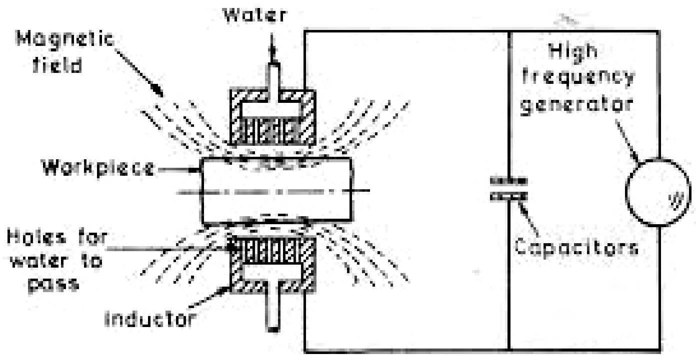


Fig. 44.3. Operation of induction hardening.

Application

The induction hardening is employed for hardening the surfaces of gears, tool drivers, wrist pins, crank shaft bearing journals, cylinder liners, rail ends, machine tools ways, and pump shaft.

Advantages

1. The required for heating in induction hardening is very less.
2. The process can be easily automated.
3. External as well as internal surface can be hardened.

Disadvantages

1. It requires large capital equipment expenditures.
2. It is economical only for large quantity production.
3. It is difficult to handle the irregular shape components.

4) Define Annealing. Explain the type of annealing process.(NOV 2013)

The term **annealing** refer to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled.

Annealing process consists of following three stages:

a) Heating to the desired temperature.
b) Holding or soaking at that temperature.
c) Cooling or quenching, usually to room temperature.

In practice, annealing is one of the most widely used process in the heat treatment of iron and steels.

Types of annealing

1. Full annealing,
2. Process annealing,
3. Stress relief annealing,
4. Recrystallisation annealing, and
5. Spheroidise annealing.

1. Full Annealing

In fact, the actual definition of annealing describes only the full annealing. That is, full annealing consists of heating the steel to a temperature at or near the critical point, holding there for a time period and then allowing it to cool slowly in the furnace itself.

The main objects of full annealing are:

- ✓ To soften the metal,
- ✓ To refine its crystalline structure, and
- ✓ To relieve the stresses.

Material: The full annealing is specially adopted for steel casting and steel ingots.

Process of full annealing

✓ In full annealing, hypoeutectiod steels are heated to 30 to 60^0 C above the upper critical point i.e., A_3 line as shown in fig.This is to convert the structure to homogeneous single-phase austenite of uniform composition and temperature , held at this temperature for a period of time, and then slowly cooled to room temperature.

✓ Cooling is usually done in the furnace it self by decreasing the temperature 10 to 30^0C per hour to at least 30^0C below the A_1 line. Then, the alloy is removed from the furnace and air cooled to room temperature.

✓ Now the resulting structure is coarse pearlite with excess ferrite. In this condition, the steel is quite soft and more ductile.

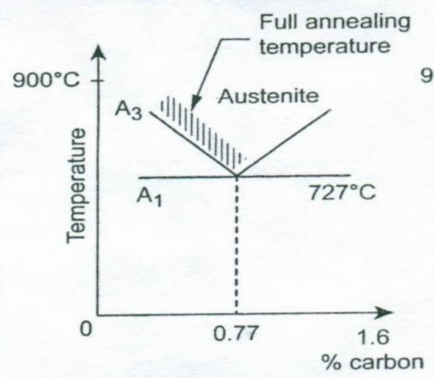


Fig. 2.1. Full annealing temperatures for hypo eutectoid steel

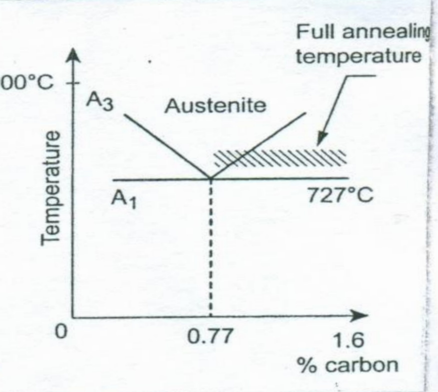


Fig. 2.2. Full annealing temperatures for hyper eutectoid steel

✓ The procedure for hypereutectoid steel are the same, except that the hypereutectoid steels are heated to 30 to 60^0C above the A_1 line as shown in fig.

✓ In this case, the resulting structure of a hypereutectoid steels will be coarse pearlite plus excess cemenite in dispersed spheroidal form.

✓ This structure imparts much improvement in mechanical properties, high ductility and high toughness.

Process Annealing :

✓ Purpose: Process annealing is a heat treatment that is often used to soften and increase the ductility of a previously strain-hardened metal.

✓ Material: Process annealing is extensively employed for steel wires and sheet products.

✓ Operation: In process annealing, the low carbon steels are heated to a temperature slightly the A_1 line as shown in fig. This process induces single phase morphology.

✓ Application: This process has wide application in preparing steel sheet and wires for drawing.

Stress Relief Annealing (or) Commercial Annealing

- ✓ Purpose**:** The stress relief annealing is a heat treatment process that is employed to eliminate internal residual stress induced by casting, quenching, machining, cold working, welding, etc.
- ✓ Causes of internal residual stresses**:** Internal residual stresses may develop in metals/alloys due to:

1. Plastic deformation process such as machining and grinding;
2. Non-uniform cooling of a metal that was processed or fabricated at an elevated temperature, such as weld or a casting;

Effects of internal residual stresses**:** If the internal residual stress are not removed, then distortion or warpage of the material may result.

Operation: In stress relief annealing, the steel parts are heated in the range of 550^{0}C to 650^{0}C, held for a period of time, and then cooled slowly. **Stress** relief is also known as recovery.

Recrystallisation Annealing

It is a process by which distorted grains of cold worked metal are replaced by new, strain-free grain during heating above a specific minimum temperature.

Recrystallisation temperature

The temperature at which crystallization takes place i.e., new grains are formed is called **recrystallisation temperature.**

Operation

In this heat treatment process, cold worked steel is heated to a temperature above recrystallization temperature, held at this temperature for some time, and then cooled.

It may be noted that the recrystalisation process does not produce new structures**.**

Spheroidizing or Spheroidise annealing

Purpose: Medium and high carbon steels having a microstructure containing even coarse pearlite is too hard to conveniently machine or plastically deform. These steels are Spheroidise annealed.

Objects of spheroidising are:

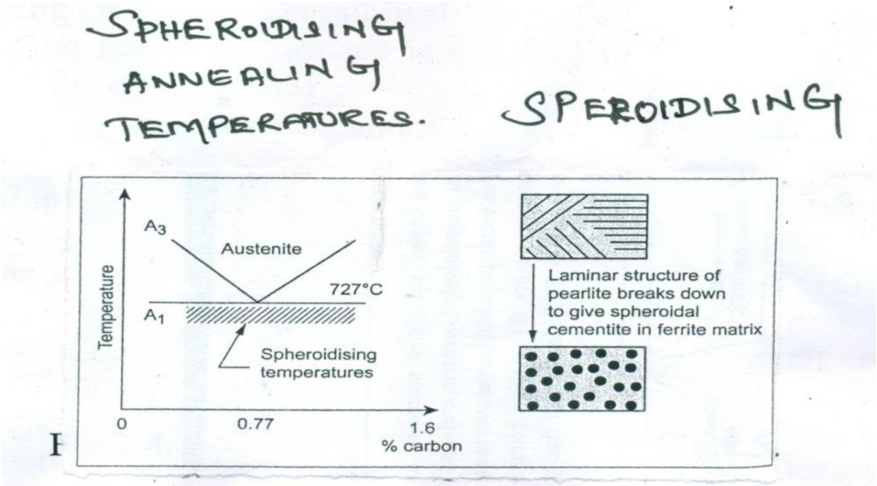
1. To soften steels.
2. To increase ductility and thoughness.

3. To improve machinability and formability.
4. To reduce hardness, strength, and wear resistance.

Materials: Spheroidizing is extensively employed for medium and high carbon steels.

Operation

1. Prolonged heating at a temperature just below the A_1 line followed by relatively slow cooling.
2. Prolonged cycling between temperatures slightly above and slightly below the A_1 line.
3. In the case of tool or high alloy steels, heating to 750^0C to 800^0C or higher and holding at this temperature for several hours, followed by slow cooling.
4. A typical Spheroidizing annealing temperatures range depicted in fig.



The Spheroidizing process result is a coalescence of the Fe_3C to form the spheroid particles, as shown in fig. Thus the actual structure is a matrix of ferrite with Fe_3C in the form of spheroid globules.

5.Describe the following process.

a) Normalizing **b) Hardening**
b) Quenching **d) Tempering**

NORMALIZING

- ❖ It is similar to full annealing, but cooling is established in still air rather than in the furnace.
- ❖ Full annealing is an expensive and time consuming process.

Objects of normalising:

Some of the purposes of normalizing:

1. To refine the grain structure.

2. To increase the strength of the steel
3. To provide a more uniform structure in castings and forgings.
4. To relieve internal residual stresses due to cold working.
5. To achieve certain mechanical and electrical properties.

Materials:

The normalizing process is extensively employed for low and medium carbon steels as well as alloy steels.

Operation:

In normalizing, the steel is heated to 50^0 C to 60^0 C above its upper critical temperature(i.e., above the A_3 line) for hypoeutectoid steel or above the A_{cm} line for hypoeutectoid steels, as shown in Fig. . It is held at this temperature for a short time and then allowed to cool in still air.The normalizing process provides a homogeneous structure consisting of ferrite and pearlite for hypoeutectoid steels.

NormalisingVs Full Annealing:

The difference between normalizing and full annealing is presented in Table

S.No	Normalising	Full annealing
1.	Normalizing is more economical than full annealing (since no furnace is required to control the cooling rate)	Full annealing is costly.
2.	Noemalising is less time consuming.	Full annealing is more time consuming.
3.	Normalising temperature is higher than full annealing.	Annealing temperature is lower than normalizing.
4.	It provides a fine grain structure.	It provides coarse grain structure.
5.	In normalizing, the cooling is established in still air. So the cooling will be different at different locations. Thus properties will vary between surface and interior.	In full annealing, the furnace cooling ensures identical cooling conditions at all locations within the metal, which produces identical properties.

Quenching:

- ✓ Refers accelerated cooling.
- ✓ The cooling can be accomplished by contact with a quenching medium which may be a gas, liquid, or solid.
- ✓ Most of the times, liquid quenching media is widely used to achieve rapid cooling.

Types of Quenching Medi um:

Some of the quenching medium that are used generally in industries, in order of decreasing quenching severity, are given below:

1. 5-10% caustic soda
2. 5-20% brine(NaCl)
2. Cold water
4. Warm water

5. Mineral oil(obtained during the refining of crude petroleum)

6 . Animal oil

7. Vegetable oil(such as linseed, cottonseed, and rapeseed)

8. Air

Thus water produces the most severe quench followed by oil, which is more effective than air.

Table shows the applications of some of the quenching medium.

S.No	Quenching Medium	Applications
1.	Mineral oils	Used in hardening alloy steels.
2.	Water or aqueous solution of NaOH or NaCl	Used for quenching carbon and alloy steels.
3.	Water and air	Used for rails, pipes, and heavy forgings.

Selection of Quenching Medium:

The selection of quenching medium is based on the following factors:

1. Desired rate of heat removal.
2. Required temperature interval.
3. Boiling point.
4. Viscosity.
5. Flash point(if combustible)
6. Stability under repeated use.
7. Possible reactions with the material being quenched.
8. Cost.

Stages of Quenching:

The three stages of quenching are:

Stage 1: Vapour – Jacket Stage

- ✓ When a piece of hot metal is first inserted into a tank of liquid quenchant, that adjacent to the metal vapourises and forms a gaseous layer separating the metal and liquid.
- ✓ In this stage cooling is slow since all heat transport must be through a gas(by conduction and radiation)
- ✓ This stage occurs when the metal is above the boiling point of the quenchant.

Stage 2: Vapour – Transport Cooling Stage

- ✓ This stage starts when the hot metal is cooled to a temperature at which the gaseous layer is no longer stable.
- ✓ In this stage, bubbles nucleate and remove the gaseous layer; liquid contacts the metal and vapourises it and thus the process of bubbles formation continues.
- ✓ This second stage of quenching provides rapid cooling as a result of the large quantities of heat removed by the mechanism.

Stage 3: Liquid Cooling Stage

- ✓ Third stage begins when the metal cools below the boiling point of the quenchant.
- ✓ In this stage, all heat transfer occurs through conduction across the solid-liquid interface, aided by convection or stirring within the quenchant.
- ✓ The third stage of quenching provides the slowest rate of cooling.

HARDENING (BY QUENCHING)

- ➢ Refers to the heat treatment of steel which increase its hardness by quenching.
- ➢ Hardening normally implies heat-treating operations which produce microstructures which are entirely or predominantly martensitic.

Objects of Hardening:

The main purpose of hardening are:

1. To harden the steel to resist wear.
2. To enable it to cut other metals.

Operation:

The process of hardening involves the following stages:

1.Heating : The steel to be heat treated is heated slowly in a furnace to a temperature 30 ^{0}C to 50^{o}C above the upper critical temperature i.e., above the A_3 line , as shown in Fig.

2.Soaking : The heated steel is held at this temperature for considerable length of time to allow complete austenisation.

3.Cooling : The steel is cooled by quenching (in a water bath or oil bath) to the room temperature. The cooling rate should be higher than the critical cooling rate in order to get the completely martensitic structure.

Phase Transformation During Hardening:

Due to rapid cooling, the austenite(ɤ iron) will be super cooled by nearly 500^{0}C and the driving force will be large enough to convert FCC body centered tetragonal

(BCT), as shown in Fig.2.9. The resulting structure of FCC BCT is called as martensite.

A new phase transformation from austenite to martensite occurs without a compositional change.

$$\underset{\text{FCC}}{\text{Austenite}(\text{ɣ iron})} \xrightarrow{\text{rapid}} \underset{\text{BCT}}{\text{Martensite}}$$

The martensite is super- saturated solution of carbon in α-iron. Also because carbon is present in the lattice, slip does not occur easily. That's why, martensite is very hard,strong and brittle. It has needle like structure.

Factors Affecting the Hardness:

The hardness obtained from the hardening process depends upon the following factors:

1. Carbon content,
2. Quenching medium,
3. Specimen size, and
4. Other factors.

1. Carbon Content:

Since the hardness in steel is to carbon content, therefore usually the hardening process is carried out on the high carbon steels.(0.35 to 0.50%C).

As the carbon content in steel increases, the hardness obtainable also increases, as shown in Fig.2.10.

2. Quenching Medium:

- ✓ As we know, the hardness depends essentially upon the nature and properties of quenching medium.
- ✓ It may be noticed that faster the cooling the greater the hardness, slower the cooling lower the hardness.
- ✓ the quenching in water or brine solution is commonly used for hardening low and medium plain carbon steels. For high carbon and alloy steels, mineral oil is generally used as the quenching medium, because its action is not so severe as that of water. Certain alloy steels can be hardened by air cooling.

3. Specimen size:

- ✓ The specimen size also affects the hardness obtained from hardening process.
- ✓ As the specimen size increases, the hardness decreases even though all other conditions have remained the same. For eg..a 50 mm diameter steel bar will attain greater hardness than a 100 mm diameter steel for of similar composition.

4. Other Factors:

The other factors that affect the hardness obtained from hardening process include:

a) Geometry i.e.,shape of the specimen.

b) Quenching temperature.
c) Degree of agitation.
d) Surface condition of specimen.
e) Alloying elements.

TEMPERING:

The martensite which is formed during hardening process is too brittle and lacks good ductility and toughness. Hence, it cannot be used for most applications. Also the internal residual stresses that are introduced during hardening have a weakening effect. The ductility and toughness of martensite can be enhanced and these internal stresses are relieved by a heat treatment process known as tempering.

The tempering process usually follows hardening process.

Objects of Tempering:

The main purpose of tempering are:

1. To improve ductility and toughness.
2. To reduce brittleness of the hardened steel.
3. To remove the internal stresses caused by rapid cooling.
4. To impart wear resistence.

Tempering process:

- Tempering is the process of heating a martensite steel at a temperature below the eutectoid transformation temperature (i.e., between 250^0 C and 650^0C) for a specified time period, and is cooled slowly to room temperature.
- When the martensite steel is heated at temperature as low as 200^0C, the internal stresses may be relieved.
- The tempering heat treatment transforms martensite into tempered martensite by diffusional process.

The reaction of transformation of tempered of tempered martensite can be written as

Martensite → Tempered martensite

(BCT,single phase) (α + Fe3C phases)

- In the tempering process the single – phase BCT martensite (which is supersaturated with carbon) transforms to the tempered martensite (composed of the stable ferrite and cementite phases), as indicated on the iron-iron carbide phase diagram.
- Tempered martensite have substantially improved ductility and toughness than the martensite.

Microstructural changes inMartensiteUpon Tempering:

- ✓ The microstructure of tempered martensite consists of extremely small and uniformly dispersed cementite particles embedded within a continuous ferrite matrix.
- ✓ This is similar to the microstructure of spheroidire except that the cementite particles are much smaller.
- ✓ Fig. showw an electron micrograph of tempered martensite.

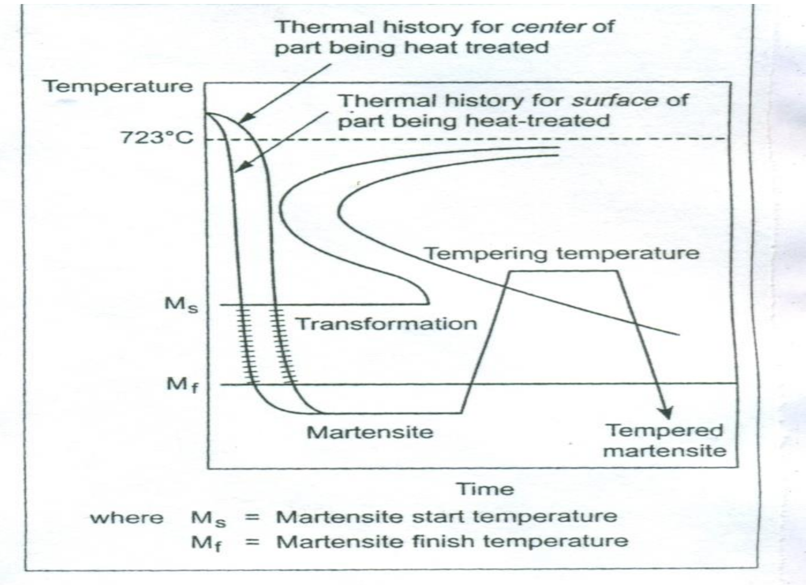


Fig. Tempering process

Effects of Tempering Tempearture on the Hardness of Steels:

- ✓ Fig. depicts the effect of increasing tempering temperature on the hardness of the several martensite steels.
- ✓ It may be seen from the Fig. that the hardness gradually decreases as the temperature is increased.
- ✓ This gradual decrease in hardness of the martensite with increasing temperature is mianly due to the diffusion of carbon atoms from their stresses interstitial lattice sites to form second-phase iron carbide precipitates.

Effect of Tempering Time on the Hardness of Steels:

- ➢ The effect of tempering time on the hardness of steels is also shown in Fig..
- ➢ It may be seen from the Fig. that the hardness decreases with the increase in tempering time.

Effect of Tempering Temperature on Mechanical properties:

- ➢ Fig.2.13(a),(b) and (c) illustrate the effect of tempering temperature on the mechanical properties such as tensile strength, impact strength, and ductility(in terms of % elongation) respectively.

- From the Fig.2.13, it may be noted that the tensile and yield strengths decrease with the increase in tempering temperature, whereas the ductility increases with the increase in tempering temperature.
- The above changes are mainly due to the fact that increasing the temperature will accelerate diffusion, the rate of cementite particle growth, and hence the rate of softening.

Classification of Tempering:

According to the tempering temperature, tempering may be classified into three classes. They are:

1.Low Temperature tempering:

- The low temperature tempering is performed in the temperature range from 150^{0}C to 250^{0}C.
- This process is used to retain hard microstructure of martensite. Also this process relieves the internal residual stresses.
- This process is generally applied on cutting and measuring tools of carbon and low alloy steels and the parts which are surface hardened and case-carburised.

2.Medium Temperature Tempering:

- The medium temperature tempering is performed in the temperature range from 350^{0}C to 450^{0}C.
- This process develops tempered-troostite structure.
- This process increases endurance limit and elastic limit.
- This process is applied on spring steels and die steels.

3.High Temperature Tempering:

- The high temperature tempering is performed in the temperature range from 500 ^{0} C to 650 ^{0}C.
- This process develops sorbite structure.
- It eliminates the intenal stresses completely.
- This process is applied on structural steels.

6.Determining Hardenability (Jominey End – Quench Test):

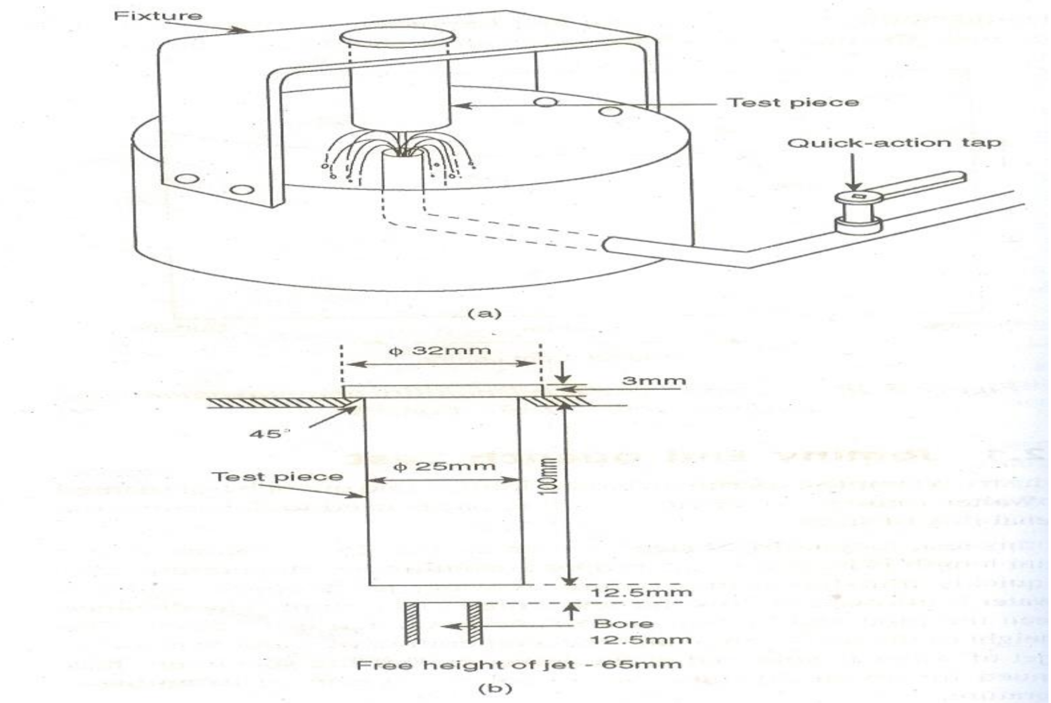
- ✓ The most widely adopted method of determining hardenability is the Jominey end-quench test method.
- ✓ The Jominey end-quench test method is universally adopted because:
  - i. It is relatively easy to perform.
  - ii. It has excellent reproducibility.
  - iii. It gives information useful to a designer as well as manufacturer.

End- Quench Specimen:

A bar of the steel to be tested is machined to give a cylinder 111.6mm (4 inch) long and 25.4mm (1 inch) in diameter with an upper lip. The end-quench specimen and testing arrangemet are shown in Fig. and respectively.

Testing Procedure:

a. The standard test-piece is heated to above the upper critical temperature of the steel i.e., until it becomes completely austenitic.
b. It is then quickly transferred from the furnace, and immediately dropped into position in the frame of the apparatus shown in Fig.
c. Here it is quenched at one end only, by a standard jet of water at 25 ^{0} C.Thus, different rates of cooling are obtained along the length of the test-piece.
d. When the test-piece has cooled, a 'flat' approximately 0.4 mm deep is ground along the length of the bar, as shown in Fig.. Now Rockwell C hardness readings are taken every 1.6 mm (1/16 inch) along the length, from the quenched end.
e. Finally,the results are plotted as shown in Fig
➢ From the Fig., it is clear the greatest hardness is at the quenched end, where martensite is formed;and the lower hardness is farther away.



Use of Hardenability Curves:

✓ The main practical uses of end-quench hardenability curves are:
✓ If the quench rate (i.e., cooling rate) for a given part is known,theJominy hardenability curve for that material.

Cooling rates can be determined by thermocouples embedded in the bars during the quenching operation.

7. Explain in detail Martempering of Austempring process of heat treatment.

MARTEMPERING:

Martempering, also known as marquenching, is a interrupted cooling procedure used for steel to minimize the stresses, distortion and cracking of steels that may develop during rapid quenching.

MARTEMPERING PROCESS:

- Step 1: Austenitizing the steel, i.e., heating the steel above its critical range to make it all austenite.
- Step 2: Quenching the austenitized steel in hot oil or molten salt at a temperature just slightly above the martensite start temperature (M_s).
- Step 3: Holding the steel in the quenching medium until the temperature is uniform throughout and stopping this isothermal treatment before the austenite-to-bainaite transformation begins.
- Step 4: Cooling at a moderate to room temperature to prevent large temperature differences between center and surface. Fig.shown a cooling path for the martempering process.
    - ✓ The resulting microstructure of the martempered steel is untempered martensite.
    - ✓ Now the untempered martensite structure is transformed into tempered martensite structure by the conventional tempering heat treatment processing rapid quenching.

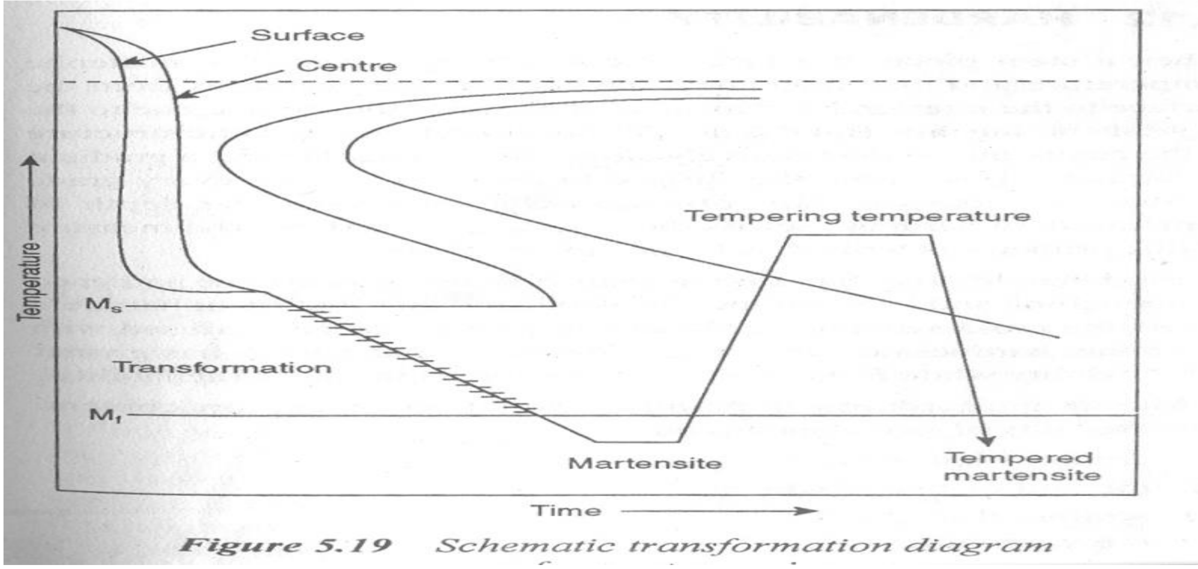


Figure 5.19 Schematic transformation diagram

Application:

The martempering process is mostly used in alloy steels.

Advantages:

1. Minimized quenching stresses.
2. Minimized chances of formation of quenching cracks.
3. Less distortion or wapring.

AUSTEMPERING:

Austempering is another type of interrupted quenching that forms bainite structure.

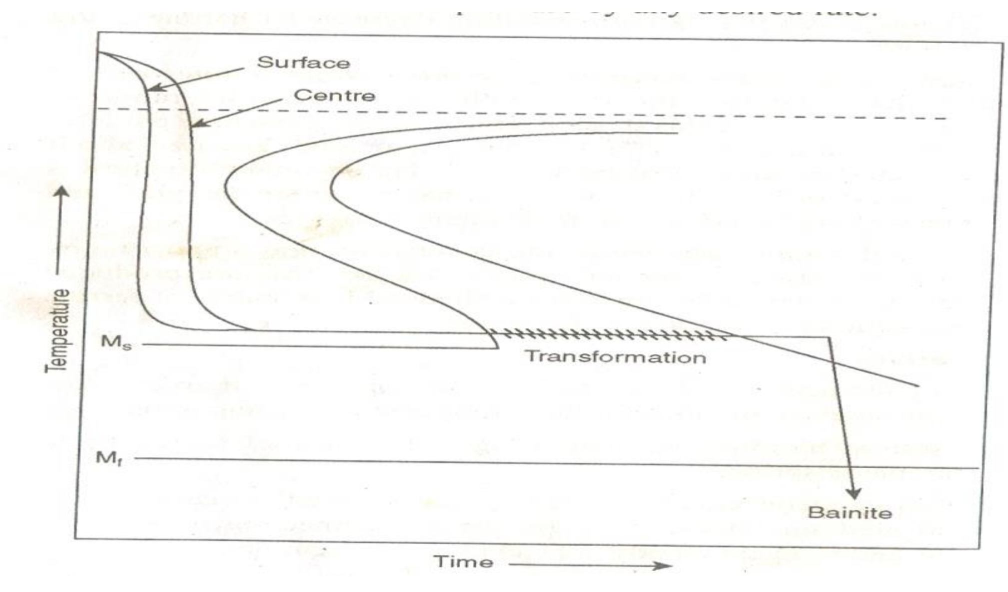
It is used to make tough and strong steels.

AUSTEMPERING PROCESS:

Step 1: Austenitizing the steel.

Step 2: Quenching the austenitised steel in a molten salt bath at a temperature just above the martensite start temperature (M_s) of the steel.

Step 3: Holding the steel isothermally to allow the austenite-to-bainite transformation to take place.



Step 4: Slow cooling to room temperature in air. Fig. shows a cooling path for the AUSTEMPERING process.

✓ The resulting microstructure of the austempering process is bainite. Unlike martempring, tempering is rarely needed after austempering.

Application:

AUSTEMPERING is widely applied on small tools, springs, retainers, automobile seat belt component, link chain, lawnmover blades and various machinery parts.

Advantages:

1. Improved ductility.
2. Increase impact strength and toughness.
3. Less danger of quenching cracks.

Disadvantages:

1. Need for a special molten salt bath.
2. The process can be used only for a limited number of steels.

8. Explain continuous- cooling transformation?

Introduction:

The data for the construction of TTT diagrams are obtained from the isothermal transformation of austeniten at differing temperatures. But most industrial heat treatments involve continuous cooling from the austenitic temperature to room temperature. Thus a TTT diagram may not give a fully accurate representation of the temperatures and times of the transformations occurring. The continuous cooling diagram gives a more accurate picture for heat treatments involving continuous cooling.

The CCT diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to indicate when transformation occur as the initially austenitised material is continuously cooled at a specified rate. In addition, it is also used to predict the final microstructure and mechanical characteristics.

CCT diagram for a Eutectoid Carbon Steel:

We know that an isothermal transformation diagram(i.e., TTT diagram) is valid only for conditions of constant temperature. Since the continuous cooling is the most practical method of heat treatment,therefore the TTT diagram must be modified for transformations that occur as the temperature is constantly changing.

For continuous cooling, the time required for a reaction to begin and end is delayed.Thus the isothermal curves are shifted to longer times and lower temperatures. A plot containing such modified beginning and ending reaction curves is termed a continuous cooling transformation diagram.

Fig. shows a CCT diagram for a eutectoid carbon steel superimposed over a TTT diagram for the steel.

In Fig, the continuous-cooling diagram transformation start and finish lines are shifted to longer times and slightly lower temperatures in relation to the isothermal diagram. Also there are no transformation lines below about 450^0 C for the austenite-to-bainite transformation.

Intersection of the cooling curve with the beginning TTT curve indicates the start of transformation. Time at temperature, in propotion to the time required to the required for complete transformation,indicates the degree to which transformation has progressed.

1.Cooling curve A: Curve A represents a very slow cooling rate such as in annealing. This cooling rate allows transformation to pearlite to start at a_1 and complete at b_1.

2.Cooling curve B: Curve B represents more rapid cooling(as in normalizing). This transformation will start at a_2 with the formation of coarse pearlite and finish at b_2 with the formation of fine pearlite.

3.Cooling curve C: In curve C,the transformation to pearlite at a_3 but is interrupted at b_3 ; and no further transformation takes place until the remaining austenite begins to change to martensite(at c_3). The final transformation being complete at d_3. Thus the resulting structure is a mixture of martensite and pearlite.Since the transformation takes place in two steps, it is called ***split transformation.***

4.Cooling curve D: Curve D represents very rapid cooling. It avoids the formation of ferrite, cementite, pearlite, or bainite. This might be a water quench to produce martensite.

5.Cooling curve E: Curve E is tanget to the nose of CCT curve. The curve E represents critical cooling rate, which will produce a fully hardened(i.e., 100%) martensitic structure.

Fig. shows the schematic interpretation of the effect of cooling rate on approximate transformation temperature, and microstructure of a eutectoid carbon.

1.With continuous cooling of plain carbon steels,one can produce only pearlite,martensite, or a mixture of the two.

2.There is no mechanism by which pearlite can be transformed into martensite or martensite into pearlite without first reheating above the upper critical temperature to austenitize.

Critical Cooling Rate:

Definition: The slowest rate of cooling of austenite that will result in 100% martensite transformation is known as the critical cooling rate.

Importance: The critical cooling rate is most important in hardening.In order to obtain a 100% martensitic structure on hardening,the cooling must be much higher than the critical cooling rate.

Factors affecting the critical cooling rate are:

1.Chemical composition of steel,

2.Hardening temperature, and

3.Metallurgical nature(i.e., purity) of steel.