

Material Science

HEAT TREATMENT

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Heat Treatment Of Steel

PURPOSES OF HEAT TREATMENT

- to improve strain hardening of a cold worked metal piece and improve its ductility
- to remove gases from casting
- to improve resistance against wear, heat and corrosion
- to soften a metal to improve its machinability
- to improve the cutting ability i.e. to improve hardness of a tool steel.
- to restore electrical conductivity of a cold worked metal
- to improve magnetization property, especially of steels, for producing permanent magnets
- to refine grain structure after hot working a metal.
- to produce a hard, wear resistance case on a tough core of a steel
- to soften and toughen a high carbon steel piece
- to harden non-ferrous alloys and metals, especially aluminium alloys
- to remove effects of previously performed heat treatment operations
- to relieve internal stresses

MAJOR DEFECTS DUE TO FAULTY HEAT TREATMENT

- **Overheating:** Prolonged heating of steel at temperatures considerably above A_3 leads to the formation of very large actual grains. This is called overheating. On cooling this yields the so called *Widmanstatten* structure containing coarse crystalline martensite. This gives a steel with reduced ductility and toughness.
- **Burning:** Heating steel to still higher temperatures near melting point for a longer time leads to burning. This is accompanied by the formation of iron oxide inclusions along the grain boundaries. Burnt steel has a stony fracture. A burnt steel is irremediable and is rejected.
- **Oxidation:** This is caused due to oxidizing atmosphere in the furnace and is characterized by a thick layer of scale on the surface of the steel article. This can be prevented by using controlled atmosphere in the furnace or using molten salt baths.
- **Decarburization:** This is the loss of carbon in the surface layers of the article and results in lower hardness and lower fatigue limit. It is caused by the oxidizing furnace atmosphere. To prevent this the

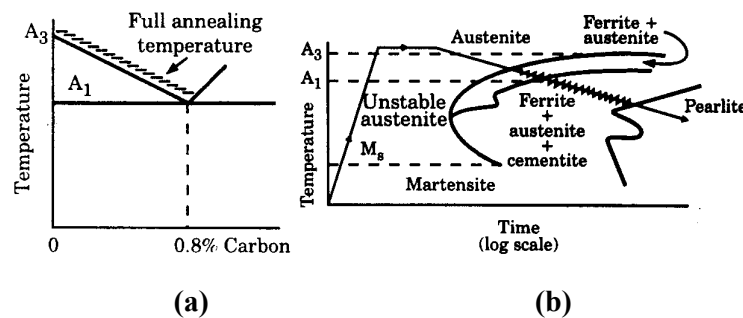
part should be heated in the neutral or reducing atmosphere or in boxes with cast iron chips etc. Molten salt baths are also safe.

- **Quenching Cracks:** These may be external or internal, longitudinal or arc like, but are zig-zag in overall appearance. These are caused by the internal stresses due to volume changes during martensite transformation. This defect can not be corrected. It can be prevented by avoiding sharp corners and sudden changes in cross sections.
- **Deformation and Warping:** Symmetrical or asymmetrical deformation of an article is caused due to volume changes in cooling, non-uniform heating or cooling and wrong quenching techniques. To prevent this, the articles may be annealed or normalized before hardening. Heating should be at low slow rate and cooling as slow as feasible.

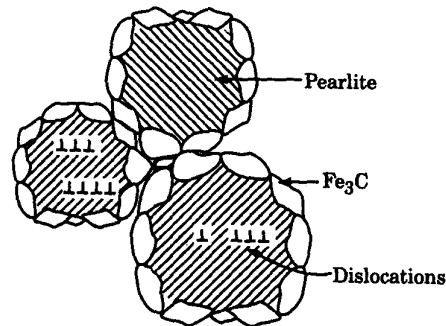
ANNEALING

Full Annealing

The term full annealing is used for the treatment that involves heating a steel to its austenitic state before subjecting it to very slow cooling. For carbon steels with less than about 0.8 per cent carbon the temperature to which the steel is heated for its microstructure to become austenitic is about 40°C above the A_3 temperature. The result of such a treatment is a microstructure of ferrite and pearlite. Figure (a) shows the relevant austenitizing temperature region on the iron-carbon diagram and figure (b), the temperature-time relationship for the process with reference to the continuous cooling transformation curve.



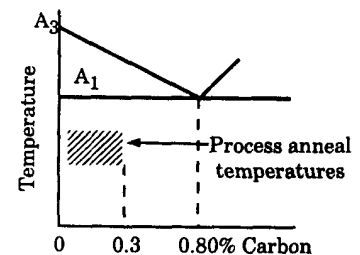
For a carbon steel with more than 0.8 per cent carbon, the steel is heated to about 40°C above the A_1 temperature before being slowly cooled. The result of such a treatment is to produce a microstructure of austenite plus cementite at the temperature just above A_1 . After cooling, the structure is pearlite plus excess cementite in dispersed *spheroidal* form. The overall result is a soft steel. The reason for not heating this steel to above the A_3 temperature is that slow cooling of such a steel results in a network of cementite surrounding pearlite (See Figure). This has the effect of making the steel relatively brittle.



Full annealing is used to refine the grain of large steel castings and forgings to give improved ductility and strength.

Sub Critical Annealing (Process Annealing)

Sub-critical annealing, generally referred to as process annealing, is used often during cold-working processes with low- carbon steels, less than about 0.3 per cent carbon, where the material has to be made more ductile for the process to continue. The process involves heating the steel to a temperature just below the A_1 temperature, holding it at that temperature for a while and then allowing the material to cool in air. This is a faster rate of cooling than that employed with full annealing, where the material is cooled in the furnace. This process leads to no change in microstructure, no austenite being produced. The result is, however, a recrystallization.. Prior to this treatment the crystals may have been deformed by the cold working process, afterwards a new crystal structure occurs with no deformation. The effect of this treatment is to give a reduction in hardness and an increase in percentage elongation. Above figure shows the region of the iron-carbon diagram relevant to process annealing.



Spheroidizing Annealing

Spheroidizing is extensively used for high carbon (tool) steels to transform lamellar pearlite into granular type. This process is performed by heating the steel slightly above the critical point A_{c1} (730 to 770⁰C) with subsequent holding at this temperature followed by slow cooling, at a rate of 25 to 30⁰ C/hour, to 600⁰ C.

The annealing temperature should be slightly above A_{c1} . Heating to higher temperature will make granular cementite difficult to obtain and will facilitate the formation of lamellar pearlite.

Spheroidized steel has a lower hardness and tensile strength and a correspondingly higher relative elongation and reduction of area than steel subject to normal annealing.

Isothermal Annealing

In this operation, steel is heated as for ordinary annealing and then cooled comparatively rapidly (in air or by a blast in a furnace). The steel is held isothermally at this temperature during a certain period of time to provide for complete austenite decomposition. This is followed by comparatively rapid cooling.

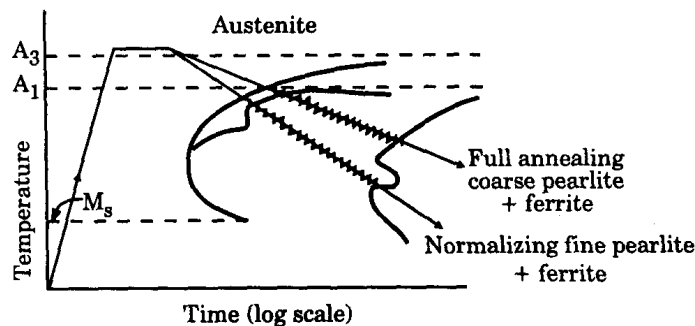
The main advantage of isothermal annealing is that it reduces the time required for heat treatment of the steel. This is especially true for alloyed steels which must be cooled very slowly to obtain the required reduction in hardness. Isothermal annealing produces good results in treating relatively small charges of rolled stock or small forgings.

Large forgings or charges of rolled stock have different cooling conditions on the surface and in the core so that the annealed structure will not be uniform when passing over to isothermal holding. Therefore, this type of annealing is not applied in such cases.

NORMALIZING

This is used as a finishing treatment for carbon steels giving higher strength than annealing. The normalizing of steel is carried out by heating about 40°C above the upper critical temperature (A_3) line followed by cooling in still air to room temperature. The result of such a treatment is a ferrite and pearlite microstructure, the hardness and strength being slightly greater than that which would have occurred with full annealing.

The purpose of normalizing is to produce a hard and stronger steel than full annealing, so that for some applications normalizing may be a final heat treatment. Normalizing may also be used to improve machinability and improve the response in hardening operations.



The increase in cooling rate due to air cooling as compared with furnace cooling affects the transformation of austenite. There will be less *proeutectoid* ferrite in normalized hypo eutectoid steels and less *pro eutectoid* cementite in *hypereutectoid* steels as compared with annealed ones. Since it was cementite network which reduced the strength of annealed hypereutectoid steels, normalized steels should show an increase in strength.

Apart from influencing the amount of *pro eutectoid* constituent that will form, the faster cooling rate in normalizing will also affect the temperature of austenite transformation and the fineness of pearlite. In general, the faster the cooling rate, the lower the temperature of austenite transformation and the finer the pearlite.

The advantages of this method are:

- In comparison to fully annealed material, normalizing produces stronger material.
- Normalizing refines the grains.
- Normalizing produces homogenized structure.
- Normalizing is used to improve properties of steel castings instead of hardening and tempering.
- Strength and hardness are increased.
- Better surface finish is obtained in machining.
- Resistance to brittle fracture is increased in hot-rolled steel.
- Crack propagation is checked.

SEVERITY OF QUENCHING

Severity of quench is a term often used to indicate the rate of cooling; the more rapid the quench, the more severe is the quench. Of the three most common quenching media - water, oil, and air - water produces the most severe quench, followed by oil, which is more effective than air.- The degree of agitation of each medium also influences the rate of heat removal. Increasing the velocity of the quenching medium across the specimen surface enhances the quenching effectiveness. Oil quenches are suitable for the heat treating of many alloy steels. In fact, for higher-carbon steels, a water quench is too severe because cracking and warping may be produced. Air cooling of austenitized plain carbon steels typically produces an almost completely pearlitic structure.

During the quenching of a steel specimen, heat energy must be transported to the surface before it can be dissipated into the quenching medium. As a consequence, the cooling rate within and throughout the interior of a steel structure varies with position and depends on the geometry and size.

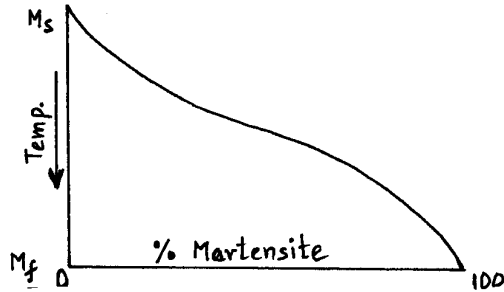
HARDENING

Under slow cooling rates, the carbon atoms are able to diffuse out of the austenite structure. The iron atoms then move slightly to become bcc(body centered cubic). This transformation takes place by a process of nucleation and growth and is time dependent. With a further increase in cooling rate, in sufficient time is allowed for the carbon to diffuse out of solution, and although some movements of the iron atoms take place, the structure can not become bcc while the carbon is trapped in solution. The resultant structure, called **martensite**, is a supersaturated solution of carbon trapped in a body- centered tetragonal structure. Two dimensions of the unit cell are equal, but the third is slightly expanded because of the trapped carbon. This highly distorted lattice structure is the prime reason for the high hardness of marten site.

Characteristics of Martensite Transformation

- The transformation is diffusion less.
- There is no change in chemical composition.
- The transformation proceeds only during cooling and ceases if cooling is interrupted. The amount of martensite formed with decreasing temperature is not linear. The number of martensite needles produced at first is small; then the number increases, and finally, near the end, it decreases again(Fig. below).
- The temperature of the start of martensite formation is known as the M_s temperature and that of the formation of martensite transformation is known as the M_f temperature. If the steel is held at any temperature below the M_s , the transformation to martensite will not proceed again unless the temperature is dropped.
- The martensite transformation of a given alloy can not be suppressed, nor can the M_s temperature be changed by changing the cooling rate. The temperature range of the formation of martensite is the characteristic of a given alloy and can not be lowered by increasing the cooling rate.
- Martensite is probably never in a condition of real equilibrium, although it may persist indefinitely at room temperature. The structure can be considered as a transition between stable austenite phase and the final equilibrium condition of a mixture of ferrite and cementite.
- The most significant property of martensite is its hardness. The high hardness of martensite is believed to be a result of the severe lattice distortions produced by its formation, since the amount of carbon present is many times more than can be held in solid solution. The maximum hardness obtainable from a steel in the martensite carbon seems to be a function of carbon content only.
- The martensitic transformation occurs without a compositional change. The transformation is a process of shear, that occurs without any need for diffusion. The atomic movements that bring about the transformation are only a fraction of an interatomic distance. The shear changes the *shape* of the transforming region. This results in a considerable amount of strain energy, due to the resistance of the matrix (parent phase) to the shape change. As a result of the strain energy factor, martensite has a **plate like shape**.

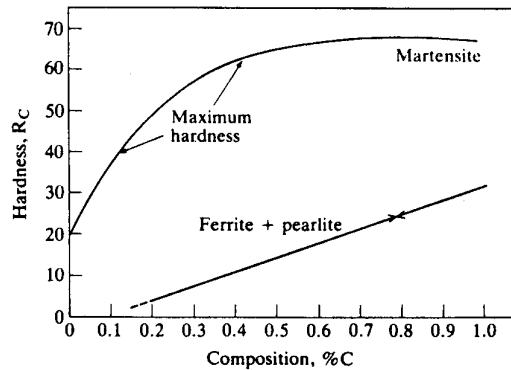
The basic purpose of hardening is to produce a fully martensitic structure, and the minimum cooling rate ($^{\circ}\text{C}$ per second) that will avoid the formation of any of the softer products of transformation is known as the critical cooling rate.



Hardenability of steels

Following figure shows the maximum possible *hardnesses* for increasing amounts of carbon in steels; these maximum hardnesses are obtained only when 100 percent martensite is formed.

A steel that transforms rapidly from austenite to ferrite plus carbide has low *harden ability* because ($\alpha + C$) is formed at the expense of the martensite. Conversely, a steel that transforms very slowly from austenite to ferrite plus carbide has greater hardenability. Hardnesses nearer the maximum can be developed with less severe quenching in a steel of high hardenability, and greater hardnesses can be developed at the center of a piece of steel even though the cooling rate is slower there.

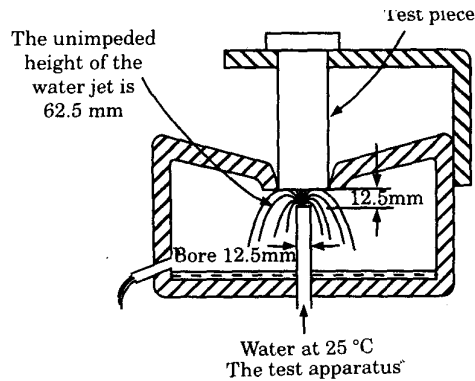


We may note that hardenability is not “hardness”, which is the resistance to indentation; rather, hardenability is a qualitative measure of the rate at which hardness drops off with distance into the interior of a specimen as a result of diminished martensite content

Hardenability Test – Jominy Test

The Jominy test involves heating a standard test piece of the steel to its austenitic state, fixing it in a vertical position and then quenching the lower end by means of a jet of water (See figure below). This method of quenching results in different rates of cooling along the length of the test piece. When the test piece is cool,

after the quenching, a flat portion is ground along one side of the test piece, about 0.4 mm deep, and hardness measurements made along the length of the test piece.



STRENGTHENING OF MATERIALS

Strain Hardening (Work Hardening)

When metals are cold worked, their strength and hardness increase. Annealed crystals have a dislocation density of about 10^8 m^{-2} . This can be increased to $10^{10} - 10^{12} \text{ m}^{-2}$ by moderate cold working and to $10^{14} - 10^{16} \text{ m}^{-2}$ by heavy cold working. As the dislocation density increases, the stress required to move any one dislocation increases due to the interfering effect of the stress fields of the surrounding dislocations. This phenomenon is the basis of work hardening and is described by means of the following equation:

$$\tau = \tau_0 + A\sqrt{\rho}$$

where τ is the stress to move a dislocation in a matrix of dislocation density ρ , τ_0 is the stress to move the dislocation in the same matrix with zero dislocation density and A is a constant.

Precipitation Hardening (Age Hardening)

Precipitation of a second phase from a supersaturated solid solution is in practice a very versatile and common strengthening technique. The supersaturated solution is obtained by sudden cooling from a sufficient high temperature. The heat treatment that causes precipitation of solute is called aging. The process can be applied to a number of alloy systems, although the specific behaviour varies. In general, the system must obey the following rules.

- Form a supersaturated solid solution at high temperatures.
- Reject a finely dispersed precipitate during aging (i.e., the phase diagram must show a decline solvus line.)

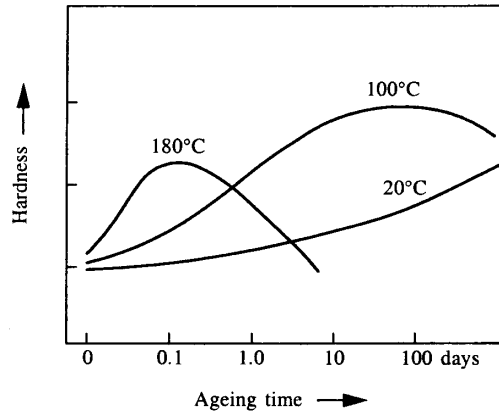
The precipitation treatment consists of the following steps

1. *Solubilization*: This involves heating of the alloy to the monophasic region and maintaining it there for a sufficiently long time to dissolve any soluble precipitates.

2. *Quenching*: This involves cooling very rapidly to room temperatures or lower so that the formation of stable precipitates is avoided. Thus, one obtain a supersaturated solution.

3. *Aging*: The treatment consists in leaving the material at room temperature or above, and it results in rather fine scale transition structures (= 10 mm)

Age curve for duralumin (an aluminium alloy) is shown below.



Hardness is a measure of the strength of the alloy. Obviously, the maximum hardness and strength is obtained only for the right combination of temperature and time. This combination is a function of the copper content and the other impurities in aluminium.

The increase in the hardness in the initial stages of the ageing curves can be attributed to the precipitation process taking place progressively. After reaching a peak value, the hardness starts to decrease. This phenomenon is called *overaging*. As the precipitate particles are very fine in size, they have a high surface to volume ratio. Therefore, they have a tendency to combine, that is, a number of small particles merge to form a large particle. For a given volume fraction of precipitate particles, the coarsening(combining) process decreases the total number of precipitate particles and increases the interparticle spacing. The hindrance to the dislocation motion is thereby reduced, accounting for the decrease in hardness beyond the peak in the curve. A temperature between 100 °C to 180 °C (see figure) would be the optimum ageing temperature, where the ageing time is not unduly large. An alloy aged to the optimum peak at such a temperature would not overage during service at room temperature.

If the precipitation occurs at normal ambient temperatures, it is called natural aging. Some alloy systems needed to be aged at higher temperatures and the process is known as artificial aging. Most precipitation hardened alloys are limited in their maximum service temperatures, which may lose their strength at elevated temperatures due to over-aging.

Detailed studies has shown that the supersaturated atoms of solute tend to accumulate along specific crystal planes. The concentration of solute atoms in these positions lowers the concentrations in other locations, producing less supersaturation and therefore a more stable crystal structure. At this stage, the solute atoms have

not formed a phase that is wholly distinct: a **coherency** of atom spacing exists across the boundary of the two structures. Dislocation movements proceed with difficulty across these distorted regions; consequently, the metal becomes harder and more resistant to deformation under high stresses.

Dispersion Strengthening

In dispersion strengthening, hard particles are mixed with matrix powder and consolidated and processed by powder metallurgy techniques. Here second phase shall have very little solubility in the matrix, even at elevated temperatures. Because there is very little solubility, the particles resist growth or over-aging to a much greater extent than the second phase particles in a precipitation hardening system. Theoretically, at least, it is possible to produce infinite number of dispersion-hardened systems by mixing finely divided metallic powders and second phase particles (oxides, carbides, nitrides, borides, etc).

Dislocations moving through the matrix, which is either precipitation hardened or dispersion strengthened, have two alternatives. They can either cut through the precipitate particles *or* bend around and bypass them. The first alternative is possible only when the slip plane is continuous from the matrix through the precipitate particle and when the stress to move a dislocation in precipitate is comparable to that in matrix. Cutting of particles is easier for small particles which can be considered as segregated solute atoms. There are many particle properties that can dictate the ease of shearing, for example: coherency strains, stacking-fault energy, ordered structure, modulus effect, interfacial energy, morphology and lattice friction stress.

Cutting of particles is not possible when there is an interface or an abrupt change in orientation. Under such instances, dislocations have to bend around them, and bypass.

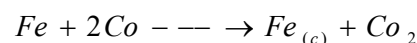
Case Hardening

It is also called *surface heat treatment*. It is meant for hardening the surfaces only. In case hardening, the core remains as soft as before. Numerous industrial applications require a hard wear resistant surface called the case and a relatively soft, tough inside called the core.

There are five principal methods of case hardening:

- Carburizing
- Nitriding
- Cyaniding or Carbonitriding
- Flame Hardening
- Induction hardening

Carburizing: This is the oldest and one of the cheapest methods of case hardening. A *low carbon steel*, usually about 0.20 % carbon or lower placed in an atmosphere that contains substantial amounts of carbon mono oxide. The usual carburizing temperature is 1700° F(750° C). At this temperature, the following reaction takes place:



Where $Fe_{(c)}$ represents carbon dissolved in austenite. Very quickly, a surface layer of high carbon (about 1.2%) is built up. At the surface is the hypereutectoid zone consisting of pearlite with a white cementite network, followed by eutectoid zone of only pearlite and finally the hypoeutectoid zone of pearlite and ferrite.

The carburizing equation given previously is reversible and may proceed to left, removing carbon from the surface layer if the steel is heated in an CO_2 rich environment. This is called decarburization. Decarburization may be prevented by using an endothermic gas atmosphere in the furnace to protect the surface of the steel from oxygen, carbon dioxide and water vapour.

Commercial carburizing may be accomplished by means of pack carburizing, gas carburizing, and liquid carburizing. In pack carburizing, the work is surrounded by a carburizing compound (charcoal + coal + 20% barium carbonate) in a closed container. The container is heated to the proper temperature for the required amount of time and the slow cooled. It is a method performed in batches. Gas carburizing may be either batch or continuous and gives a better surface heat treatment. The steel is heated with carbon mono oxide. Gas carburizing allows quicker handling by direct quenching, lower cost, cleaner surroundings, closer quality control, and greater flexibility of operation in comparison with pack carburizing. Liquid carburizing is a method of case hardening steel by placing it in a bath of molten cyanide so that carbon will diffuse from the bath into the metal and produce a case comparable to one resulting from pack or gas carburizing.

The advantages of liquid carburizing are following:

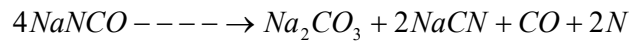
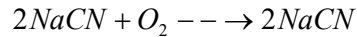
- Freedom from oxidation and sooting problems
- Uniform case depth and carbon content
- A rapid rate of penetration
- The that the bath provides high thermal conductivity, thereby reducing the time required for steel to reach the carburizing temperature.

Disadvantages are:

- Parts must be thoroughly washed after treatment to prevent rusting
- Regular checking and adjustment of the bath composition is necessary to obtain uniform case depth
- Some shapes can not be handled because they either float or will cause excessive drag out of salt
- Cyanide salts are poisonous and require careful attention to safety.

Cyaniding and Carbonitriding : Cases that contain both carbon and nitrogen are produced in liquid salt baths (cyaniding) or by use of gas atmosphere (carbonitriding). The temperatures used are generally lower than those used in carburizing, being between 1400° and 1600° F (760 to 870° C) exposure is for a shorter period, and thinner cases are produced. In cyaniding baths of higher sodium cyanide concentrations are employed, the most commonly used mixture is made up of 30% sodium cyanide, 40% sodium carbonate, and 30% sodium

chloride. This mixture has a melting point of 1140°F and remains quite stable under continuous operating conditions. Reactions are following:



Carburizing is a case hardening process in which a steel is heated in a gaseous atmosphere of such composition that carbon and nitrogen are absorbed simultaneously. The process is also known as *dry cyaniding*, gas cyaniding, and nitrating. A mixture of carrier gas, enriching gas, and ammonia. The carrier gas is a mixture of nitrogen, hydrogen and carbon mono oxide. The enriching gas is usually propane, and is primary source of carbon added to the surface. At the furnace temperature, the added ammonia breaks up to provide nitrogen to the surface of the steel.

Nitriding : This is a process of case hardening of alloy steel in an atmosphere consisting of a mixture in suitable proportions of ammonia gas and dissociated ammonia. The best results are obtained for those steels that contained one or more of major nitride forming alloying elements. These are aluminium, chromium, and molybdenum. The nitrogen must be supplied in the atomic or nascent form; molecular nitrogen will not react. Wear resistance and fatigue resistance are outstanding characteristics of the nitride case.

Carbonitriding. In this process, both carbon and nitrogen are diffused into the steel surface. The process is performed in a gaseous atmosphere in a furnace using propane gas and a small fraction of ammonia. Propane provides carbon and ammonia provides hardness of the order of 60-65 HRC, which can be obtained by carbonitriding. Low-carbon and low alloy steels are carbonitrided. For the reduction of brittleness, carbonitrided parts are tempered. Case depth of 0.2-0.25 mm is obtained on plain carbon steels.

Flame Hardening: The remaining two methods, flame hardening and induction hardening, do not change the chemical composition of the steel. They are essentially shallow hardening methods. In flame hardening, heat may be applied by a single oxyacetylene torch. Depth of the hardened zone may be controlled by an adjustment of flame intensity, heating time, or speed of travel.

Four methods are in general use for flame hardening

- stationery
- progressive
- Spinning
- progressive-spinning.

In the first both torch and work are stationery. In the progressive method, the torch moves over a stationary work piece. this is used for hardening of large parts. In the spinning method, the torch is stationery while the work rotates. This method is used to harden parts of circular cross section such as pulleys.

Induction Hardening: Induction hardening depends for its operation on localized heating produced by currents induced in a metal placed in a rapidly changing magnetic field. The operation resembles a transformer in which

the primary coil is composed of several turns of copper tubing, and the part to be hardened is made the secondary of a high frequency induction apparatus.

When high frequency A.C. passes through the work coil, a high frequency magnetic field is set up. This magnetic field induces high frequency eddy currents and hysteresis currents in the metal. Heating results from the resistance of the metal to passage to these currents.

The case obtained by induction hardening is similar to that obtained by flame hardening, and thinner cases are possible. Plain carbon steels of medium carbon content are used for most applications.

TEMPERING

In the quenched martensitic condition, the steel is too brittle for most applications. The formation of martensite also leaves high residual stresses in the steel. Therefore, hardening is always followed by tempering, which consists in heating the steel to some temperature below the lower critical temperature. The purpose of tempering is to relieve residual stresses and to improve the ductility and toughness of the steel.

Tempering releases the stresses and reduces the brittleness. Tempering causes the transformation of the martensite into less brittle structure, i.e., a fine pearlitic structure termed as *troostite*. Troostite is much tougher, although somewhat softer than martensite. Most c.s. cutting tools have this type of structure. Once the tempering temperature has been reached, it is normal to quench the steel. All structures resulting from tempering are termed **tempered martensite**.

The tempering range of 205 to 425°C is a dividing line between applications that require high hardness and those requiring high toughness. If the principal desired property is hardness, the part is tempered below 205 degree Celsius; if the primary requirement is toughness, the part is tempered above 425 degree Celsius.

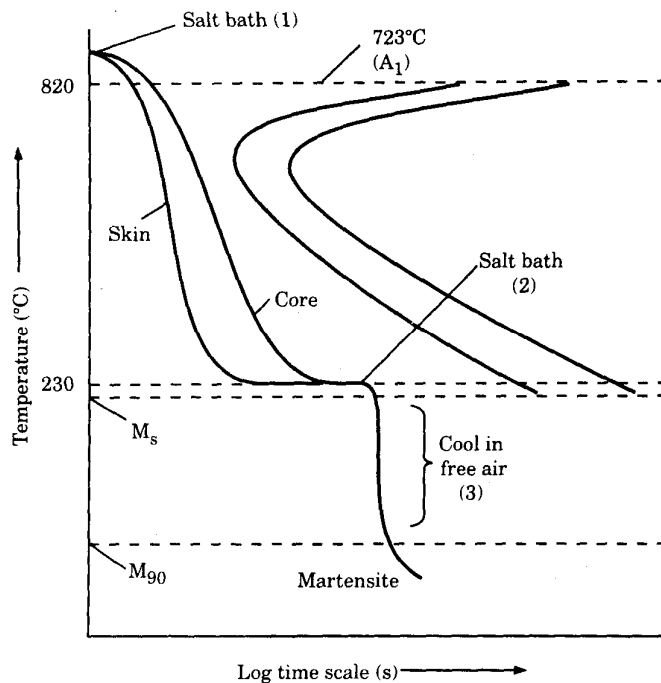
Martensite, as defined previously, is a super saturated solution of carbon trapped in a body centered tetragonal structure. This is a metastable condition, and as energy is applied by tempering, the carbon will be precipitated as carbide and the iron will become b.c.c. The precipitation of the transition carbide may cause a slight increase in hardness, particularly in high carbon steels. The steel has high strength, high hardness, low ductility, and low toughness, and many of the residual stresses are relieved (temp. range: 35 - 205°C).

Heating in the range of 225°C to 400°C changes low carbon martensite to bcc ferrite, and any retained austenite is transformed to lower bainite. The ductility has increased slightly, but the toughness is still low. Hardness is decreased.

Heating in the range from 650°C to 720°C produces large cementite particles. This structure is very soft and tough and is similar to the spheroidized cementite structure.

Martempering

In this process the steel is heated to its austenitized condition and then cooled in a bath maintained at a temperature a little above M_s . It is cooled for period enough to make its temperature uniform but not to start transformation to pearlite. It is then withdrawn and cooled in air at a rapid rate, producing martensitic structure.

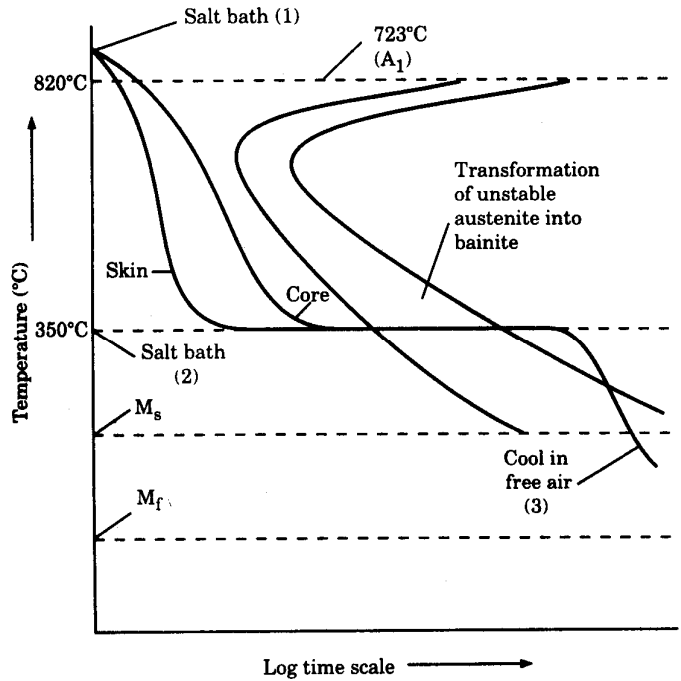


The martempering process

This martensite has lesser tendency to distortion and cracking as compared to conventional quench hardening. For better properties it may be tempered to a desired hardness. This process is better suited to alloy steels.

Austempering (Isothermal Quenching)

This is a heat treating process developed from the I-T diagram to obtain a structure which is 100% bainite. It is accomplished by first heating the part to the proper austenizing temperature followed by cooling rapidly in a salt bath held at a temperature above M_s i.e. in the bainite range (205°-425° C). The piece is left in the bath until the transformation to bainite is complete. The steel is caused to go directly from austenite to bainite, and at no time is it in the fully hardened martensitic state. Actually, austempering is a complete heat treatment, and no reheating is involved as in tempering.



The austempering process

Aside from the advantage of greater ductility and toughness along with high hardness as a result of austempering, there is also less distortion and danger of quenching cracks because the quench is not so drastic as that of the conventional method.

ASSIGNMENT

- Q.1. (AMIE S08, 10 marks):** What are the purposes of heat treatment? Draw and label Fe-Fe₃C phase diagram
- Q. 2. (AMIE S01):** Explain the different types of annealing treatments and their objectives.
- Q. 3. (AMIE W00, 6 marks):** Annealing produces softer material while normalizing produces stronger material - justify. During heat treatment, why hypo-eutectoid carbon steels are heated over AC₃, but hyper-eutectoid steels are heated over AC₁ only?
- Q. 4. (AMIE S00, 10 marks):** Describe following heat treatment processes:
- (i) full annealing (ii) normalizing (iii) quenching and tempering
- Q. 5. (AMIE S16, 17, W17, 6 marks):** What is tempering? Explain how it affects the properties of steel. What are its objectives?
- Q. 6. (AMIE W15, 6 marks):** Comparing different stages of tempering of plain carbon steel based on (i) main transformation (ii) change in volume (iii) change in hardness.
- Q. 7. (AMIE W14, 4 marks):** Explain why recrystallization annealing is preferred over full annealing in some cases.
- Q. 8. (AMIE S16, 8 marks):** In the annealing of materials, explain on recovery, recrystallization and grain growth.
- Q. 9. (AMIE S15, 4 marks):** What are the aims of stress relieving annealing?
- Answer: Stress relieving does not involve a change in the base metallurgical structure. After finish-machining a forging of a given hardness, stress relieving it will eliminate residual stresses in the forging that occur as a result of machining or welding, but will not reduce its strength or hardness: annealing it, however, will.
- Q. 10. (AMIE S01, 08, W01, 02, S00, W00):** Differentiate between annealing and normalizing. Discuss the purposes for which these treatments are done.
- Q. 11. (AMIE S06, 4 marks):** What do you mean by normalizing and tempering, and indicate how those heat treatments affect the properties of steel?
- Q. 12. (AMIE S05):** State the advantages of normalizing over annealing.
- Q. 13. (AMIE S09, 5 marks):** Discuss the heat transfer characteristics during normalising and its effect on mechanical properties.
- Q. 14. (AMIE S09, W12, 14, 6 marks):** Discuss the tempering process. What are main aims of tempering? Suggest whether tempering should be done at higher or lower temperature with reasons.
- Q. 15. (AMIE W09, 11, S01, 10, 13, 14, 17, 4 marks):** Distinguish between Martempering and Austempering
- Q. 16. (AMIE W00, 6 marks):** What is martempering? What are the effects of tempering on the mechanical properties of steel?
- Q. 17. (AMIE S02):** Explain the term martensitic transformation. Describe main features of martensitic transformations.
- Q. 18. (AMIE W06, 4 marks):** What are M_s and M_f temperatures? Discuss the factors that determine the temperatures.
- Q. 19. (AMIE W08, 6 marks):** How does tempering become different from martempering? What is M_s and M_f temperatures? Why is sub zero cooling applied in some tool steels?
- Q. 20. (AMIE W02):** Differentiate between martensite and pearlite.
- Q. 21. (AMIE W09, 4 marks):** State the difference between (i) martensite and tempered martensite (ii) upper bainite and lower bainite.
- Q. 22. (AMIE W06, 11, 12, 13, S10, 12, 13, 16, 4 marks):** Define hardness and hardenability, explaining their difference. Mention the factors which affect hardenability.
- Q. 23. (AMIE S05, 09, 4 marks):** What is hardenability? Why is it not so high in plain carbon steels?

- Q. 24. (AMIE W15, 6 marks):** Define hardenability. What is the severity of quench? What is its impact on hardenability?
- Q. 25. (AMIE S06, 7 marks):** What is the purpose of hardening of steel? State the theory of hardening of steel.
- Q. 26. (AMIE S06, 5 marks):** How is hardenability test carried out?
- Q. 27. (AMIE S11, 6 marks):** Define hardenability of metals. describe Jominy's hardenability test in brief.
- Q. 28. (AMIE S06, 7 marks):** When do you recommend for a case hardening process for an steel component? State the basic principles of case hardening.
- Q. 29. (AMIE S05):** What is tempering? Is it essential for high carbon steel after quenching?
- Q. 30. (AMIE S11, 6 marks):** Discuss different mechanisms of hardening in metals and alloys.
- Q. 31. (AMIE W11, 12, 13, 14, 15, S12, 13, 17, 6 marks):** What is age hardening? What are the basic requirements for an alloy to behave as age hardenable. Mention the steps in the process of age hardening.
- Q. 32. (AMIE W05, 6 marks):** Differentiate between age hardening and dispersion hardening, emphasizing on how dislocations interact with the second phase and suitability for application of the materials strengthened by those methods at high temperatures.
- Q. 33. (AMIE S09, 10, 5 marks):** What are the different stages of age hardening treatment for aluminium alloys?
- Q. 34. (AMIE S14, 5 marks):** What are the main requirements for an alloy to be age-hardenable? What are the driving force for age hardening?
- Q. 35. (AMIE S15, 10 marks):** Compare the following: (i) age hardening and tempering (ii) martempering and austempering
- Q. 36. (AMIE S06, 12, 16, W11, 12, 13, 4 marks):** Mention four strengthening mechanisms of metals and alloys, and explain any one of them.
- Q. 37. (AMIE S13, 6 marks):** How can metal alloys be strengthened?
- Q. 38. (AMIE S06, 5 marks):** Discuss the mechanism of age hardening of Al alloys.
- Q. 39. (AMIE W06, 08, 4 marks):** What is strain hardening (work hardening)? Name one application where it is advantageous and one example where it is problematic.
- Q. 40. (AMIE W11, 12, 13, S13, 17, 9 marks):** Briefly explain the following surface hardening treatments (i) carburizing (ii) nitriding (iii) carbonitriding.
- Q. 41. (AMIE S12, W 17, 5 marks):** Discuss the following case hardening methods (i) nitriding (ii) cyaniding
- Q. 42. (AMIE S14, 5 marks):** Define carbonitriding. What are the advantages of carbonitriding over carburizing?
- Q. 43. (AMIE S10, 7 marks):** Describe different methods of carburizing.
- Q. 44. (AMIE W08, 4 marks):** Describe a method of carburizing of low carbon steels.
- Q. 45. (AMIE S06, 5 marks):** Discuss the nitriding process.
- Q. 46. (AMIE S11, 8 marks):** Discuss different methods of carburizing, nitriding, and carbonitriding.
- Q. 47. (AMIE W14, 15, 6 marks):** Compare (i) gas carburizing and carbonitriding (ii) flame and induction hardening.
- Q. 48. (AMIE S15, 6 marks):** Define cyaniding. What are the aims of cyaniding?
- Q. 49. (AMIE W09, 4 marks):** On quenching, high carbon steel get hardened but austenitic stainless steel do not - explain.
- Q. 50. (AMIE S14, 4 marks):** What is the severity of quench? What is its impact on hardenability?
- Q. 51. (AMIE W09, 6 marks):** Without phase change can you harden a metal? Give two common examples.

Q. 52. (AMIE W09, 4 marks): For better hardenability, alloy steels are favoured over plain carbon steels - explain.

Q. 53. (AMIE W16, 5 marks): Justify with reason whether ball bearing should be oil hardened or water quenched.

Answer: The faster the cooling rate the higher the hardness (in steels). Water-quenched steels will generally be harder than oil-quenched steels. This is mainly because the thermal conductivity of water is higher than the thermal conductivity of most oils; consequently, the rates of cooling will be less rapid (or lower) in oils compared with water.

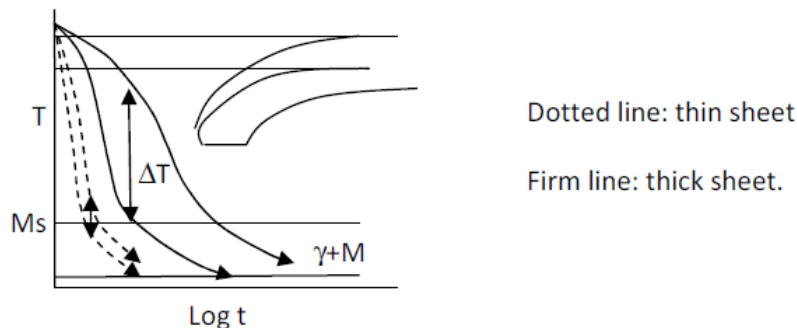
Q. 54. (AMIE W16, 6 marks): A piece of steel which was quenched after prolonged holding at 700°C was found to have ferrite martensite structure. Explain when would you expect this to happen?

Answer: Eutectoid temperature of steel is a function of its composition. For plain carbon steel it is around 720°C. To get martensite the steel should be heated beyond this temperature. However presence of alloying elements which stabilize austenite (such as Mn, Ni) can bring down eutectoid temperature. In this case steel must be an alloy steel whose eutectoid temperature is less than 700°C. Therefore it must have been quenched from ferrite – austenite region and the austenite on quenching got transformed to martensite resulting in a ferrite – martensite structure.

Q. 55. (AMIE W16, 6 marks): Explain why thicker sections are more susceptible to cracking during hardening heat treatment.

Answer: The difference in cooling rate between the centre and the surface is much more in a thicker section. As soon as the temperature at the surface crosses M_s temperature, martensite forms accompanied by volume expansion. The core is still soft austenite and can accommodate deformation if required. However later when its temperature goes below M_s it would expand, when outer core which is already transformed is hard and cannot accommodate deformation. A tensile stress therefore develops at the surface and it becomes prone to cracking. If thickness is less the difference in temperature is not large. Transformation takes place almost simultaneously with little chance of developing high tensile stress at the surface.

The following sketch illustrates this.



Q. 56. (AMIE W16, 4 marks): Hardness of a quenched and tempered steel is reported to be RC 35. What additional test will you recommend to know that it has indeed been given this heat treatment?

Answer: Examine its microstructure to see if it has tempered martensitic structure. Fine pearlite can also give similar hardness.

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