

Chapter 3

Heat Treatment of Steels

Heat treatment may be defined as ‘an operation or combination of operations of heating and cooling of a metal or an alloy in the solid state for obtaining certain desirable conditions or properties’. Heating and cooling for the sole purpose- mechanical working (e.g., hot rolling) is excluded from the meaning of this definition.

The main objective of heat treatment processes for steel are:

1. to increase strength, toughness, hardness and ductility;
2. to soften steel;
3. to relieve internal stresses and strains;
4. to refine the grain;
5. to normalize steel which has already been subjected to mechanical or heat treatment operation.

In general, the properties of high carbon steels are altered by heat treatment to a much greater extent than those of low carbon steels. The reason is that changes in properties are mostly brought about by changes in the form and distribution of carbon, which is obviously low in low carbon steels.

The changes in the properties of steel after heat treatment are due to the phase transformations and structural changes that occur during the heat treatment. The factors which determine and control these structural changes are called principles of heat treatment. The important principles of heat treatment are as follows:

1. Phase transformations during heating.
2. Effect of cooling rate on structural changes during cooling.
3. Effect of carbon content and alloying elements.

3.1 Phase Transformations in Steel during Heating

Before heating, microstructure of steel consists of ferrite, pearlite and carbides in widely different amounts depending upon the carbon content and alloying elements in the steel. During heating the first structural change in steel begins when its temperature reaches lower critical temperature, A_{c1} . At this temperature pearlite changes into austenite. The phase transformation occurs by nucleation of austenite phase at the interfaces between the ferrite and carbide (cementite) crystals. The rate of

nucleation increases with increase in the ferrite-cementite interfacial area. As the temperature increased, more and more ferrite and cementite are dissolved in austenite and the structure becomes completely austenitic after reaching the upper critical temperature. The formation of homogeneous austenite occurs after holding the steel at this temperature. The formation of homogeneous austenite is dependent upon the time and temperature of heatings.

The formation of homogeneous austenite takes place in four stages:

1. Nucleation of austenite from pearlite;
2. Transformation of ferrite and cementite;
3. dissolution of carbides and
4. the formation of homogeneous austenite

3.2 Transformation of Austenite during cooling

After the formation of homogeneous austenite, the steel is allowed to cool. Depending upon the rate of cooling, austenite can be made to transform, to different phases. Ferrite, pearlite and cementite are obtained during slow cooling, while bainite and martensite are formed when steel is cooled rapidly.

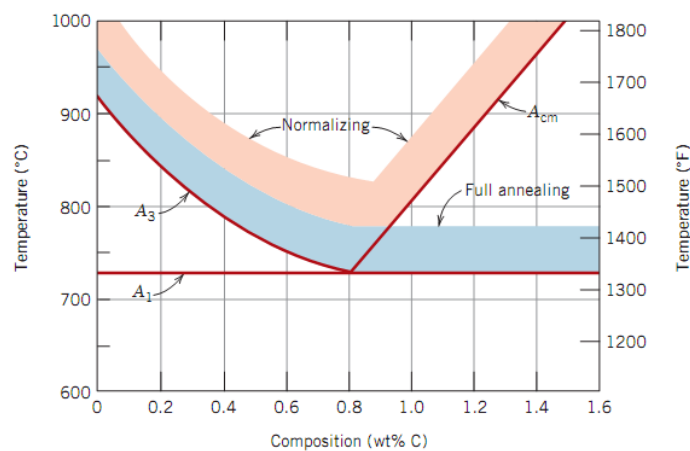


Figure 3.1 the iron–iron carbide phase diagram in the vicinity of the eutectoid, indicating heat-treating temperature ranges for plain carbon steels.

Different types of heat treatment procedures are employed to enhance the properties of steel alloys. However, before they are discussed, some comment relative to the labeling of phase boundaries is necessary. Figure 3.1 shows the portion of the iron–iron carbide phase diagram in the vicinity of the eutectoid. The horizontal line at the eutectoid temperature, conventionally labeled A₁, is termed the lower critical temperature, below which, under equilibrium

conditions, all austenite will have transformed into ferrite and cementite phases when slow cooling is applied, Martensite and retained austenite when rapid cooling is applied. The phase boundaries denoted as A_3 and A_{cm} represent the upper critical temperature lines, for hypo-eutectoid and hypereutectoid steels, respectively. For temperatures and compositions above these boundaries, only the austenite phase will prevail.

Heat treatment process

A heat treatment process consists of the following steps:

- i) The steel is heated to a high temperature called austenitizing temperature. During heating, the previous structure of steel is converted into austenite phase.
- ii) After reaching the austenitic temperature, steel is held at this temperature for some period of time, called the soaking period. Soaking results in the formation of homogeneous austenite throughout the entire cross section.
- iii) Steel having a homogeneous austenite structure is cooled back to room temperature, at a particular cooling rate depending upon the properties required.
- iv) if necessary, steel may be reheated to a higher temperature (lower critical temperature) and cooled again.

The above sequence of heating and cooling may vary from a most simple form of heating in a closed furnace and cooling in the air to a more complex form which requires preheating, soaking in a controlled atmosphere and two-step cooling. Depending upon the method of heating, the furnace atmosphere, the heating temperature, the cooling medium used, and the properties desired, heat treatment processes may be divided into following basic types:

1. Annealing;
2. Normalizing
3. Hardening
4. Tempering

The basic types of heat treatments are widely used in industry depending upon the properties required. Details of these processes, their purposes, phase transformations and the resulting properties shall be discussed in the following sections.

3.3.1 Annealing Process

The term annealing refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Ordinarily, annealing is carried out to:

- (1) relieve stresses;
- (2) increase softness, ductility, and toughness; and/or
- (3) produce a specific microstructure.

A variety of annealing heat treatments are possible; they are characterized by the changes that are induced, which many times are micro-structural and are responsible for the alteration of the mechanical properties.

Any annealing process consists of three stages:

- (1) Heating to the desired temperature,
- (2) Holding or “soaking” at that temperature, and
- (3) Cooling, usually to room temperature.

Time is an important parameter in these procedures. During heating and cooling, there exist temperature gradients between the outside and interior portions of the piece; their magnitudes depend on the size and geometry of the piece. If the rate of temperature change is too great, temperature gradients and internal stresses may be induced that may lead to warping or even cracking. Also, the actual annealing time must be long enough to allow for any necessary transformation reactions.

Annealing temperature is also an important consideration; annealing may be accelerated by increasing the temperature, since diffusional processes are normally involved.

Process annealing is a heat treatment that is used to negate the effects of cold work that is, to soften and increase the ductility of a previously strain-hardened metal. It is commonly utilized during fabrication procedures that require extensive plastic deformation, to allow a continuation of deformation without fracture or excessive energy consumption. Recovery and recrystallization processes are allowed to occur. Ordinarily a fine-grained microstructure is desired, and therefore, the heat treatment is terminated before appreciable grain growth has occurred. Surface oxidation or scaling may be prevented or minimized by annealing at a relatively low temperature (but above the recrystallization temperature) or in a non-oxidizing atmosphere.

Stress Relief

Internal residual stresses may develop in metal pieces in response to the following:

- (1) plastic deformation processes such as machining and grinding;
- (2) non-uniform cooling of a piece that was processed or fabricated at an elevated temperature, such as a weld or a casting; and
- (3) a phase transformation that is induced upon cooling wherein parent and product phases have different densities.

Distortion and warpage may result if these residual stresses are not removed. They may be eliminated by a stress relief annealing heat treatment in which the piece is heated to the recommended temperature, held there long enough to attain a uniform temperature, and finally cooled to room temperature in air. The annealing temperature is ordinarily a relatively low one such that effects resulting from cold working and other heat treatments are not affected.

Normalizing

Steels that have been plastically deformed by, for example, a rolling operation, consist of grains of pearlite (and most likely a proeutectoid phase), which are irregularly shaped and relatively large, but vary substantially in size. An annealing heat treatment called normalizing is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse-grained ones. Normalizing is accomplished by heating at least 55°C above the upper critical temperature for hypo-eutectoid and hyper-eutectoid compositions (less than 0.77%C and greater than 0.77%C respectively). After sufficient time has been allowed for the alloy to completely transform to austenite a procedure termed austenitizing the treatment is terminated by cooling in air.

A heat treatment known as *full annealing* is often utilized in low and medium carbon steels that will be machined or will experience extensive plastic deformation during a forming operation. In general, the alloy is treated by heating to a temperature of about 50°C above the upper critical line (to form austenite) for compositions less than the eutectoid, or, for compositions in excess of the eutectoid. The alloy is then furnace cooled; that is, the heat treating furnace is turned off and both furnace and steel cool to room temperature at the same rate, which takes several hours.

The micro-structural product of this anneal is coarse pearlite (in addition to any pro-eutectoid phase) that is relatively soft and ductile. The full anneal cooling procedure is time consuming; however, a microstructure having small grains and a uniform grain structure results.

Spheroidizing

Medium and high carbon steels having a microstructure containing even coarse pearlite may still be too hard to conveniently machine or plastically deform. These steels, and in fact any steel, may be heat treated or annealed to develop the spheroidite structure. Spheroidized steels have a maximum softness and ductility and are easily machined or deformed. The spheroidizing heat treatment, during which there is a coalescence of the Fe_3C to form the spheroid particles, can take place by several methods, as follows:

- Heating the alloy at a temperature just below the eutectoid in the region of the phase diagram.
- Heating to a temperature just above the eutectoid temperature, and then either cooling very slowly in the furnace, or holding at a temperature just below the eutectoid temperature.
- Heating and cooling alternately within about $\pm 50^\circ\text{C}$ of the line of Figure 3.1.

To some degree, the rate at which spheroidite forms depends on prior microstructure. For example, it is slowest for pearlite, and the finer the pearlite, the more rapid the rate. Also, prior cold work increases the spheroidizing reaction rate.

3.3.2 Hardening of Steel

Hardening of steel is done to increase the strength and wear resistance of steel. It is done for most applications that require the steels to be used as tools to work other materials such as drill bits, forming tools, saw blades, lathe cutters, etc. One of the pre-requisites for hardening is sufficient carbon and alloy content.

Hardening may also be required for an application for which high strength is required such as springs. Some times steels are hardened to improve a physical property such as coefficient of thermal expansion or some magnetic property.

Conventional heat treatment procedures for producing martensitic steels ordinarily involve continuous and rapid cooling of an austenitized specimen in some type of quenching medium, such as water, oil, or air. The optimum properties of steel that has been quenched and then tempered can be realized only if, during the quenching heat treatment, the specimen has been converted to a high content of martensite; the formation of any pearlite and/or bainite will result in other than the best combination of mechanical characteristics. During the quenching treatment, it is impossible to cool the specimen at a uniform rate throughout the surface with all always cool more rapidly than interior regions. Therefore, the austenite will transform over a range of temperatures, yielding a possible variation of microstructure and properties with position within a specimen.

The successful heat treating of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors:

1. the composition of the alloy,
2. the type and character of the quenching medium, and
3. the size and shape of the specimen.

Successful hardening of steel requires two conditions to be met.

1. the formation of homogeneous austenite
2. rapid cooling of austenite which will result in the transformation of martensite.

Hardenability

“Hardenability” is a term that is used to describe the ability of an alloy to be hardened by the formation of martensite as a result of a given heat treatment. 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. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but to a large degree throughout the entire interior. One standard procedure that is widely utilized to determine hardenability is the Jominy end-quench test.

The Jominy End-Quench Test

With this procedure, except for alloy composition, all factors that may influence the depth to which a piece hardens (i.e., specimen size and shape, and quenching treatment) are maintained constant. A cylindrical specimen 25.4 mm (1.0 in.) in diameter and 100 mm (4 in.) long is austenitized at a prescribed temperature for a prescribed time. After removal from the furnace, it is quickly mounted in a fixture as diagrammed in Fig. 3.2a. The lower end is quenched by a jet of water of specified flow rate and temperature. Thus, the cooling rate is a maximum at the quenched end and diminishes with position from this point along the length of the specimen. After the piece has cooled to room temperature, shallow flats 0.4 mm (0.015 in.) deep are ground along the specimen length and Rockwell hardness measurements are made for the first 50 mm (2 in.) along each flat (Figure 3.2b); for the first 12.8 mm, hardness readings are taken at 1.6 mm intervals, and for the remaining 38.4 mm (in.), every 3.2 mm (in.). A hardenability curve is produced when hardness is plotted as a function of position from the quenched end.

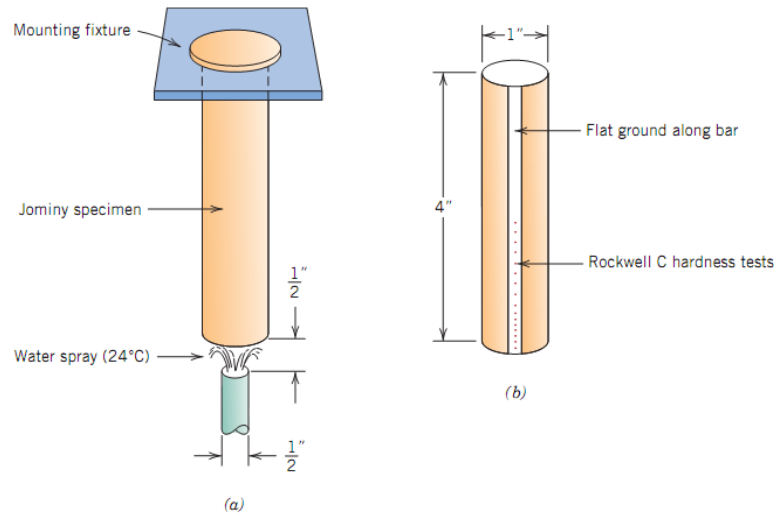


Figure 3.2. Schematic diagram of Jominy end quench specimen (a) mounted during quenching and (b) after hardness testing from the quenched end along a ground flat.

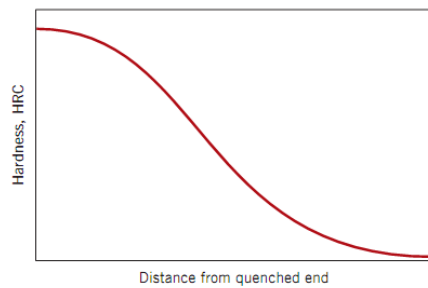


Figure 3.3. Typical hardenability plot of Rockwell C hardness as a function of distance from the quenched end.

A typical hardenability curve is represented in Figure 3.3. The quenched end is cooled most rapidly and exhibits the maximum hardness; 100% martensite is the product at this position for most steels. Cooling rate decreases with distance from the quenched end, and the hardness also decreases, as indicated in the figure. With diminishing cooling rate more time is allowed for carbon diffusion and the formation of a greater proportion of the softer pearlite, which may be mixed with martensite and bainite. Thus, a steel that is highly hardenable will retain large hardness values for relatively long distances; a low hardenable one will not. Also, each steel alloy has its own unique hardenability curve.

Sometimes, it is convenient to relate hardness to a cooling rate rather than to the location from the quenched end of a standard Jominy specimen. Cooling rate taken at 700°C is ordinarily

shown on the upper horizontal axis of a hardenability diagram; this scale is included with the hardenability plots presented here.

This correlation between position and cooling rate is the same for plain carbon and many alloy steels because the rate of heat transfer is nearly independent of composition. On occasion, cooling rate or position from the quenched end is specified in terms of Jominy distance, one Jominy distance unit being 1.6 mm.

A correlation may be drawn between position along the Jominy specimen and continuous cooling transformations. For example, Figure 3.4 is a continuous cooling transformation diagram for a eutectoid iron–carbon alloy onto which are superimposed the cooling curves at four different Jominy positions, and corresponding microstructures that result for each. The hardenability curve for this alloy is also included.

Significance of hardenability

From the heat treatment point of view, hardenability is a very important property. The significant properties of hardenability are:

- i) It determines the cooling rate, or the quenching medium which should be used for quenching a given sample of steel. Lower the severity of the quenching medium, lesser would be the distortion and cracking of the part.
- ii) Hardenability tells about the maximum hardness possible on the surface and below the surface for the given composition and size of the steel sample by quenching in different media. There fore steel selection for strength is usually made on the basis of hardenability.
- iii) Hardenability determines how the distribution and depth of hardness will vary with the change in the size of the sample.
- iv) Hardenabilty calculations can be used to predict the formation of compressive and residual stresses after quenching in load bearing and fatigue resistance steels.
- v) Hardenability greatly affects the cracking tendency after welding of steel components.

Factors affecting hardenability

Hardenability is dependent largely upon the amount of alloying elements present in the steel. However to some extent it is affected by the following factors:

1. the mean composition of austenite

2. the homogeneity of austenite
3. the grain size of the austenite
4. the mean metallic inclusions in the austenite
5. the undissolved carbides and nitrides in the austenite

Influence of Quenching Medium, Specimen Size, and Geometry

The preceding treatment of hardenability discussed the influence of cooling or quenching rate on the hardness. The cooling rate of a specimen depends on the rate of heat energy extraction, which is a function of the characteristics of the quenching medium in contact with the specimen surface, as well as the specimen size and geometry.

“Severity of quench” is a term often used to indicate the rate of cooling; the more rapid the quench, the more severe 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 ordinarily produces an almost totally pearlitic structure.

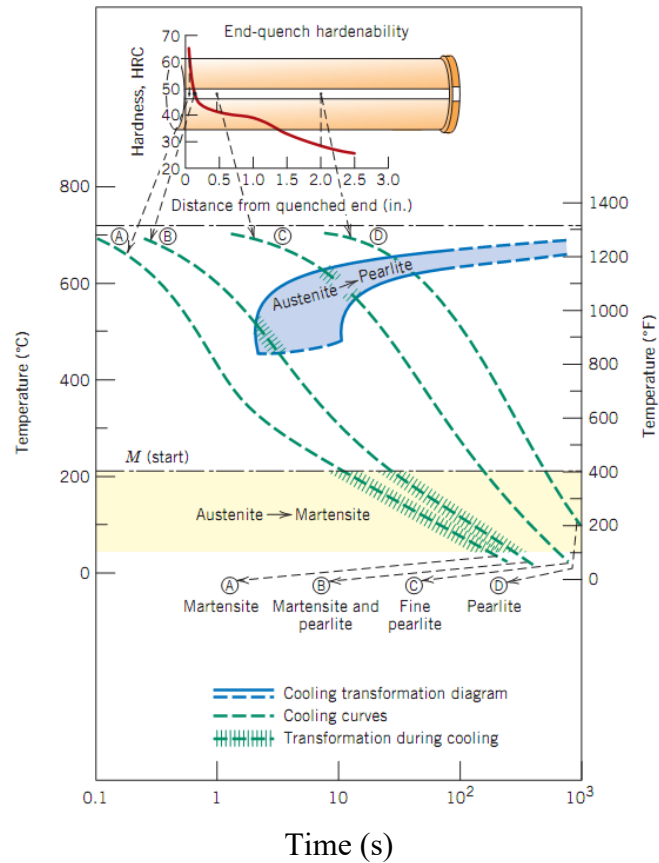


Figure 3.4 Correlation of hardenability and continuous cooling information for an iron carbon alloy of eutectoid composition.

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. Figures 3.5 a and b show the quenching rate at 700°C as a function of diameter for cylindrical bars at four radial positions (surface, three-quarters radius, midradius, and center). Quenching is in mildly agitated water Figure 3.5 a and oil Figure 3.5 b; cooling rate is also expressed as equivalent Jominy distance, since these data are often used in conjunction with hardenability curves. Diagrams similar to those in Figure 11.17 have also been generated for

geometries other than cylindrical (e.g., flat plates).

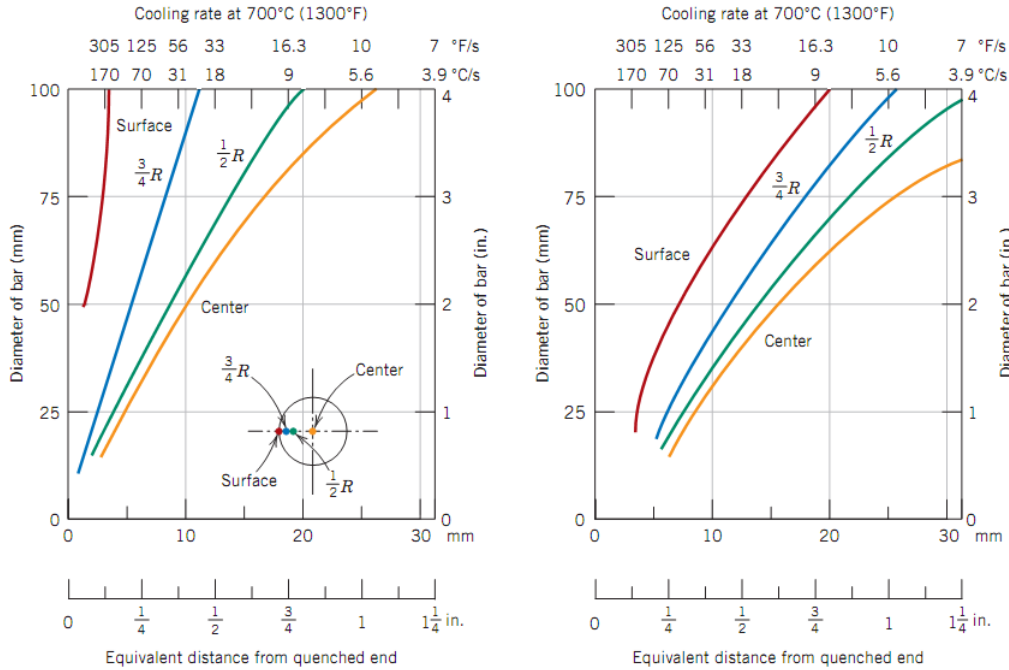


Figure 3.5 Cooling rate as a function of diameter at surface, three-quarters radius, midradius, and center positions for cylindrical bars quenched in mildly agitated (a) water and (b) oil. Equivalent Jominy positions are included along the bottom axes.

One utility of such diagrams is in the prediction of the hardness traverse along the cross section of a specimen. For example, Figure 3.6 a compares the radial hardness distributions for cylindrical plain carbon (1040) and alloy (4140) steel specimens; both have a diameter of 50 mm (2 in.) and are water quenched. The difference in hardenability is evident from these two profiles. Specimen diameter also influences the hardness distribution, as demonstrated in Figure 3.6 b, which plots the hardness profiles for oil-quenched 4140 cylinders 50 and 75 mm in diameter.

As far as specimen shape is concerned, since the heat energy is dissipated to the quenching medium at the specimen surface, the rate of cooling for a particular quenching treatment depends on the ratio of surface area to the mass of the specimen. The larger this ratio, the more rapid will be the cooling rate and, consequently, the deeper the hardening effect. Irregular shapes with edges and corners have larger surface-to-mass ratios than regular and rounded shapes (e.g., spheres and cylinders) and are thus more amenable to hardening by quenching.

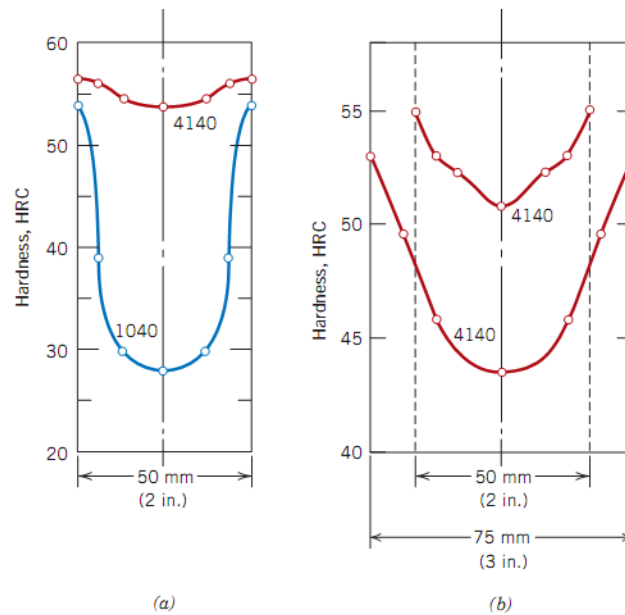


Figure 3.6 Radial hardness profiles for (a) 50 mm diameter cylindrical 1040 and 4140 steel specimens quenched in mildly agitated water, and (b) 50 and 75 mm diameter cylindrical specimens of 4140 steel quenched in mildly agitated oil.

3.4. Tempering of Steel

Structure of steel obtained after hardening is not suitable for engineering applications. It possesses the following drawbacks.

- i) martensite obtained after hardening is extremely brittle and will result in failure of engineering components by cracking.
- ii) Formation of martensite from austenite by quenching produces high internal stresses in the hardened steel. Existence of these high internal stresses in an engineering component is undesirable because it can result in heavy distortion and cracking of the part during service.
- iii) Structure obtained after hardening consists of martensite and retained austenite. Both these phases are metastable and will change to stable phases with time. Subsequent transformation of these unstable phases to more stable phases results in change in dimension and properties of the steel, which may be undesirable for many engineering applications.

Therefore, structure of hardened steel should be improved by applying tempering heat treatment process to take care of the above drawbacks. Tempering is achieved by heating previously hardened

steel to a temperature below the lower critical temperature and cooling back to room temperature. All hardened steels must be tempered immediately after hardening.

Tempering temperature for a hardened steel can vary from 100⁰C to 680⁰C depending upon the requirements. Tool steels are generally tempered at low temperatures to give high hardness and wear resistance. Low alloy constructional steels are tempered above 400⁰C to get a good combination of strength and ductility. Spring steels are tempered between 300 to 400⁰C to get the desired properties.

3.4.1 Changes occurring during tempering

Tempering process produces some changes in the structure and properties of steel. These changes are as follows:

1. *Relief of internal stresses*: Hardening process produces internal stresses in the steel due to the following two reasons.
 - i) An increase in volume of the specimen due to transformation of austenite to martensite. The resulting stresses are called structural stresses.
 - ii) A rapid decrease in the temperature of the specimen, causing what is known as thermal stresses.

These internal stresses in hardened steel may be decreased (relieved) by heating the steel. Heating upto 250⁰C relieves most of these stresses.

2. *Formation of stable phases*: Microstructural phases such as, martensite and retained austenite, formed after hardening, are not stable phases. They change or transform with time to other stable phases. This transformation is undesirable, because it results in changes in dimensions and physical and mechanical properties of the steel. During tempering unstable martensite changes to tempered martensite and then ferrite-carbide mixture, and retained austenite changes to bainite and to fine mixture of ferrite and carbide.
3. *Increase in toughness*: Ductility and toughness of hardened steel can be increased by tempering at successively higher temperatures. Increased ductility and toughness are obtained due to formation of tempered martensite, ferrite, and at high temperatures, coarsening and spheroidization of carbides.

Defects of heat treatment

When a component fails to achieve the expected results due to an error on the part of the heat treater or non- functioning of heat treating equipment, it is called a heat treatment defect. Common types of defect encountered in the heat treatment of steel are as follows:

- i) *lower hardness strength after hardening*: It is due to lower hardening temperature, insufficient soaking time, delayed quenching, higher tempering temperature and decarburization.
- ii) *Overheating*: during over heating, grain growth occurs, and consequently a coarse grain structure is obtained. Such a coarse grained structure will have poor mechanical properties, such as low toughness, ductility and impact strength. Prolonged heating at higher temperature results in decarburization and excessive scaling of steel. Excessive over heating will make the steel very brittle.
- iii) *Soft spots*: it is the variation in hardness on the surface of hardened steel. It could be related to heat treating equipment and the skill of the operator.
- iv) *Oxidation and decarburization*: oxidation results in the formation of thick layer of scale on the surface of the steel. The scale peels off and decreases the dimensions of the part. Decarburization is a function of time and temperature. It decreases the carbon content on the surface of the steel.
- v) *Distortion and warping*: distortion refers to dimensional changes of the part after hardening, while warping refers to asymmetrical changes in shape after heat treatment. Slow heating and slow cooling are very important to prevent distortion and warping.
- vi) *Quench cracking*: is fine crack on the surface of the steel. This is the most serious defect in heat treatment because the defect cannot be corrected and the component becomes a scrap. Quench crack may be developed due to rapid heating, overheating, fast quenching, delayed tempering, faulty design of the tool component, presence of holes in dies, etc.