

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical background

2.1.1 Hardenable Carbon Steels

Because of their versatility and low cost, carbon steels have wider use than any other metal. There are many reasons why the carbon steels prove satisfactory on reappraisal. Firstly, their hardenability is adequate for many parts, and for some parts shallower hardening is actually an advantage because of minimized quench cracking. Secondly, refinements in heat treating methods, such as induction hardening, make it impossible to gain higher properties from carbon steels than previously. Also new compositions are added to the carbon steel permitting more discriminating selection.

Carbon steels can be grouped into three arbitrary classifications based on carbon content, that are:

1. Steels with 0.10 to 0.25% C
2. Steels with 0.25 to 0.55% C
3. Steels with 0.55 to 1.00% C

2.1.1.1 Steels with 0.25 to 0.55% C

These kinds of steels are normally used in the hardened and tempered condition because a wide range of mechanical properties can be produced by selection of quenching medium and tempering temperature. There are the most versatile of the three groups of carbon steels and are most commonly used for shafts, couplings, tie rods and various machinery parts.

There is a continuous change from water hardening to oil hardening types in this group of steels. The hardenability is very sensitive to changes in chemical composition, particularly to the content of manganese, silicon and residual elements, and to grain size; and the steels are sensitive to section changes.

The rate of heating parts for quenching has an effect on hardenability under certain conditions. If the structure is nonuniform, as a result of severe handling or lack of

proper normalizing or annealing, extremely rapid heating, such as may be obtained in liquid baths, will not allow sufficient time for diffusion of carbon and other elements in the austenite. As a result, nonuniform or low hardness will be produced unless the duration of heating is extended. In heating the steels containing free carbide, sufficient time have to be allowed for the solution of the carbides; otherwise the austenite at the time of quenching will have a lower carbon content than is represented by the chemical composition of the steel, and disappointing results may be produced deliberately.

These medium-carbon steels should usually be either normalized or annealed before hardening, in order to gain the best mechanical properties after hardening and tempering. Parts that are made from bar stock are frequently given no treatment prior to hardening, but it is common practice to normalize or anneal forgings.

These medium-carbon steels are widely used for machinery parts for moderate duty. When such parts are to be machined after heat treatment, the maximum hardness is usually held to 321 Bhn, and is frequently much lower. (Prabhudev, 1988)

Water is the quenching medium most commonly used because it is the cheapest and easiest to install. Caustic soda solution (5 to 10% NaOH by weight) is used in many instances with improved results. Compared with water, it is faster and more thorough and more uniform quench, producing better mechanical properties in all but light sections. More scale is removed from the parts because of its rapid action.

Oil quenching is used, when the section is light or the properties needed after heat treatment are not high. This nearly always eliminates the breakage problem and is very effective in reducing distortion.

A wide range in austenitizing temperatures is made necessary in order to meet required conditions. Lower temperatures should be used for the higher-manganese steels, light sections, coarse-grained material and water quenching; and higher temperatures are required for lower manganese, heavy sections, fine grain and oil quenching.

2.1.1.2 Mechanical properties

When carbon and alloy steels are quenched to martensite and tempered to the same hardness, they have similar tensile properties in that portion of the cross section

which reacts to the quench. If carbon steel has the hardenability required by the critical section of the part and the quench used, the resulting tensile strength, yield strength and elongation in the fully hardened zone will be in the same range as in a similar zone in an alloy steel quenched and tempered to the same hardness. The similarity in properties of the hardened zone holds, regardless of the depth of hardening, but the strength of the piece will be governed by the thickness of the hardened zone (depth of hardening).

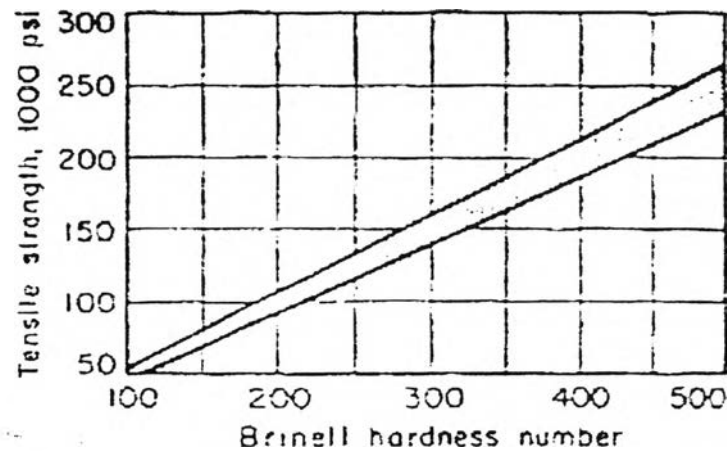


Figure 2.1 Relation of tensile strength and hardness for hardened and tempered (SAE Handbook)

The relation between hardness and tensile strength for constructional steels, both carbon and alloy, is illustrated in Figure 2.1. Because of the effect of cold working, this relationship is unreliable for cold drawn steels. The effect of tempering temperature on tensile strength and hardness is shown in Figure 2.2.

The important exception to this similarity of properties is the relationship between tensile strength and reduction of area. For any tensile strength the reduction of area is less for carbon steels than for alloy steels.

General correlation among mechanical properties of steels, shown in Figure 2.1 and 2.2, has no details reported regarding the size, number of the specimens that used in obtaining these data. But the specimens are closely controlled in chemical composition, grain size, section size, and condition of heat treatment. Normal variations

in composition and grain size from heat to heat and within one heat produce a considerable scatter of results in sections of the same size.

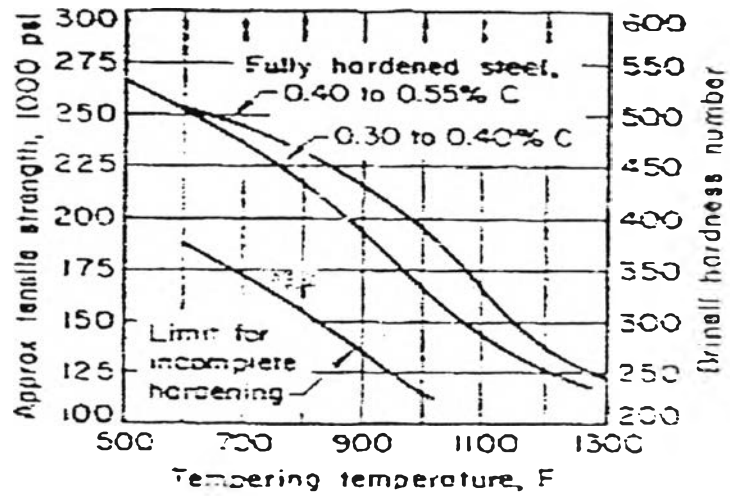


Figure 2.2 Effect of tempering temperature on the tensile strength and hardness of carbon and alloy steels with 0.3 to 0.55% C (SAE Handbook)

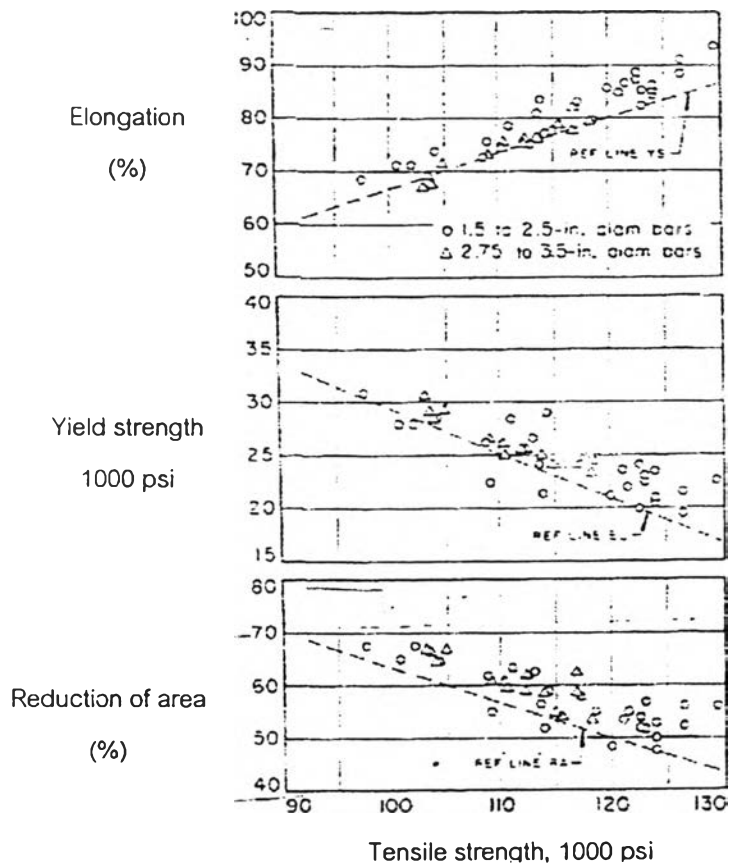


Figure 2.3 Relation among mechanical properties of 1045-carbon steel (Grossmann and Bain, 1964)

Because of the lower hardenability of carbon steels, mechanical properties of carbon steels, particularly when quenched and tempered, are influenced more by changes of section size than alloy steels. Besides the effect of section size on specific properties, the relation of one property to another is affected by size of the heat treated section. This is implied by the tensile and yield strength relationship. As the section size increases, incomplete hardening will lower the ratio of yield strength to tensile strength.

Figure 2.3 give detailed tensile property relations for 1045 carbon steel. These data are for steels in the quenched and tempered condition.

Increasing carbon content brings about a consistent increase in tensile and yield strength and decrease in elongation and reduction of area, regardless of whether the steel is in the hot rolled or quenched and tempered condition (provided the ranges of tempering temperature are the same). The tensile strength decreases as the section size increases, for a given composition and heat treatment, and there is some lowering of the ratio of yield to tensile strength.

Variations in chemical composition within a specific grade contribute to the scatter of mechanical properties. This is illustrated by the test data in Figure 2.4, where the properties for two heats of quenched and tempered 1050 steel are compared for a tempering range of 600 to 1200°F.

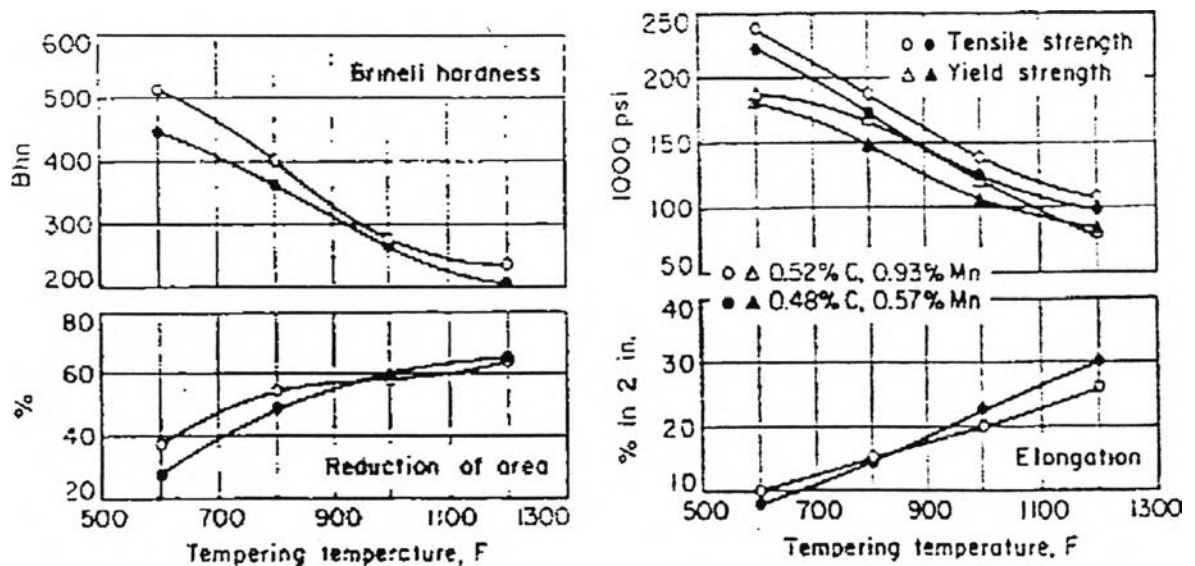


Figure 2.4 Effect of carbon, manganese, and tempering temperature on mechanical properties of two heats of water-quenched 1050 steel. (Zakharov, 1962)

When the carbon steels are quenched to obtain an almost completely martensitic structure, the hardness will decrease as the tempering temperature is increased. In Figure 2.5, in a straight-line relation, for tempering temperatures to 1200°F or higher. The rate of hardness decrease with tempering temperature is greater for carbon steels than for alloy steels. (Neely, 1994)

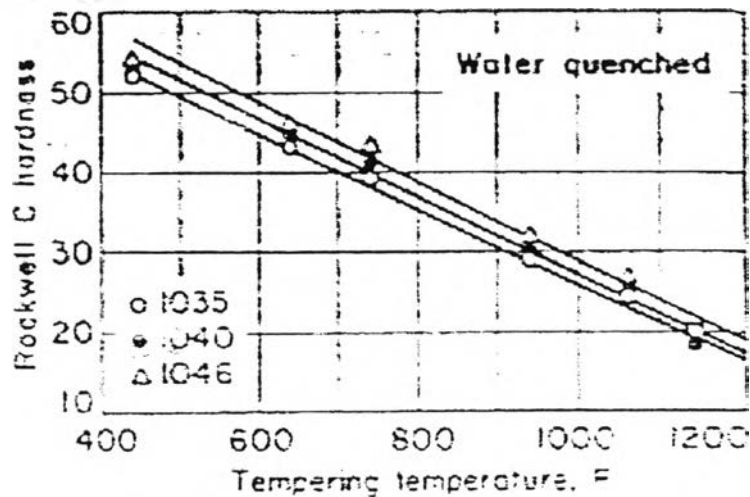


Figure 2.5 Effect of tempering temperature on the hardness of 1035, 1040 and 1046 carbon steel (Neely, 1994)

2.1.1.3 Chemical composition of 1045 carbon steel

According to Heat Treater's Guide from American Society for Metals 1982, it indicates that this material, 1045-carbon steel, composes of

C	Mn	P	S
0.43-0.50	0.6-0.9	0.040 max	0.050 max

2.1.1.4 Similar steels (U.S. and/or Foreign) 1045

1. UNS G10450
2. ASTM A510, A519, A576, A682
3. FED QQ-S-635 (C1045), QQ-S-700 (C1045)

4. SAE J403, J412, J414
5. DIN 1.1191 (West Germany)
6. AFNOR XC 42, XC 42TS, XC 45, XC 48 (France)
7. JIS S 45 C, S 48 C (Japan)
8. SS₁₄ 1672 (Sweden)

2.1.1.5 Characteristics

The 1045 medium-carbon steel is available in a variety of product forms, mainly as stock for forging, and also available as special quality grades of proprietary steel compositions. Its characteristics are excellent forgeability, fair machinability, responds readily to heat treatment, as-quenched hardness of at least 55 HRC, and slightly higher, when carbon is near high side of the allowable range. It is used extensively for parts to be furnace heated or heated by induction prior to quenching.

2.1.2 Hardenability of carbon steels

Carbon steels with low manganese and a virtual absence of residual nickel, chromium and molybdenum, are the lowest in hardenability of all steels. This holds true for nearly all carbon levels, because in the absence of higher manganese or other alloy elements, carbon functions almost entirely to control maximum hardness and has only a minor effect on hardenability.

Manganese has a marked effect on hardenability. Even a difference of 0.25% makes a significant difference on the end-quench hardenability of 0.50% C steel, illustrated in Figure 2.6.

Steels are not necessarily better because they are higher in hardenability. They are better only when the hardenability is required. There are various applications where minimum, rather than maximum, hardenability is needed, which accounts for the many low manganese grades melted. For instance, it is often desirable to produce thin layers of maximum hardness on shaft bearings or cam contours. This is usually accomplished by induction hardening, however if the hardened area is too deep, an unfavorable stress pattern will be established, with resultant cracking in quenching or premature failure in service. In another example, cams are manufactured from standard 1050 steel (0.60 to

0.90% Mn) and induction hardened to Rockwell C 60 to a depth of about 1/16-inch. If the hardened zone become as deep as 1/8 inch, a significant number of parts cracked. Using a modified grade of 1050 steel (0.30 to 0.60% Mn), that resulted in a shallower hardened zone after induction hardening eliminates cracking.

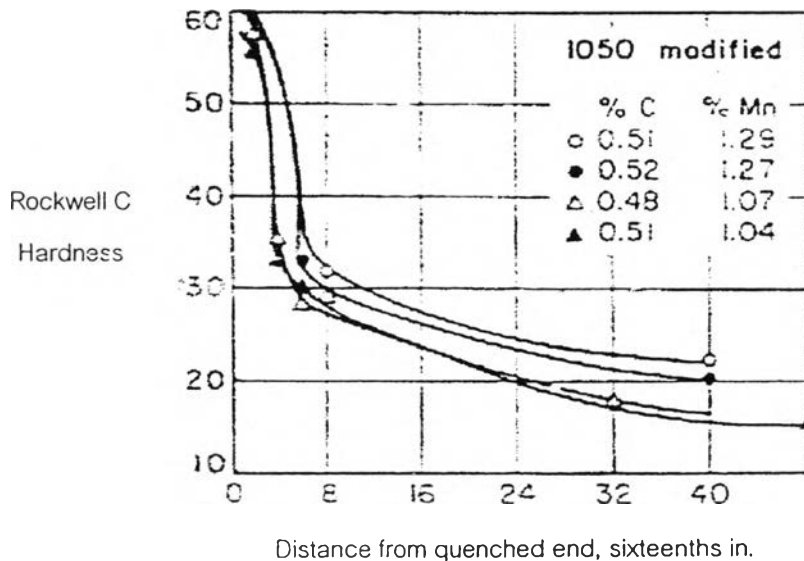


Figure 2.6 Effect of variations in carbon and manganese contents on end-quench hardenability of modified 1050 steel (Metals Handbook, 1978)

It is more economical to use carbon steels whenever possible. The higher-manganese grades cost more than lower-manganese grades, but less than the lowest-cost alloy grades.

2.1.2.1 Distortion in heat treatment

Carbon steels normally distort more in heat treatment than alloy steels because carbon steels require a water or brine quench to develop full hardness. This often eliminates selection of carbon steels for critical parts.

Many factors contribute to the total distortion that occurs during heat treatment. These include residual stresses that may be present as a result of machining or other cold working operations, the method of placing in the furnace, the rate of heating, and the natural volumetric changes that take place with phase transformations. However, the most important single factor is the uneven cooling rate during quenching, caused mainly

by the shape of the parts. Symmetrical parts with little or no variation in section may have almost no distortion, while complicated parts with wide variations in section may distort so much that they cannot be used or at least require excessive finishing operations.

Other factors being equal, the distortion in carbon steels will increase as the carbon content increases, because of the gradual lowering of M_s temperature with increasing carbon.

Although other variables are kept to a minimum, there is also a significant variation in the magnitude of distortion and direction of dimensional change among different heats of the same grade of steel. This happens because of several factors, including with minor variations in composition and grain size, but largely because of the history of the steel with regard to hot working, cold working and heat treatment.

Because of the several variables that contribute to the total distortion in a specific instance, prediction of distortion in actual parts, based upon the behavior of small test pieces, is seldom reliable.

2.1.3 The selection of steel for hardenability

Hardenability of steel is the property that determines the depth and distribution of hardness induced by quenching. It follows that hardenability is the most important factor in selection of steel for heat-treated parts because the primary objective in quenching is to gain satisfactory hardening.

Hardenability should not be confounded with hardness as such or with maximum hardness. The maximum attainable hardness of any steel relies on carbon contents. The maximum hardness values, which can be obtained with small test specimens under the fastest rates of water quenching are nearly always higher than those developed under production heat treating conditions because the limitations in quenching larger sizes result in less than 100% martensite formation.

2.1.3.1 Steel composition

The chemical composition at the austenitizing temperature and the austenite grain size at the moment of quenching direct the hardenability of steel almost entirely.

The chemical composition of the austenite may not be the same as that exposed by the chemical analysis of the steel since some carbide may not be dissolved at the austenitizing temperature. Such carbide would be included in the chemical analysis but, being undissolved in the austenite, neither their carbon nor alloy content can contribute to hardenability; also, by nucleating transformation products, undissolved carbides can actively decrease hardenability.

2.1.3.2 Alloying elements

The most important function of the alloy elements in heat treatable steel is to increase hardenability, which makes possible the hardening of larger sections than is possible with carbon steel, and the use of the gentler oil quench to reduce distortion and sometimes to prevent quench cracking.

When the alloy steels are considered, it is found that all compositions develop the same hardness below Rockwell C 50. However, it should not be inferred that all tempered martensite of the same hardness are alike in all respects.

The cheapest means of increasing hardenability at a given carbon content is by increasing the manganese content. For instance, two carbon steels of the same carbon content (0.37 to 0.44%), are 1040 and 1041 steel. The 1041 steel contains minimum of 1.35% Mn and the 1040 contains 0.60% Mn. The minimum hardenability for the 1041 steel is considerably higher than that for the 1040 steel. In fact 1041 steel is nearly equal in minimum hardenability to 1340H that has 1.45% Mn min. (Bain and Paxton, 1966)

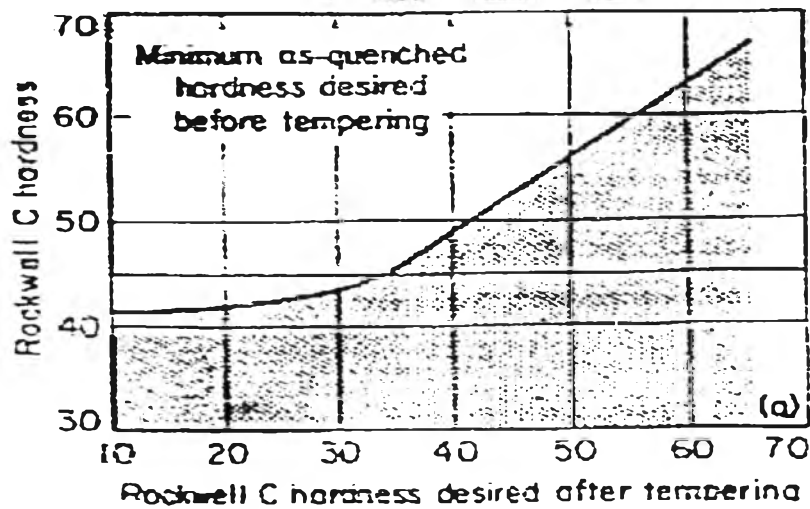
Also Chromium and Molybdenum, already referred to as increasing hardenability, are among the most economical elements per unit of increased hardenability. Another element is boron, which markedly increases hardenability when it is added to the steel.

2.1.3.3 As-quenched hardness

Two basic items of knowledge wanted before the steel is selected are: (1) the as-quenched hardness that is necessary prior to tempering to final hardness in order to

attain the best stress-resisting microstructure in the part, and (2) the depth below the surface to which this hardness must extend.

The relation shown in Figure 2.7 is a recommendation for as-quenched hardness as a function of the hardness desired after tempering. This figure does not specify the degree of hardening (percentage martensite) preferred in obtaining the as quenched hardness indicated, and it is possible to choose steels, which would produce these hardness with less than 90% martensite.



Rockwell C Hardness

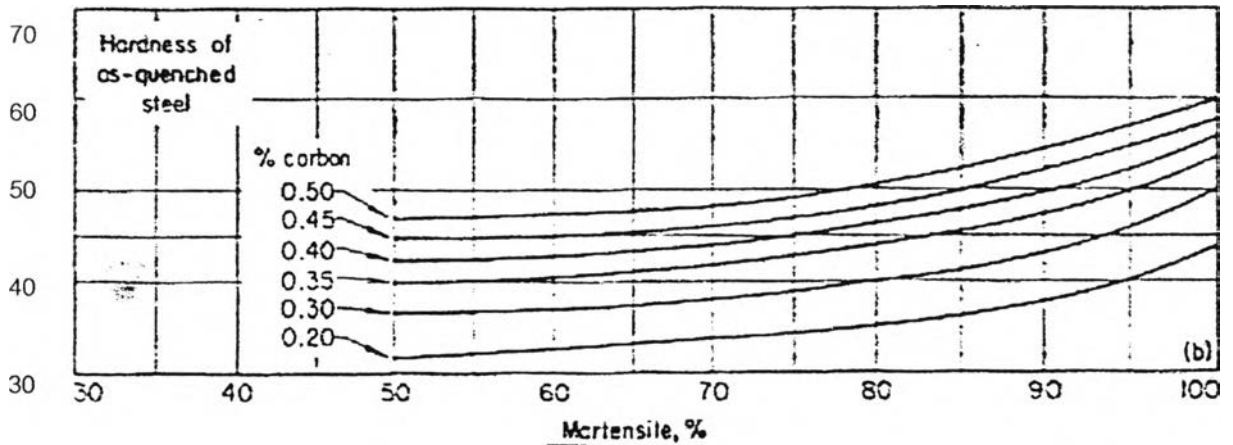


Figure 2.7 (a) Minimum as-quenched hardness recommended for various final hardness after tempering. (b) Dependence of hardness of as-quenched steel on martensite percentage and carbon. (Iron and Steel Technical Committee of the SAE War Engineering Board)

Normal and economical approach is to select the lowest-carbon steel that will produce the indicated quenching medium determined by attending circumstances. With such a procedure, the structures possessing the indicated hardness would be fully hardened. That is, they would contain more than 90% martensite, which is a common practical definition of full hardening. The percentage martensite and depth to which parts are hardened not only affect the serviceability of the parts but also it affects the hardenability required.

2.1.3.4 Steels for case hardening

The steels for case hardening are specified on the basis of core hardenability. Though the same considerations generally apply as for the selection of uncarburized grades, there are some peculiarities in carburizing applications.

First, in a case hardened steel the hardenability of both case and core have to be considered. Core and case have quite different hardenability because of the difference in carbon content, and this difference is much greater for some steel than for others. Besides, the two regions have different functions to perform in service. Until lean alloy steels introduced, there was little need to be concerned about case hardenability because the alloy content combined with high carbon content always provided adequate hardenability. When the alloy content rise above 2%, the temperature range of martensite formation in the case is often lowered enough so that elaborate treatments are necessary to combat the retention of excessive amounts of austenite.

2.1.4 Metallurgical principles of heat treatment

Figure 2.8 illustrates a simplified equilibrium diagram for carbon steel. At temperatures below 721°C , steel with 0.3 to 0.83 percent carbon is in its normal state with the pure iron (ferrite) accompanied by pearlite (a mixture of ferrite and cementite, cementite being ferrite and carbon in layers). If the temperature is raised above 721°C (the so-called A_{c1} line), the cementite starts to go into solution and, when the A_{c3} line is reached, all the material has changed to austenite --- a ferrite with a completely different crystal structure form the original ferrite. If the surface is now cooled quickly to $350/200^{\circ}\text{C}$, it can miss the reformation of the original ferrite and pearlite and pass directly to the

martensite stage, when the carbon comes rapidly out of solution, leaving martensite, this hard crystalline structure in which the crystals interlock to form a very hard steel. This rapid cooling is called quenching.

In steels of higher carbon content (0.8 to 1.7 percent carbon) the number of martensite crystals increases and the steel becomes harder. The steel is not taken all the way to the A_{cm} line but to a lower temperature, shown as the hardening temperature, and cooled from there. The required hardening temperatures and quench temperatures are shown on Figure 2.8.

If the quench is not done rapidly, the material will revert to its original composition. The rate of cooling must not be below a critical value. For 0.3 percent carbon steels, this rate is only just achievable with intensive water sprays: as the carbon content rises, the critical value falls. Alloying ingredients, such as molybdenum, chromium, manganese, and nickel, lower the critical cooling rate.

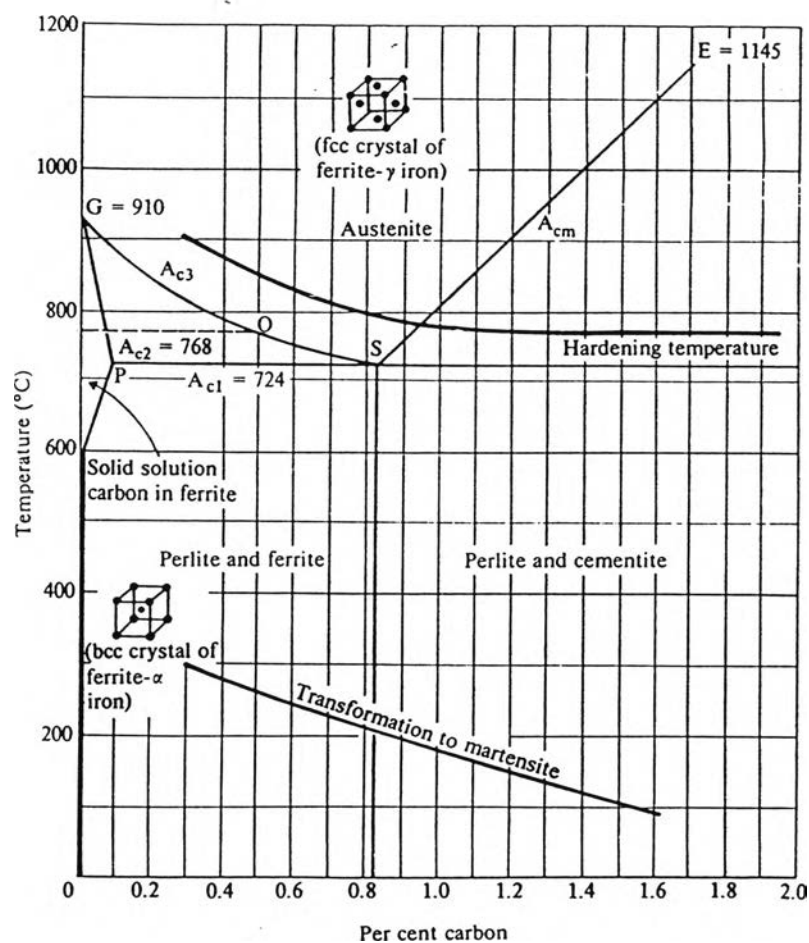


Figure 2.8 Hardening temperatures for plain carbon steel (ASM Metals Handbook, 1982)

From Figure 2.8, other points should be noted. First at the 0.83 percent carbon line, the steel is in eutectoid state. This means that when the point S is reached, the A_{c3} and A_{c1} lines must meet and the transformation from pearlite to austenite is instantaneous, with no intermediate or partial solution state. It also implies that the optimum combination of ferrite and cementite, as pearlite, is at 0.83 percent carbon. Above this percentage, the excess carbon forms extra cementite; below it the lack of carbon results in pure iron or ferrite.

Performing two operations carries out the process of hardening steel. The first step is to heat the steel to the austenite range (austenitizing), which is heating to a temperature above the upper critical temperature. The second step is that of rapid cooling or quenching near to room temperature.

Austenitizing produces the solid solution of carbon in the face-centered cubic structure. The temperature used for austenitization is normally about 50°F (28°C) above the A_{c3} lines. Alloys with 0.8 percent carbon or less will become 100 percent austenite at this temperature, whereas steel with more than 0.8 percent carbon will be austenite with some free cementite.

Higher carbon steels that contain carbide-forming elements such as chromium, molybdenum, tungsten, or vanadium require more soaking time at the austenitizing temperature since the complex carbides are relatively slow to dissolve. If the temperature is too low, there may be incomplete solution of carbides and the steel may still contain undissolved ferrite grains that are not beneficial in hardened tool steel. If the temperature is too high, large grains may form and cause cracking during heat treatment, resulting in failure of the part. Most steel producers publish data sheets containing correct austenitizing temperatures for various alloys.

Quenching undercools the austenite to form a new structure below the M_s temperature. This structure is called martensite. The martensite is an extremely hard acicular or needlelike structure that, for most purposes, is too brittle to be of any use, and a tempering process is needed as an additional operation to toughen it.

Martensite may be recognized by its acicular structural appearance when viewed in a microscope. With the exception of some isothermal quenching process, the object of the quenching process for steel is to cool it rapidly enough to produce

martensite. Martensite has a profound and useful effect on steel, of which the hardening properties are well known.

Two facts emerge from this metallurgy are (1) the heating rate should be rapid, so that the hardening temperature is reached rapidly, to avoid grain growth in the overheated surface and (2) the quench should be quickly and effective, as the deeper layers will not form martensite unless they are cooled at the critical rate.

2.1.5 Austenitizing temperatures for hardening carbon steels

The temperatures recommended for austenitizing carbon steels prior to hardening are given in Table 1A in appendix. These temperatures are quoted from the 1964 Edition of the SAE Handbook.

In several applications, the rate of heating to the austenitizing temperature is less important than other factors in the hardening process, which are maximum temperature obtained through the section, temperature uniformity, time at temperature, and rate of cooling. The nature of the furnace atmosphere, thermal conductivity of the steel, and the thickness of section all influence the behavior of steel part in relation to the rate of heating.

The difference in temperature rise within thin and thick sections of objects of varying cross section is a major problem in practical heat treating operations. Whenever possible, provision should be made for retarding the heating of the thinner sections in order to minimize thermal stress and distortion. When temperature uniformity is the ultimate objective of the heating cycle, this is more safely attained by slow heating than by rapid heating. Furthermore, the maximum temperature in the austenite range should not exceed that required achieving the necessary extent of solution of carbide.

2.1.6 Quenching of steel

The quenching of steel is the rapid cooling of steel from a suitable elevated temperature. This is normally achieved by immersion in water or oil, even though forced air is sometimes used. As a result of quenching, production parts must develop an acceptable as-quenched microstructure and, in critical areas, mechanical properties that will meet minimum specifications after the articles are tempered.

The performance of quenching relies upon the cooling characteristics of the quenching medium as related to the ability of the steel to harden. Accordingly, varying the steel composition or the temperature, the temperature, agitation, and type of quenching medium may change the results. Design of the part contributes to the mechanical properties and the distortions that will ensue from a particular quench. Also the design of quenching system and the thoroughness cause the success of the process.

The manner or condition, in which the quenching medium is used, can modify the rate of heat extraction of which a quenching medium is capable. These modifications will result in the assignment of specific names to many quenching methods such as time quenching, selective quenching, direct quenching, spray, fog and interrupted quenching.

The direct quenching is the most widely used method. When carburized work is quenched from the carburizing temperature, or from a slightly lower temperature, the term direct-quenching is used to distinguish this method from the more indirect practice of carburizing, slow cooling, reheating and quenching. Direct quenching practice is simple and economical, and distortion of carburized parts is often less with direct quenching than with reheating and quenching.

When the cooling rate of the object being quenched must be changed suddenly at some time during the cooling cycle, time quenching is used. The alteration in cooling rate may comprise either an increase or a decrease, depending upon which is wanted to gain decided results. The usual practice is to lower the temperature of the part by quenching it in a medium for a short time until the workpiece cool below the nose of the time-temperature transformation curve. And then remove the part and quench it in the second medium, so that it cools slowly throughout the martensite transformation range. In several applications the second medium is air.

2.1.6.1 Carbon content and hardenability in quenching

Maximum hardness obtainable in the steel quenched at a sufficient rate to avoid the nose of the TTT curve depends on the carbon content. The cooling rate necessary to gain fully martensitic structure relies on the hardenability of the steel quenched. The

relation of carbon content and percentage martensite to hardness is illustrated in Figure 2.9.

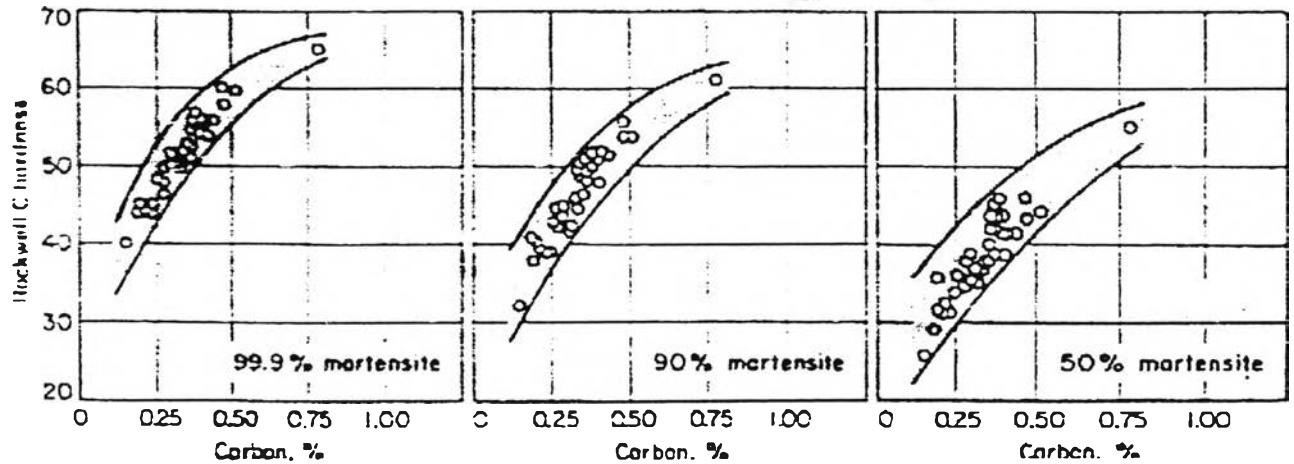


Figure 2.9 Relation of carbon content and percentage martensite to Rockwell C hardness (ASM Handbook)

Depending upon the carbon content and hardenability of the steel, the cooling rate should be fast enough so that at least 90% martensite will be produced in critically stressed areas of the part. Lower percentages of martensite are often acceptable in areas subject to lower stresses in service. Higher percentages of martensite in the as-quenched structure will produce higher fatigue and impact properties.

2.1.6.2 Cooling rate

When carbon steel is quenched from the austenitizing temperature, the cooling rate equal to or greater than about 100°F per second is essential for avoiding the nose of the TTT curves. The cross section of the piece has to cool at this rate to gain the maximum amount of martensite. Under ideal conditions, water provides a cooling rate of about 5000°F per sec. at the surface of 1/2 inch in diameter by 4 inch-long steel cylinder (Bullens, 1988). This rate decreases rapidly below the surface. Therefore, for carbon steel, only light sections with a high ratio of surface area to volume can be fully hardened through the cross section.

The high temperature gradient is developed between the surface and the center when water or brine is used. This temperature gradient produces greater distortion and increases the hazard of cracking in all but simple, symmetrical shapes. Quenching in oil results in a much lower temperature gradient from surface to center, decreased distortion, and less probability of cracking.

2.1.6.3 Water quenching

Water and water-base solutions are the least expensive quenching mediums and are used whenever the part is such that it will not distort excessively or crack when being quenched.

As a quenching medium, plain water approaches the maximum cooling rate attainable in liquid. Other advantages are that it is inexpensive and readily available, and is easily disposed of without attendant problems of pollution or health hazard. Including, it is an effective means of breaking scale from the surface of steel parts that are quenched from furnaces in which protective atmospheres have not been employed. The disadvantages of plain water are that water quenched steel parts may rust unless immediately treated with rust preventive, and its rapid cooling rate persists throughout the lower temperature range, in which distortion or cracking may be occurred. So water is restrained to the quenching of simple, symmetrical parts made of the shallower-hardening grades of steel (plain carbon or low alloy). The another advantage of using water is that its vapor blanket stage may be lengthened. This prolongation that varies with the degree to which the complexity of the part being quenched encourages vapor entrapment and with the temperature of water, results in uncertain hardness and unfavorable distribution of stress, which may cause distortion or cracking. Water quenching temperature, agitation and contamination must be controlled to obtain reproducible results.

Temperature from 55 to 75 °F of the water will provide uniform quenching speed and reproducible results. The surface cooling power of water decreases rapidly as water temperature increases. Hot water has a low cooling power because, as the boiling point is approached, the cooling action resembles that of steam.

Agitation is important in water quenching because it disperses vapor bubbles from parts and directs cooler water against the steel. Agitation can be easily provided by mechanical impellers, recirculating pumps or controlled overflow.

Contamination of water quench baths by dissolved salts is likely to increase the cooling rate, because salts effectively reduce the duration of the vapor blanket stage. But, contaminants ----- algae, slimes, soaps or emulsion formers ----- reduce the cooling rate by trapping the steam or vapor film and thus preventing cooler water from contacting parts quickly enough to produce uniform results.

2.1.7 Tempering of steel

Tempering of steel consist of heating previously hardened steel to a temperature below the transformation range and cooling it at a suitable rate, primarily to increase ductility and toughness.

2.1.7.1 Famous parameters

The microstructure and mechanical properties of tempered steel rely on the temperature and duration of tempering. The carbide particles become larger and fewer in number as temperature and time increase. This alternation in microstructure normally results in lower hardness and strength but higher ductility and toughness.

Hardness may either remain unaffected by tempering or even be increased, under certain conditions. For instance, tempering the hardened steel at very low tempering temperatures may cause no change in hardness but may accomplish the desired increase in yield strength. As well as, alloy steels containing various percent of one or more of the strongly carbide forming elements are capable of secondary hardening. That is, these steels may become somewhat harder as a result of tempering.

Time and temperature are interdependent variables in tempering. Within limits, lowering temperature and increasing time can produce the same result as raising temperature and decreasing time.

2.1.7.2 Tempering the carbon steels

Ability for tempering carbon steel decreases with an increase in carbon content. Steel as quenched in production is seldom fully martensitic. Often, only 50 to 90% martensite is present at the center of the section, and sometimes the central structure may be bainite and pearlite. For reasoning design of parts and as an aid in heat treating them, it is important to know the ability for tempering of structures other than martensite. Ideally, this information is available for all structures found in the end-quenched hardenability bars of the standard steels.

Variation in hardness after tempering is most frequently the result of differences in hardenability and prior microstructure. When previous microstructure is the same, control of temperature is the most important parameter in control of the tempering process.

Generally, control of tempering temperature to within ± 5 °F is adequate and is within the practical limits of most furnace and molten-bath equipment. Temperature variations are infrequently permitted to exceed ± 10 °F unless mechanical property requirements are correspondingly broad.

2.1.8 Induction hardening

Heat for hardening or tempering the steel part may be generated within the part by electromagnetic induction. Any electrical conductor can be heated by electromagnetic induction. As alternating current from the converter flows through the inductor, or work coil, a highly concentrated, rapidly alternating magnetic field is established within the coil. The strength of this field depends primarily on the magnitude of the current flowing in coil. The magnetic field established induces an electric potential in the part to be heated, and since the part represents a closed circuit, the induced voltage causes the flow of current. The resistance of the part to the flow of the induced current causes heating by losses.

The method is known as induction hardening, when surface hardening is done by means of induction hardening. This method concerns with heating the component by an induced current to temperatures at which the rate of formation of austenite is very quick, and then quenching it to transform the austenite to martensite. The hardness

formed is somewhat higher than that attained by conventional methods of hardening; the fatigue strength obtained is also higher (Metals Handbook, 1978). For the purpose of induction hardening it is usual to employ an alternating current at a frequency ranging from 50 c/s to 1000 kc/s.

The pattern of heating obtained by induction is determined by (1) the shape of the induction coil producing the magnetic field, (2) the number of turns in the coil, (3) the operating frequency, and (4) the alternating current power input.

The advantage of induction hardening over the conventional methods is mainly the rapid heating of the surface of the component without an appreciable rise in the temperature of the core. This condition makes it possible to case harden components in a few seconds with very little distortion and without the formation of an oxide layer or a decarburized zone. The use of steels of inferior quality for the same practical applications is also made possible. The rapid heating method employed in induction heating enables the heat treatment to be performed directly in the machining production line without interrupting the technological sequences of operations thus reducing the overall cycle time to a minimum.

Most induction surface-hardening applications need comparatively high power densities and short heating cycles in order to restrict heating to the surface area. The principal metallurgical advantages that may be gained by surface hardening with induction include increased wear resistance and improved fatigue strength.

2.1.8.1 Equipment for induction hardening

High frequency motor-generators and valve-generators are used as sources of power supply for induction hardening. The motor-generator sets are employed in cases where the frequencies required do not exceed 10,000 cycles per second and valve-generators in those cases where still higher frequencies are wanted. The depth of heat penetration diminishes, as the frequency increases.

Surface heating by high frequency electric current is determined on the basis of the following main factors, namely, the frequency and the time of heating. The frequency is normally chosen to give the optimum range of case depth. In appendix, table 2A

shows the frequencies most widely applied in practice to gain different case depth for various diameters of the component.

The primary considerations for induction hardening are the depth of heating and the size of the part. As the frequency governs the depth of penetration, the equipment should be selected mainly keeping this in view (Table 3A in appendix).

On the basis of the required depth of hardened part and the size of the component, Table 2A indicates the power sources and the frequencies required.

As it is desirable to use the available electrical capacity to the full, it is a good practice, when deciding the plant, to select a frequency that will work satisfactorily taking the minimum time for induction hardening. If a greater depth of hardening is desired, then a lower frequency is selected, and to produce a thin case of hardness the highest possible is used.

2.1.8.2 Heating inductors

The heating effect attained with the aid of a generator is not only dependent upon the generator output and heating time, but also on the manner in which the component is heated depending on the shape of the inductor and its position with respect to the work piece. The depth and configuration of the heated layer obtained on the surface of a component depends on the shape of the inductor, the distance between the inductor and the zones to be heated, and also upon the magnitude of the power-input into the frequency of the supply current. Hence the design of the inductor or work coil should be such as to direct the eddy current only into those sectors of the component, which require heat treatment. The distance required for a stationary component should be about 2 to 3 mm, for rotating parts it should be 2 to 4 mm and for a progressive shape it will be about 2 to 5 mm depending upon the type of component (Guthrie and Archer, 1975)

The tighter the gap between the component and inductor, the higher is the degree of efficiency. The clearance between the component and the inductor should remain within 2 to 6 mm (Seulen, 1956). Inadequate spacing may cause a contact between the work and the inductor, or puncture the air gap between them, and overheat the external layer particularly when vacuum-tube oscillators are used. Larger clearances

may be chosen for deeper hardening and the spacing of turns in the multi-turn inductor should be minimum to ensure uniform heating. Usually it will be about 2 to 4 mm. and the some spacing is maintained between the coil and the work piece. By varying the distance it is possible to influence the rate of heating to a very large extent.

2.1.8.3 Selection of prior structure

Steel structure prior to induction hardening is of great importance, especially in the case of very thin sections requiring very short heating time. The heating up process in induction hardening is very fast (less than a few seconds) and so there is little time available for the carbide solution necessary for the production of martensite. It is not desirable that if the structure is not favorably resolved, no proper transformation will take place. To some extent the higher temperatures that are possible with furnace hardening can compensate for very short heating time without the danger of grain size enlargement (Principles of Heat Treatment of Steels, 1980)

The initial microstructure of steel exerts considerable influence on the process of austenite formation. The smaller the size of the pearlite particles, the higher the rates of formation of the austenite nuclei and of the growth of the austenite grain. Therefore in induction hardening of medium carbon steel, a sorbite initial structure is recommended, which is characterized by a smaller grain size and a more uniform distribution of the grain of cementite. The diffusion path of carbon in the process of the austenite formation in steel possessing a sorbite structure is shorter than in the normalized steel whose structure composes of free ferrite and pearlite.

Steel containing more than 0.5% carbon are frequently spheroidized for improved machinability, however this structure has the poorest response to induction hardening, and hence requires higher hardening temperatures. It is about 150 to 160°C more than the normal hardening temperature. But this will result in coarsening the austenite grain size and may lead to quenching cracks.

2.1.8.4 Induction hardening temperature

The heating temperature is the most important variable in induction hardening. To gain satisfactory properties it is necessary to heat the steel to the temperature higher

than the normal hardening temperature, so that the carbon diffusion is sufficiently rapid. For example with 0.45% carbon steel it requires a temperature of about 900 to 950°C for induction hardening. If the steel is having carbide forming elements it may be necessary to increase the hardening temperature by 70 to 150°C above the conventional hardening temperature to take full advantage of the alloying elements (Marten and Wiely, 1945). The exact heating temperature relies on the length of the heating cycle, the alloying elements present, the specific effects desired for the alloying elements and the surface hardness needed. These higher temperatures at the surface are used to attain an adequate solution of the carbon and alloying elements in the austenite with very short heating cycle.

The temperature required depends upon the rate of heating as well. As the heating rate is greater, higher hardening temperatures are required to gain the maximum hardness value. For instance, at a rate of temperature for full quench hardening is 840°C; at a rate of 400°C/second a temperature of 920°C is required; and at a rate of 700°C/second heating up to 960 to 1000°C is required (Figure 2.10).

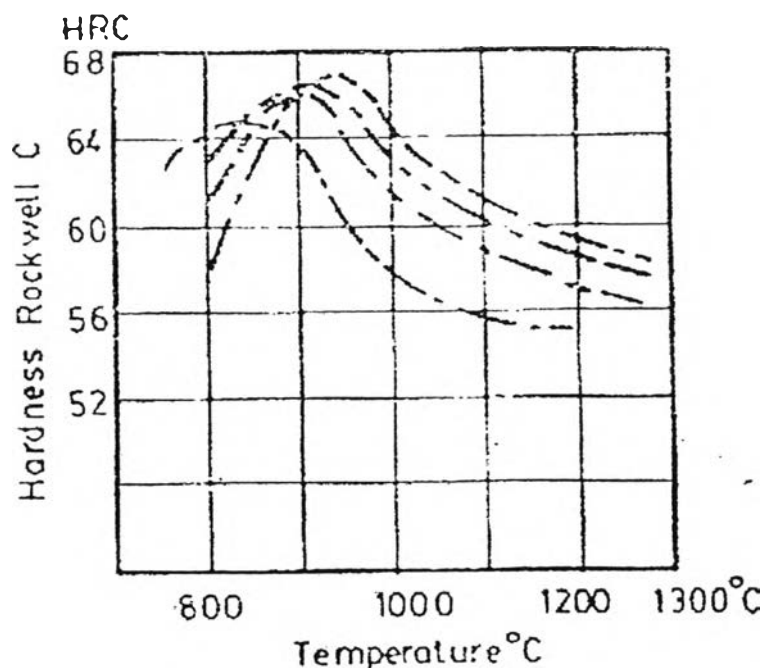


Figure 2.10 Variation in surface hardness of AISI 4150-steel as a function of quenching temperature at different heating rates (Metals Handbook, 1964)

The heating conditions at which the maximum hardness is obtained are generally called the optimum hardness conditions. This condition can be selected in accordance with the type of steel, the shape of the component, the required thickness of the hardness layer and the frequency of the supply current.

2.1.8.5 Method of induction hardening

Induction hardening may be accomplished by many ways, but in this research the progressive hardening is mentioned. In the progressive hardening, the part of the surface to be hardened is exposed to heating at any one moment, whereas the remainder stays cold. During hardening the component to be hardened performs two movements at the same time. As it rotates, it moves along the axis, while the inductor remains stationary. Heat is applied progressively whilst cooling is effected by means of quench being fixed at the outgoing side of the coil. The shaft to be hardened is slowly moved through the coil that rapidly raises the surface layer to the hardening temperature. This hot zone then moves throughout the quenching ring situated below the coil. The generator power and the speed at which the work passes through the coil determine the surface temperature. Increasing the generator power or slowing down the speed of the component both serve to raise the surface temperature and vice versa. If both the generator power and component speed are increased, penetration will be less, while conversely the combination of low power and low work speed will produce a deep penetration.

The depth of the hardened layer may be varied considerably even in similar jobs of the same material heated by currents of the same frequency. The depth of hardness is influenced by the time factor, and with increasing time the heat is transformed according to the thermal conductivity of the material from the outside to the interior resulting in higher depth of case. In progressive hardening the heating time is controlled by the ratio of the active length of the inductor coil and the travelling speed of the job. In this case also lowering of the specific density, together with reduction in the rate of travel of the work, causes an increase in the depth of hardening.

There is a relationship between power density, hardened depth, heating time, and frequency. There is also a choice between very rapid heating that just allows time to

heat to the hardened depth required, and heat-conduction cycle, which allows heat flow to about three times the depth required. The latter produces a more gentle transition between the hardened surface and the soft core. Power densities can be lower and heating times longer, allowing greater accuracy in time control. Also the grade of steel, the rapidity of cooling, the previous metallurgical treatment of the metal, and the coil design all affect the depth of hardness.

2.1.8.6 Quenching

The process of hardening is critically controlled by the rate of cooling. Natural cooling is not fast enough to obtain the martensite structure. So the fast rate of cooling is effected by forced quenching using water, oil, water emulsion or forced air depending on the type of material. The appropriate choice of the cooling medium is essential because an application of a wrong liquid will either result in an insufficient hardness or in a hardened layer with material crack. Water is suitable for plain carbon steel, low alloy steels and cast irons. Moreover, water is easiest to handle, simple to install and maintain, and generally less hazardous than other mediums. Oil is the preferred choice for materials requiring a very mild quench, whether spray or immersion, and is used for highly alloyed steels, high carbon steels and for parts with abrupt sections. Water emulsion is also used in case where the quench rate must be between water and oil.

2.1.8.7 Tempering

Tempering of induction hardened components is not recommended for parts in which the maximum wear resistance or fatigue properties are desired. A low temperature anneal reduces internal compressive stresses which contribute towards a higher hardness and endurance limit. The components to be ground after induction hardening should be tempered at 150-160°C to avoid cracks during grinding. A higher tempering temperature may be adopted to reduce hardness to the specified value of HRC.

Induction tempering may be applied to reduce the hardness of the parts, in particular on previously induction hardened parts. This is more suitable for symmetrical shaped components. These components may be heat-treated to uniform desired

properties. With this method differential hardness may be attained in a component, with a consequent improvement in quality.

2.1.8.8 Steels for induction hardening

The basis of selection of induction hardening steels is similar but not identical to that of choosing steels hardened by other methods. The steels with carbon content of about 0.30% and above are mainly used for induction hardening. Steel having less than 0.3% carbon is not generally induction hardened because the hardness produced will be too low. In practice, surface hardening of component is seldom done on the steel containing more than 0.5% carbon since the higher the carbon the greater the risk of cracking. The addition of special alloying elements does not greatly influence the degree of hardness. Sometimes in order to gain greater depth of hardened area, addition of alloying elements is carried out more with a view of improving the strength of the steel in terms of tensile, yield, impact and fatigue properties. This improved strength enables the desired hardness to be obtained (Marten and Wiely, 1945).

The property of surface heating by induction influences to the choice of steel. The problem of incomplete transformation below the surface does not occur as only the surface layers heated. Also, the fast rate of heating of the surface means that fast quench can be used without the risk of distortion due to internal stresses. The core of the part therefore retains its initial strength, as it has not been heated or hardened at all. These two effects mean that plain carbon steel can often be substituted for more expensive alloy steel previously hardened by heating methods (Smith S., 1954). Another reason for preferring carbon steels for induction hardening is that they go into solution faster at lower temperature than alloy steels. It means that shorter heating time is used, with less loss of heat to the center and with increased production rates.

According to ISO 683/XII-June 1972, Flame and Induction Hardening Steels. The 1045 carbon steel is extensively used for all kinds of components used in machine tool as well as automobile industries such as gears, spindles, pinions, shafts, tilting levers, gudgeon pins and similar parts of machinery. In appendix, table 4A indicates the mechanical properties and chemical composition of International Standard steels that are mainly used.

2.2 Literature surveys

Pearson E. A. (1998), Careful consideration of materials selection, prior microstructure, and geometrical features in a part's design stage can pay off big in subsequent prototype heat treat development and production processing.

Dughiero F, and Battistetti M. (1989), An inverse problem concerning the industrial process of steel bars hardening and tempering is considered. The associated optimization problem is formulated in terms of membership functions and, for the sake of comparison, also in terms of quadratic residuals; both geometric and electromagnetic design variables have been considered. The numerical solution is achieved by coupling a finite difference procedure for the calculation of the electromagnetic; and thermal fields to a deterministic strategy of minimization based on modified Fletcher and Reeves method.

Amstead B. H., Ostwald P. F. and Begeman M. L. (1990), An important feature of induction hardening is its rapidity of action, since it requires only a few seconds to heat a depth 3.2 mm. The actual time will depend primarily upon the frequency used, power input, and depth of hardening required.

Neely J. E. (1994), When a soft, tough core and an extremely hard outside surface are needed, one of several case-hardening techniques is used on the low carbon steels. It should be noted that surface hardening is not necessarily the same as carburizing case hardening. Induction hardening on the surfaces of gears, lathe ways and many products depend on the carbon that is already contained in the ferrous metal. The surface of the part is generally hardened from 1/32 to 1/8 inches deep.

In *Advanced Materials & Processes*, Aug98, Vol. 154 Issue 2, they mentioned about surface heating by induction is used primarily in the surface hardening of steel parts such as gears and shafts. In this type of application, high power densities and short heating times are used when thin cases are required.

Typical power ratings for induction surface hardening are based on the need to very rapidly heat to austenitizing temperature, and have proven to be appropriate through years of experience. When using these or other fixed ratings, however, the effect of heating time on case depth (graph) also must be considered.

For greater depths of hardening, lower kilowatt inputs are used. These values are based on use of proper frequency and normal overall operating efficiency of equipment. These values may be used for both static and progressive methods of heating; however, for some applications, higher inputs can be used for progressive hardening. Kilowattage is read as maximum during heat cycle. Low kilowatt input may be used when generator capacity is limited. These kilowatt values may be used to calculate largest part hardened (single shot method) with a given generator.

Ochi T., Kanisawa H., Sato H. and Watanabe T. (1997), An increase in the torsional strength of automotive shafts has been a subject of particular interest. Induction hardening can afford a medium-carbon steel shaft desirable torsional strength. When case hardness exceeded a certain level, the fracture mode of some test-pieces changed from mode 3 to mode 1 with intergranular fracture. The purpose of this study is to establish a method of increasing strength of shaft steels to mode 1 fracture. The effects of carbon, silicon and molybdenum on torsional strength in mode 1 fracture were investigated.

Kim W. B. and Na S. J. (1993), High frequency induction heating is a method of surface treatment which restricts the hardening area using the skin effect. Since the penetration depth of the magnetic field in the workpiece is dependent on the frequency, the required size of hardening area can be obtained by selecting an appropriate frequency. In this study the transient heat flow and thermal stress were analysed for the high frequency induction surface hardening of a blade mould by using the modified two-dimensional finite element method. Besides the volume change in the phase transformation, the effect of transformation plasticity was also considered as an additional strain in the numerical analysis of the high frequency induction hardening process.