An Investigative Study on Enhancement of Hardness of Low Carbon Steel

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Abstract – Mild steel also known as plain-carbon steel, is the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications, more so than iron. Low-carbon steel contains approximately 0.05 to 0.32% C and are ductile, malleable, tough, machinable and weldable. Heat treatment is the only option to increase the hardness of low carbon steels which cannot be hardened in cold working. When heat treatment is chosen to increase the hardness in case of low carbon steels, only the Hardening operation is considered. Heat treatment is an operation that involves heating the steel to temperatures around 850–900ºC and quenching them to achieve a Martensitic Microstructure. The material which possesses martensitic structure is treated as hardened highly and easily. Heat treatments to form martensite are generally applied to steels containing more than 0.3% C. In these steels, the gains in hardness are most substantial. But, steels containing less than 0.3% C are difficult to harden in heavy sections as they can't obtain martensite as micro structure. In this work, different types of quenching media had been selected to investigate their influence on hardness at different quenching temperatures.The prime object of this investigation is toillustrate the effect of heat treatment on low carbon steel (AISI 1020) to expose its mechanical property(hardness) and microstructural (microstructures) properties.

Index Terms – Plain-carbon steel, Heat treatment, martensitic structure, quenching media, hardness, microstructures.

1. HEAT TREATMENT- INTRODUCTION

Heat Treatment is an endeavour to obtain the maximum efficiency of the material under the demanding conditions of service. Steel is an outstanding versatile engineering material. Metals Hand Book defines heat treatment as, "A combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties, that is, it as an operation or combination of operations of heating and cooling of a solid metal or an alloy to endow it with certain predetermined physical and mechanical properties". These properties are dependent on the microstructure of the alloy, i.e., the nature, shape, size, distribution and amount of these micro-constituents, which are controlled by the changes in the alloy composition and the heat treatment. [1]

1.1. Stages of heat treatment

Heat treating is accomplished in three major stages:

Stage l: Heating the metal slowly to ensure a uniform temperature

Stage 2: Soaking (holding) the metal at a given temperature for a given time and cooling the metal to room temperature.

Stage 3: Cooling the metal to room temperature

1.1.1. Heating stage

The primary objective in the heating stage is to maintain uniform temperatures. If uneven heating occurs, one section of a part can expand faster than another and result in distortion or cracking. Uniform temperatures are attained by slow heating. The heating rate of a part depends on several factors. One important factor is the heat conductivity of the metal. A metal with a high-heat conductivity heats at a faster rate than one with a low conductivity. Also, the condition of the metal determines the rate at which it may be heated. The heating rate for hardened tools and parts should be slower than unstressed or untreated metals. Finally, size and cross section figure into the heating rate. Parts with a large cross section require slower heating rates to allow the interior temperature to remain close to the surface temperature that prevents warping or cracking. Parts with uneven cross sections experience uneven heating; however, such parts are less apt to be cracked or excessively warped when the heating rate is kept slow.

1.1.2. Soaking stage

After the metal is heated to the proper temperature, it is held at that temperature until the desired internal structural changes take place. This process is called SOAKING. The length of time held at the proper temperature is called the SOAKING PERIOD. The is used for metals that require a rapid cooling rate, and soaking period depends on the chemical analysis of the oil mixtures are more suitable for metals that need a metal and the mass of the part. When steel parts are slower rate of cooling. Generally, carbon steels are uneven in cross section, the soaking period is deter-water-hardened and alloy steels are oil-hardened. Ferrous metals are normally quenched in water.

During the soaking stage, the temperature of the metal is rarely brought from room temperature to the final temperature in one operation; instead, the steel is slowly heated to a temperature just below the point at which the change takes place and then it is held at that temperature until the heat is equalized throughout the metal. We call this process PREHEATING. Following preheat; the metal is quickly heated to the final required temperature.

When a part has an intricate design, it may have to be preheated at more than one temperature to prevent cracking and excessive warping. For example, assume an intricate part needs to be heated to 815°C for hardening. This part could be slowly heated to 315°C, soaked at this temperature, then heated slowly to 650°C, and then soaked at that temperature. Following the final preheat, the part should then be heated quickly to the hardening temperature of 815°C.

NOTE: Nonferrous metals are seldom preheated, because they usually do not require it, and preheating can cause an increase in the grain size in these metals.

1.1.3. Cooling stage

After a metal has been soaked, it must be returned to room temperature to complete the heat-treating process. To cool the metal, it can be placed in direct contact with a cooling medium composed of a gas, liquid, solid, or combination of these. The rate at which the metal is cooled depends on the metal and the properties desired. The rate of cooling depends on the medium; therefore, the choice of a cooling medium has an important influence on the properties desired. Quenching is the procedure used for cooling metal rapidly in oil, water, brine, or some other medium. Because most metals are cooled rapidly during the hardening process, quenching is usually associated with hardening; however, quenching does not always result in an increase in hardness; for example, to anneal copper, you usually quench it in water. Other metals, such as air-hardened steels, are cooled at a relatively slow rate for hardening. Some metals crack easily or warp during quenching, and others suffer no ill effects; therefore the quenching medium must be chosen to fit the metal. Brine or water is used for metals that require a rapid cooling rate, and oil mixtures are more suitable for metals that need a slower rate of cooling. Generally, carbon steels are water-hardened and alloy steels are oil-hardened. Non-ferrous metals are normally quenched in water.

1.2. Objectives of heat treatment:

The main objectives of heat treatment as follows:

- to increase strength, hardness and wear resistance *(bulk hardening, surface hardening)*
- to increase ductility and softness *(tempering, re-crystallization annealing)*
- to increase toughness *(tempering, re-crystallization annealing)*
- to obtain fine grain size *(re-crystallization annealing, full annealing, normalizing)*
- to remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding *(stress relief annealing)*
- to improve machinability *(full annealing and normalizing)*
- to improve cutting properties of tool steels *(hardening and tempering)*
- to improve surface properties *(surface hardening, corrosion resistance-stabilizing treatment and high temperature resistance-precipitation hardening, surface treatment)*
- to improve electrical properties *(re-crystallization, tempering, age hardening)*
- to improve magnetic properties *(hardening, phase transformation)*

2. EXPERIMENTAL PROCEDURE

In this project, the main focus was concentrated on enhancement of hardness of the selected low carbon steel, i.e., Mild steel (AISI 1020) by a heat treatment process, HARDENING. It was discussed earlier in Chapter-1, that there are certain heat treatment variables that affect the microstructure and properties of any metal. Amongst those variables few such as Type of process (Hardening in this project), Quenchant type, and Quench rate had been selected for experimental investigation of enhancement of hardness of the selected mild steel in this project and its microstructure also studied under controlled environment.

2.1. Hardening

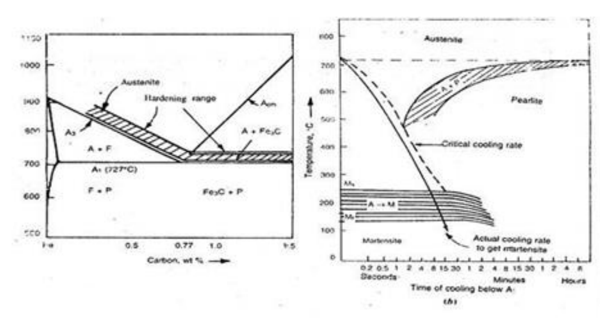

Fig 1: Hardening of steels (A) Austenitising range for hardening of plain carbon steels, A= Austenite, F= Ferrite, P= Perlite, (B) CCT curve of eutectoid steel. Critical Cooling Rate as well as rate faster than this illustrated.

Martensite is the hardest micro-structure that can be produced in any carbon steel, but it can be produced only if the transformation of Austenite to mixtures of ferrite and carbide is avoided by faster cooling (quenching) the steel. Hardening consists of heating the steel to proper austenitizing temperature, soaking at this temperature to get fine grained and homogeneous austenite and then cooling the steel at a rate faster than its critical cooling rate (Fig 1 B.).Such cooling is called quenching. Normally, carbon steels are quenched in water, alloy steels in oil.

2.2. Objectives of hardening

1. Main aim of hardening tools is to induce high hardness. The cutting property of the tool is directly proportional to the hardness of the steel.

2. Many machine parts and all tools are also hardened to achieve high wear resistance. Higher is the hardness, higher is the wear and abrasion resistance. For examples, spindles, gears, shafts, cams, etc.

3. The main objective of hardening the machine components made of structural steels of the pearlitic class is, to develop high, yield strength with good toughness and ductility, so that higher working stresses are allowed. But higher yield strength (and tensile strength) with good toughness and ductility are achieved not in the hardened state, but after high temperature tempering of hardened steels, i.e., hardening is done of structural steels, to prepare the structure for certain transformations which take place during tempering. Tempered structures have high toughness and ductility, the value of which in the hardened state is nearly zero.

2.3. Process of quenching

This experiment was performed to harden the plain carbon steel (Mild Steel). The process involvedputting the red hot mild steel directly in to a liquid medium.

a) The specimen was heated to the temp of around 900 ^{0}C and wereallowed to homogenize at that temp.

b) An oil bath was maintained at a constant temperature in which the specimen hadto be put.

c) After attaining the homogenization, the specimen was taken out of the furnace and directly quenched inthe oil bath.

d) After around half an hour the specimen was taken out of the bath and cleanedproperly.

e) Now the specimen attains the liquid bath temp within few minutes. But the rateof cooling is very fast because the liquid doesn't release heat readily.

2.4**.** General characteristics of quenching media

The effectiveness of a quenching medium to provide desired cooling rate depends on its characteristics such as [2]:

1. Temperature of the coolant: in water and brine, the cooling rate decreases as the temperature of the coolant increases. Oils show increased cooling rate with the rise of temperature.
2. Boiling point: lesser is the boiling point of a coolant, more easily the vapours form to increase the cooling rate. Coolants of higher boiling point should provide better cooling rate.
3. Specific heat of coolant: A coolant with low specific heat will get heated up at a faster rate than the one with higher specific heat.
4. Latent heat of vaporisation: A coolant with low latent heat of vaporisation changes into vapour easily, and thus provides slower cooling rate.
5. Thermal conductivity of the coolant: A coolant with high thermal conductivity transfers the heat rapidly from the component to its entire mass increasing cooling rate of component.
6. Viscosity: the coolant with low viscosity not only provides faster rate of cooling, but decreases the vapour-blanket stage.
7. Velocity past the immersed object or agitation of the object: Both these factors help in maintaining uniform temperature of the cooling bath.

2.5. General requirements of a quenching medium

Though the main requirement of a quenching medium is to provide the desired rate of cooling, however, the commercial adaptability depends on:

- ❖ General ability.
- ❖ Low cost.
- ❖ The cooling characteristics should be stable with continued use, and with moderate changes in temperature.
- ❖ Corroding action on steels components, containers.
- ❖ Fire hazards.
- ❖ Ease of handling.

3. EXPERIMENTATION

The experimental procedure for the project work can be listed as:

1) Specimen preparation

2) Heat treatment

3) Hardness measurement

4) Microstructure study

3.1. Specimen preparation

Fig 2: Photographical view of Specimen

The first and foremost job for the experiment is the specimen preparation. Thespecimen size should be compatible to the machine specifications. The samples were obtained from the same material suppliedby a mild steel trader. The sample chosen was Mild steel, AISI 1020. It is one of the American standard specifications of the mildsteel having the pearlitic matrix (up to70%) with relatively less amount of ferrite(30-40%). And so it has low hardness with moderate ductility and high strength asspecified below. So it is said that it is basically a pearlitic/ferritic matrix. [3]

The chemical composition of the steel studied is close to nominal composition of AISI 1020. Thechemical composition of the steel studied is given in Table 1.

Table 1: The composition of the selected specimen, AISI 1020.

C	Si	Mn	Cr	Ni	P	S	Fe
0.20	0.22	0.66	0.055	0.18	0.015	0.028	Balanced

3.2. Heat treatment

Low Carbon Steel is primarily heat treated to create matrix microstructures andassociated mechanical properties not readily obtained in the as-cast condition. Ascastmatrix microstructures usually consist of ferrite or pearlite or combinations ofboth, depending on cast section size and/or alloy composition The principleobjective of the project is to carry out the heat treatment of Low carbon steel andthen to measure hardness and to study micro structure. Only hardening process of heat treatment had been adopted in this project.

The hardening treatment had been carried out with various quenchants maintained at different temperatures. The quenchants are maintained at (1) Room temperature, (2) 20^{0}C above room temperature, (3) 40^{0}C above room temperature.

The quenchants had been selected as per the requirements mentioned above and the used quenchants in this project are:

- Water
- Air
- Coconut oil
- Neem oil
- Brine solution
- Sun flower oil
- 2-T oil

3.3. Hardness measurement

After performing all the experiments, the samples were settled to cool to the room temperature and then their hardness was measured using hardness tester in both Brinell (BHN) and Rockwell (RHN) as shown below.[4]

Fig 3: Hardness Tester

3.4. Hardness test methods:

1) Brinell Test Method

All Brinell tests use a carbide ball indenter. The test procedure is as follows:

- The indenter is pressed into the sample by an accurately controlled test force.
- The force is maintained for a specific dwell time, normally 10 - 15 seconds.
- After the dwell time is complete, the indenter is removed leaving a round indent in the sample.
- The size of the indent is determined optically by measuring two diagonals of the round indent using either a portable microscope or one that is integrated with the load application device.

The Brinell hardness number is a function of the test force divided by the curved surface area of the indent. The indentation is considered to be spherical with a radius equal to half the diameter of the ball. The average of the two diagonals is used in the following formula to calculate the Brinell hardness.

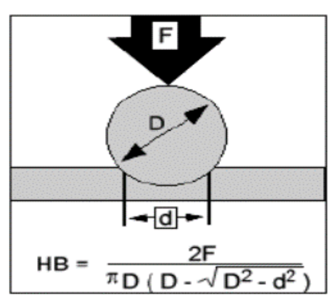

Fig 4:Brinell hardness Test method.

where:

HB = the Brinell hardness number

F = the imposed load in kg

D = the diameter of the spherical indenter in mm

d = diameter of the resulting indenter impression in mm

2)Rockwell Hardness Test

Types of the Rockwell Test

There are two types of Rockwell tests:

1. Rockwell: the minor load is 10 kgf, the major load is 60, 100, or 150 kgf.

2. Superficial Rockwell: the minor load is 3 kgf and major loads are 15, 30, or 45 kgf.

In both tests, the indenter may be either a diamond cone or steel ball, depending upon the characteristics of the material being tested.

Rockwell Scales

Rockwell hardness values are expressed as a combination of a hardness number and a scale symbol representing the indenter and the minor and major loads. The hardness number is expressed by the symbol HR and the scale designation.

There are 30 different scales. The majority of applications are covered by the Rockwell C and B scales for testing steel, brass, and other metals. However, the increasing use of materials other than steel and brass as well as thin materials necessitates a basic knowledge of the factors that must be considered in choosing the correct scale to ensure an accurate Rockwell test. The choice is not only between the regular hardness test and superficial hardness test, with three different major loads for each, but also between the diamond indenter and the 1/16, 1/8, 1/4 and 1/2 in. diameter steel ball indenters.

For soft materials such as copper alloys, soft steel, and aluminum alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the "B" scale. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. There are several Rockwell scales other than the "B" & "C" scales, (which are called the common scales). A properly reported Rockwell value will have the hardness number followed by "HR" (Hardness Rockwell) and the scale letter. For example, 50 HRB indicates that the material has a hardness reading of 50 on the B scale.

If no specification exists or there is doubt about the suitability of the specified scale, an analysis should be made of the following factors that control scale selection:

- ✓ Type of material
- ✓ Specimen thickness
- ✓ Test location
- ✓ Scale limitations

Rockwell testing machine uses two loads with one is applied directly after the other. The first load (known as the minor load) of 10 kg is applied to the sample to help seat the indenter and remove the effects, in the test, of any surface irregularities. The purpose of the minor load is to create a uniformly shaped surface for the application of the major load. The difference in the depth of the indentation between the minor and major loads provides the Rockwell hardness number.

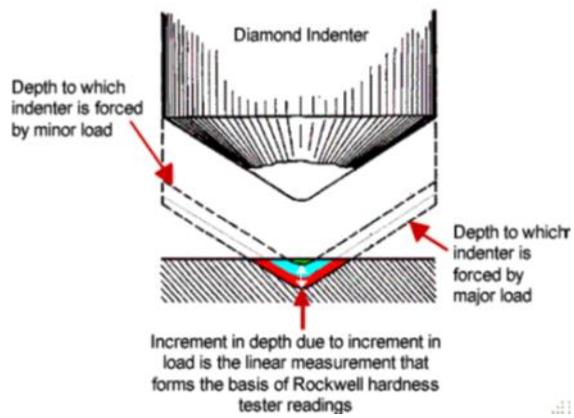

Fig 5: Rockwell hardness Test method.

The standardized a set of scales (ranges) for Rockwell hardness testing under use is normally designated by a letter. This set is given below.

- ❖ A scale – It is used for cemented carbides, thin steel, and shallow case hardened steel.
- ❖ B scale – It is used for copper alloys, soft steels, aluminum alloys, and malleable iron, etc.
- ❖ C scale – It is used for steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than the harness value of B100.
- ❖ D scale – it is used for thin steel, medium case hardened steel, and pearlitic malleable cast iron.
- ❖ E scale – It is used for cast iron, aluminum and magnesium alloys, and bearing metals.
- ❖ F scale – It is used for annealed copper alloys and thin soft sheet metals.
- ❖ G scale – It is used for phosphor bronze, beryllium copper, and malleable irons.
- ❖ H scale – It is used for aluminum, zinc, and lead.

- K, L, M, P, R, S, and V scales – They are used for bearing metals and other very soft or thin materials, including plastics.

3.5. Microstructure study

The study of micro structure had also been studied with the help of standard metallurgical microscope and other equipment discussed below.

3.5.1. Apparatus / equipment used in this study:

1 Abrasive Cut-Off Wheel Machine: This Equipment is used to cut the sample pieces form the component of all kind of materials. These sample pieces can be used microscopic observation.

2 Specimen Mounting Press: This Equipment is used to mount specimen in bakelite. Particularly is useful in hot mounting process.

3. Belt Finishing Machine**:** This Equipment is used for rough Grinding of the Specimen.

4. Polishing Machine: This Equipment is used to polish the specimen after rough grinding with the help of polishing clothe. It also useful for rough grinding with grinding disc.

5. Metallurgical Microscope: This Microscope is used for microscopic observation of specimen with the adjustable magnification.

4. RESULTS AND DISCUSSIONS

4.1. Results:

All the specimen are tested for hardness and the results are tabulated as shown in the table 2.

*RT- room temperature and in this case it was 35^{0}C.

The initial hardness of the MS specimen before heat treatment: 38 RHN (91 BHN)

4.2. Discussions:

From the various experiments carried out following observations and inferenceswere made. It was seen that the various tensile properties followed a particularsequence:

1) More is the tempering temperature, less is the hardness or more is the softness (ductility) induced in the quenched specimen. (Ductility) induced in the quenched specimen.

2) Microstructure photographs taken by SEM and metallurgical inspectionsindicated that the surfaces of heat treated samples are martensitic.

3) The findings from the study showed that water quenched specimens proved superior to other specimens quenched in air, furnace and oil, respectively with respect to high strength properties, Brinell hardness. Water being relatively more readily available than other quenchants except air, easy to use and safe to handle is preferred. But there is a high risk of distortion/crack formation in the hardened component.

Quenching media	Temperature^{0}C					
	Room temperature (*RT)		*RT+20^{0}C		*RT+40^{0}C	
	RHN	BHN	RHN	BHN	RHN	BHN
WATER	122	292	81	153	91	190
BRINE SOLU.	81	153	95	210	97	222
AIR	71	127	97	222		
COCONUT OIL	112	269	99	234	95	210
NEEM OIL	89	180	70	125	75	137
2-T OIL	89	180	82	156	77	141
SUN FLOWER OIL	79	147	89	180	88	176

Table 2: Hardness of specimen quenched in different quenchants at different quenching temperatures.

4) It is observed that, coconut oil also imparts high hardness to low carbon steel as that of water. It gives a little more high hardness to the steel when the quenchants are maintained at high temperatures than room temperature (refer fig: 5.2). It may be due to the density and viscosity changes of coconut oil. Moreover, the surface of the steel component was also smooth and no there was no chance to distortion. But, in case of water as a quenchant, there is a chance of distortion during hardening process and hence tempering process should be followed.

5) It may be observed that, in case of Brine Solution, it gives less hardness at room temperature and hardness values increase with an increase in quenchant temperature. Brine is amore severe quench medium than water but it may tend to accelerate corrosion problems unless completely removed. In this study brine imparted good hardness in low carbon steels.

5. CONCLUSIONS

From the various results obtained during the project work it may be concluded thatthe mechanical properties vary depending upon the various heat treatmentprocesses. Hence depending upon the properties and applications required weshould go for a suitable heat treatment processes.

Tests were carried out to determine the effects of heat treatment on the hardness of locally available mild steel using different quenchants. The findings from the study showed that water quenched specimens proved superior to other specimens quenched in air**,** Brine solution, Coconut oil, Neem oil, 2-T oil.

Water being relatively more readily available than other quenchants except air, easy to use and safe to handle is preferred. It is therefore concluded that from the standpoint of strength and economy that water quenching should be used for heat-treating mild steel components. Waterquench includes its oxidizing nature,its corrosivity and the tendency to excessive distortion and cracking in case of plain carbon steels.

But it may also be concluded that, vegetable oil e.g., Coconut oil also imparted high hardness to the mild steel components almost equal to that of water and better texture too. Coconut oil and brine may be used in place of water where high hardness is required with less distortion. With these quenchants, there may be a less chance of formation of cracks in low carbon steels.

The advantages of using air are that distortion is negligible and that the steel can easily be straightened during cooling process.One drawback here is that the surface may be oxidized by this type of cooling.

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