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Impact of Quenching on the Hardenability of Steels EN-3 (~1015), EN-8 (~1040) and EN-24 (~4340) during Jominy End Quench Technique

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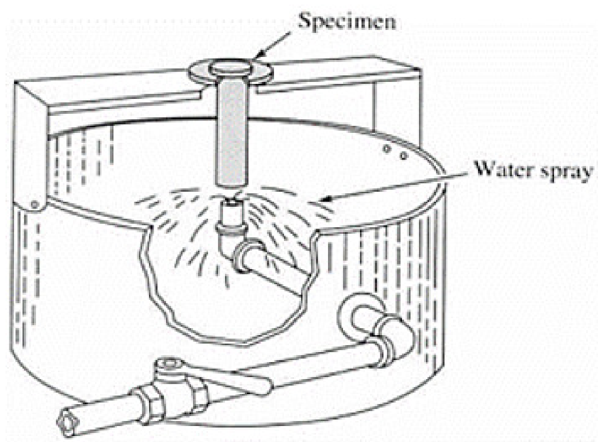
ABSTRACT: In this study, the effect of cooling rate on the hardenability of different steels materials following ASTM A255 standard test methods using the Jominy end quench technique. Steel hardening is implemented to enhance strength and wear characteristics. A reasonable carbon and alloy content are one of the guiding principles for the hardening. If the carbon content is adequate the steel can be immediately hardened. If not, the surface of the component needs to be reinforced with carbon by using diffusion solution hardening techniques. To have a better understanding of the test, three specimens with different properties were used and they are EN-3 (~1015), EN-8 (~1040), and EN-24 (~4340). The temperature of the oven was first raised to 900℃ and the three samples were then placed inside the oven for one hour to obtain the desired internal structure and to transform the structure of the EN steels to FCC microstructure. They were then cooled and then ground for easy markings of the positions. An indentation test was performed on each of the specimens by the Rockwell hardness method and this was carried out under ASTM E18 standard test methods, its value was recorded with the corresponding position. The results of the experiment revealed that sample EN-3 (~1015) produces 87 HRC hardness value at 9.0 mm position at the start and 50 HRC at the position of 97.3 mm, likewise EN-8 (~1040) produces 64 HRC hardness value at 3.0 mm depth and concluded with 43 HRC hardness value at 87.7 mm. In the case of EN-24 (~4340), the initial position where the quench started which is at 3. 8 mm produces the hardness value of 74 HRC and towards the end of the quenching position, at 103.2 mm the hardness value was seen to be 66 HRC. The data collected from the experiment is of crucial importance in the selection of the correct alloy steel and heat treatment to reduce thermal stress and fracture whenever mechanical devices of various shapes and sizes are to be made, and it also helps the engineer to provide the most appropriate type of material for a task to be carried out.

Keywords: Cooling rate, Jominy end quench test, Steel, Hardenability, Rockwell hardness, Quenching.

I. INTRODUCTION

Hardenability of steel is said to be the tendency of the steel to harden in depth when undergoing cooling by quenching and this property of steel describes how the steel transforms to martensite as a result of quenching from its austenitizing temperature to form either bainite, ferrite, or pearlite. This property is worth investigating like all the other material properties. Several factors influenced the hardenability of material such as the grain size, carbon content, and the alloying percentage content [1]. One must not confuse the hardness of steel to the hardenability of steel. It is very essential to distinguish the two words. The hardness of steel is an ability of a material to resist scratching or indentation whereas hardenability is the capacity of the steel to be hardened under the quenching condition. The Jominy end quench method is one of the techniques known for determining the hardenability of materials especially steel materials. The need for steel is gradually increasing as the technology gets more advance, and as the needs for human needs also increase. Ever since steel was discovered it has proved to have a great influence on the lives of human beings [2]. There are many types of steels available in the market, carbon steel with an alloy of iron (Fe) as well as carbon(C) are amongst the major steels. The availability of carbon in steel plays a great role. Steel is categorized with some factors including hot and cold formable, machinability, weldability, hardness, ability to resist corrosion, heat resistance as well as resistance to deformation at very high temperature. In design, during the material selection process, the design engineer needs to know the hardenability of the materials. Jominy end-quench is amongst the standard method that can help by providing the design engineer with the necessary information in hardenability.



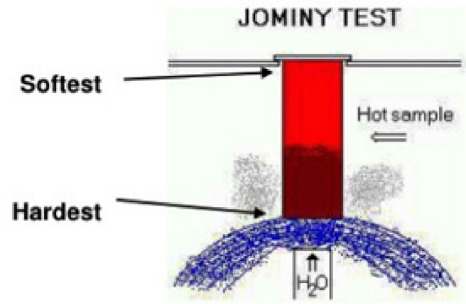


Fig. 1. (a) illustration of the setup of a Jominy end quench technique (b) Showing the hard end and softer end of the sample [1]

However, it has been established that hardenability depends primarily on the chemical composition of steel alloy [3]. The Jominy end quench technique is an experiment that is used to analyze the hardenability of substance using the Rockwell hardness test. Walter E. Jominy as well as A.L. Boegehold are the metallurgists behind the Jominy quench technique. They experimented on the hypothesis that a heated metal when quenched, the area in the immediate contact with the coolant (water) is instantaneously cooled and eventually the temperature will be uniform throughout the specimen [1, 3-4].

The specimen in Fig. 1(a) above is first prepared in the oven with an optimum temperature of 900℃, this is done to transform the structure of the EN steels to the FCC microstructure as it is the one which describes more the hardenability of a material. The process in Figure 1b is what is being referred to as quenching that is cooling the hot metal from the oven [2]. The Jominy end-quench technique works to the advantage of the manufacturing industries. It helps in knowing which steel has the greatest hardenability for industrial use such as drilling and tuning. It is very essential to have some knowledge about the type of machine that was used to conduct the practical. The Rockwell Hardness test was used to measure the length of the concavity over the force that was applied which is 60 kg [4]. The machine can test and measure any metal that was exposed to heating. It helps in providing the relevant properties for any metal especially tensile strength as well as the ductility of a metal. Steel is one of the most used alloy metals in many engineering sectors, but different types of steel apply to different types of problems therefore the hardenability of the steel is also a major property that should be of considerations. The Jominy quench technique is an experiment used to determine the hardenability of steel. The information obtained from this test can also be used to under-study its effects on microstructure and alloys of steel. Hardenability is how much is the ability of the iron-carbon alloy to undergo hardening by forming martensite. The higher the hardenability, the higher the martensite content in the steel volume" [3]. Hardenability is also associated with the carbon content especially the carbon content dissolved in austenite. As carbon content increases, the transformation from austenite to martensite becomes difficult resulting in lower strength [4]. Fig. 2 shows the graphical presentation of the percentage of carbon in the steel.

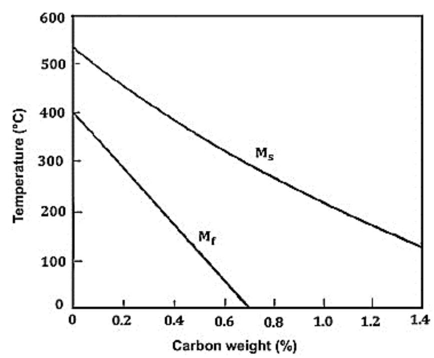


Fig. 2. Effect of the composition of carbon in steel [4].

As carbon content increases, it influences the end of martensite formation (M_f) relatively to the martensite start formation(M_s), this occurs as the temperature is lowered as shown in Fig. 2. In the above figure, it can be seen that as the carbon increases above 0.6 %, the transformation to martensite is likely to be incomplete if the process is halted at 0℃ or higher" [4].

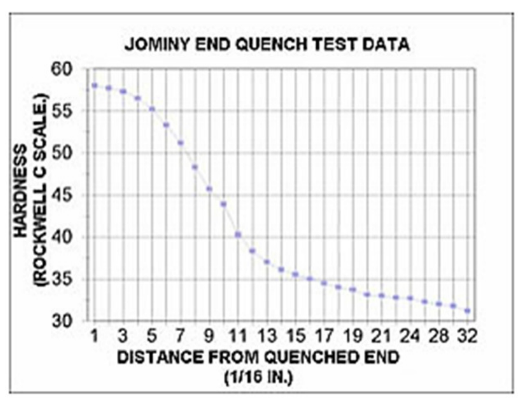


Fig. 3. Theoretical graph of Jominy test [4]

Fig. 3 shows an ideal graph of the Jominy test. The Rockwell scale decreases as the position away from the quenched end increases, this can be attributed to different factors especially grain size as well as cooling rate [5]. The hardness of steel is practically influenced by the amount of carbon content in steel and this can be demonstrated in Fig. 4.

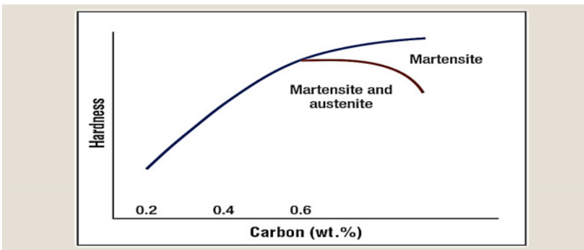


Fig. 4. Influence of carbon on the hardness of steel.

— Low carbon steel- has been known for composition between 0.05% to 0.25% carbon. This is also referred to as mild steel, which is inexpensive and easy to shape. It is much softer than the high carbon steels but when carburized its surface hardness also improves.

— Medium carbon steel- has been known for the composition of carbon between 0.29% to 0.54%. It has ductility attributes and is very strong, with long-wearing properties.

— High carbon steel - has been known for composition between 0.55 % to 0.95 % carbon. It plays pivoted roles in shape memory and it is very strong, it is ideal for producing springs and wires.

— Very high carbon steel - has been known for composition between 0.96 % to 2.1% carbon. It is extremely strong due to its high carbon content. it is also brittle and hence not used in most applications due to it requiring extra handling.

Hardening is one of the significant and most valuable characteristics of alloy steel. Hardening indicates the rate at which a specimen should be cooled. Consider the phase diagram in Fig. 5.

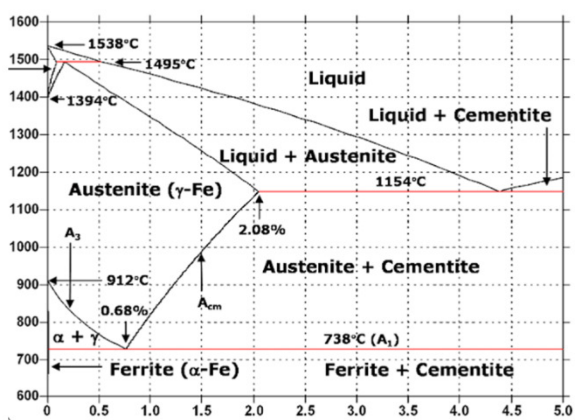


Fig. 5. Showing a phase diagram [6].

It outlines the solubility limits of iron and its changes at equilibrium. The diagram is significant in the sense that it is the fundamental pre-requisite of understanding heat treatment. Phase diagrams illustrate changes in the temperature and composition of an element. At the boundaries of the diagram a two-phase mixture exists. The diagram has a triple point, this is the point where three phases of an element are in equilibrium. The diagram also indicates a phase boundary, this is where two phases of an element occur at once. Eutectoid steel has a carbon composition of about 0.7, steel having a carbon composition that is less than 0.71 is known to be hypo-eutectoid and steel a carbon content above 0.71 is called the hypereutectoid steel [6].

Hypo-eutectic steel has less than the eutectoid carbon composition. Cementite forms between the boundary of austenite and cementite fields. The area of phase diagram labelled austenite with Greek letter gamma is a face-cantered-cubic and the area labelled ferrite with a Greek letter alpha is body-cantered-cubic [7].

Within the engineering field, it is essential to note or be aware of techniques that helps in determining the properties of a material. The main focal point of the experiment is to determine the hardness of three different specimens with different carbon content and alloying elements. A Jominy End-quench test is used in this case to examine the hardenability of the specimen. The practical was conducted using the Rockwell test machine. The test or the experiment requires that the students and the demonstrators follow the precautionary measures as the Rockwell test machine generates an excessive amount of heat which might harm the skin. The demonstrators were also aware of the specimen after removing it from the oven as it was very hot and highly impossible to hold it with bare hands. Steel plays a significant role in our lives; it is on-demand since it is needed in the manufacturing of several devices. With several different applications, different properties of steel are required to serve different purposes [8]. Therefore, several processes are required to be carried in other to achieve different properties. This report, therefore, consists of information that was collected through experimental research for hardenability. Three different specimens, with a different chemical composition, were used to investigate the factors affecting hardening.

In this study, we analyzed the hardenability of steel samples of different compositions. This experiment is aimed at investigating the hardenability of the steel alloy by heating it with specific temperature and then cool the specimen so that transformation can take place and phase change must have been established. The process is popularly known as the Jominy end-quench technique. The main objective of the experiment is to find the hardenability of steel through heat treatment. The hardenability of steel is considered as the length difference or the increment after the specimen has been treated with heat until it reaches a certain hardness level. As the workpiece undergoes through heat treatment, the exterior of the specimen cools off very quickly compared to the interior of the specimen simply because the exterior of the steelwork has direct contact with the water during the cooling process [9]. The quenching process is mainly based on providing the result of a Martensite from an ordinary steel alloy. Applying the heat treatment to a metal alloy will help in providing the relevant properties of steel, although heat treatment can be used for many purposes such as increasing the hardenability of metal or softening the metal.

The temperature that was used in the quenching machine was 900℃ which was constant although the experiment. The higher the martensite fractions develop, the higher the harness [10]. The size of the steel has a major impact on the hardenability of the steel after being quenched.

II. MATERIALS, EXPERIMENTAL SETUP AND PROCEDURE

A. Materials

Three cylindrical bar of steels specimens in which each is 100 mm long and 25 mm in diameter are at ferrite stage and are made from (EN-3(1015) 0.15 % Carbon, EN-8(1040) 0.4 % Carbon as well as EN-24(SAE 4340) 0.4 % Carbon, 0.25 % Molybdenum, 1.8 % Nickel, and 0.6 % Chromium steels) are the materials used in this study. The samples were heat-treated and milled to a certain depth. The Specimens were prepared according to ASTM A255 [11] for the hardening test. A load of 60 kg was used for the test. EN-3 and EN-8 are both carbon steels with 0.15 % C and 0.4 % C content, respectively. They are used in any steel structure. EN-24 is a carbon steel alloy of 0.4 % C, 1.8 % Ni, 0.6 % Cr, and 0.25 % Mo, as any alloy, it is a mixture/addition of different metals for better properties, it is used for more complex applications to cater for many different situations regarding weather, chemical reactions, and environmental impacts. EN-3, EN-8, and EN-24 look the same with a naked eye, whereas the microstructures are different, so in the production, there is a colour code to mark them. EN-3 is painted grey, EN-8 yellow, and lastly EN-24 black. Jominy end-quench test is focusing on the effect of cooling rate, carbon content, and the type of alloy contents in the metal on the hardness of different metals. The metals to be examined need to be heated to the temperature where they reach gamma ferrite state, where it can considerably absorb more carbon [10]. They should then be cooled to room temperature where they will be back to Martensite state

B. Heating process: Kiln Oven

A kiln is an oven or a furnace that is used to heat the steel sample that is to be used during the Jominy test. The oven that was used during this experiment uses a thermostat to regulate the temperature that is required. It uses high temperatures to transform materials into the desired properties [2]. The oven is set at 900 ℃ to prepare the specimens for quenching, this is done to achieve the desired microstructure of the steel that is usually the transformation from BCC to FCC structure. The transferring time from oven to the fixture where the quenching will be done is approximately 5 sec.

C. Quenching process

Quenching refers to a process in which a specimen is rapidly cooled in either water, air, or oil as well as other media to obtain desirable material properties. Quenching reduces the plasticity of the material, materials crystal grain size as well as increasing their hardness [12]. In the experiment, three cylindrical samples specimens of 100 mm length and 25 mm diameter each were used in this study. The steel samples were first normalized to eliminate inherent stresses steel structure as a result of previous processes such as forging. Afterward, the steel is austenized, usually at 900℃. After the specimens are ready from the oven, each testing sample was rapidly transferred to the test machine where it is held vertically at a definite position and sprayed with a control flow of water onto one end of the sample, as shown in Fig. 6, they are quenched for approximately 10 minutes by water. This cools the specimen from one end, and it was noted that as one moves further away from the quenched end, there was a decrease in the cooling rate [13].

The impact of compound expansion significantly affects the combination of steels. Alloying, as a rule, builds the hardenability of steels since it expands the time expected to frame martensite (diminishes the basic cooling rate), subsequently, the steel turns out to be increasingly pliable.

The EN24 steel has higher hardenability value compared to EN3 and EN8 steels of course to affirm that the outcomes relate to the hypothesis that was assembled. It was revealed that steel with a higher percentage of carbon tends to be liable to cracks and distortion during heat treatment, hence difficult to machine in the annealed condition, therefore, machinability is difficult in annealed conditions.

Fig. 6. (a) Jominy end-quench technique, (b) rapidly cooled steel sample by quenching.

D. Grinding process

In the next step, the test specimen was milled flat at one side to a depth of at least 0.38mm to remove decarburized material off the surface. During this grinding process, extra care must be taken to avoid that the samples are heated up by the grinding tools because this can lead to tempering and can eventually soften the steel materials. The grinder is used to create a lining on the specimen for easy position markings on the Rockwell test.

E. Rockwell hardness test

The Rockwell hardness tester is a machine employed to evaluate the hardness of a material by a method of indentation. The process of indentation using Rockwell hardness is done by following the ASTM E18 standard test methods [14]. This is achieved by obtaining the depth of the indentation by the use of over 12 different test techniques. This method of the testing hardness of a material is one of the easiest methods and is more accurate when compared to other hardness testing techniques. The samples were mounted on the Rockwell hardness testing machines one after the other, the Indentations were introduced onto the surface of the samples, the machine was loosened and then the force reapplied to get the hardness value, these dents were done over the length of the sample at different intervals, starting at the end, which was away from the jet, the load on the indenter was marked at 60 Kg and these were also carried out on all three samples. After grinding, the specimen will be ready for the Rockwell hardness test. Different positions are tested for the hardness and the Rockwell value and corresponding position are recorded. Fig. 7 shows the specimens after the removal of decarburized material and quenched, of the three specimens. The specimen is then put through the hardness test, measuring its hardness in intervals along its length, beginning at the quenched end of the specimen. For alloy steels, this interval is usually 1.5 mm and for carbon steels, the interval is usually 0.75 mm.

The Rockwell scale characterizes the indentation hardness of a material by penetrating a material with an indenter and measuring the indenter's depth of penetration. This is a direct indication of the hardness of the material [15]. The Rockwell scale uses a minor load followed by a major load and the penetration made by each is measured and the hardness value is directly read off a dial. The major advantage of the Rockwell hardness test is the display of hardness values directly, eliminating the need for tedious calculations [16].

In this practical, the c-scale is used, which uses a diamond indenter known as a Brale indenter and a 60kg weight (60kgf- kilogram-force) to obtain a value expressed in HRC. The depth of the penetration is translated to a readable scale where the harder a material is, the higher number is given by the scale [17]. Very hard steel materials such as a knife blade can give an HRC of approximately 55-62.

In determining the Rockwell hardness of a material, a material is studied under the application of a minor load followed by the application of a major load. The minor load establishes the zero datum. On this scale- the higher the reading, the harder the material. The penetration depth is inversely proportional to the hardness of a material, as a hard material will have a small penetration depth [18-19].

The equation governing the Rockwell hardness of a material is given by Eqn. 1:

$$HR = N - \frac{d}{s} \tag{1}$$

In a c-scale, the load is 150 Kgf and has a 120° diamond spheroconical indenter with N= 100 and s=0.002mm.

The process of getting the hardness value is as follows and as visually represented in figure 8:

1) Loading of an initial force- in the Rockwell hardness test, the initial force was 10kgf
2) Loading of a main load- in this experiment was 60kgf
3) Holding for a certain time-dwell time
4) Releasing of the load. The Rockwell hardness value will readily display on a dial.

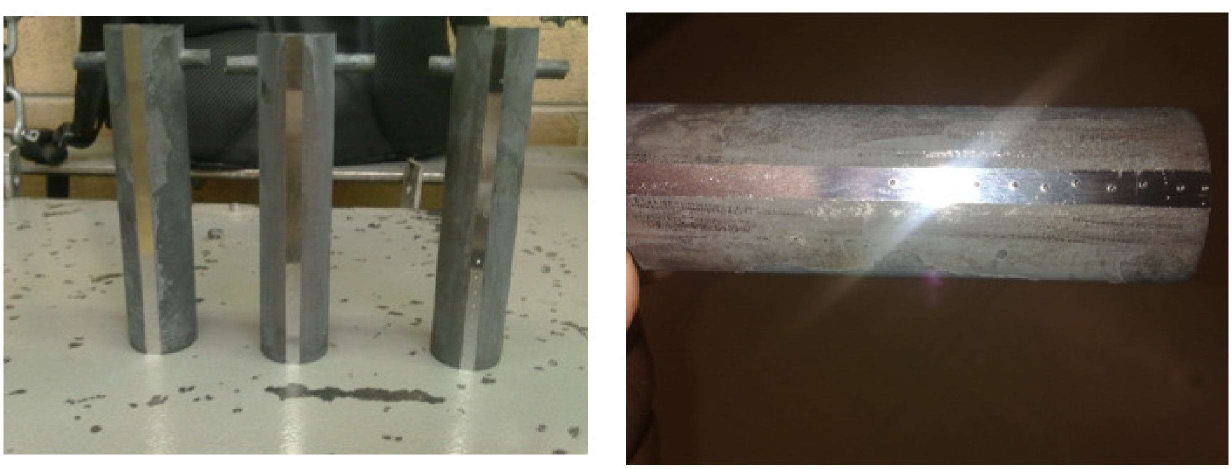


Fig. *7.* Decarburized samples before and after indentation.

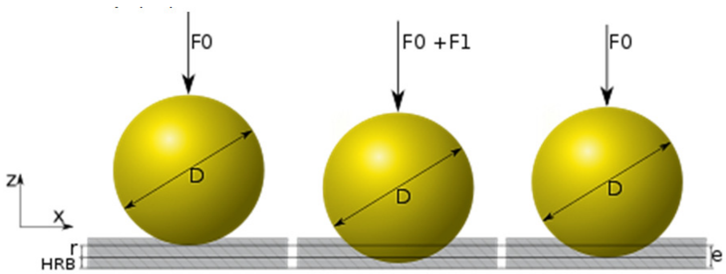


Fig. 8. Force diagram of the Rockwell hardness test [17].

III. RESULTS AND DISCUSSIONS

In the following subsections, the results obtained in the experiment carried out- The Jominy End quench test are tabulated. These results are studied and graphed to deduce conclusions about the tests on the effect of the hardenability of steel during the cooling period. Table 1 is the results of material- EN-3 (~1015), EN-8 (~1040), and EN-24 (~4340). The test specimens were subjected to a load of 60Kgf at a random impact interval. The measurements collected were recorded in Table 1. Comparison of the hardness values of all the three tested samples is presented in Fig. 9. This further reveal the relationship between the impact position from the immediate area where cooling was done and the Rockwell value along the length of the specimen [20].

Table 1 shows the data that was taken during the Rockwell hardness test. Each sample was measured at a different position (depth). EN-3 (~1015) was seen to have followed the rule of hardenability. The areas that were first exposed to running water after heat treatment were seen to have higher hardness value. The measurements start from position 9.0 mm which gives 87 HRC down to when it is 97.3 mm away from the start position and this gave 50 HRC. It was noted in the EN-3 (~1015) that the hardness values decrease as one moves away from the quenching region. The same trends were observed in EN-24 (~4340) and differ in EN-8 (~1040). In the EN-8 (~1040) steel material, the measurement of hardness starts with the position 3.0 which is the region exposed to quenching first, at this point, the value of hardness was 64 and increases until at position 9.3 mm which gave 69 HRC and at position 17 mm the hardness begins to decline and increase again until position 41 mm and last maintained the same hardness value at position 53.1 and 66.6 mm which resulted to 59 HRC and the measurement was brought to conclusion at 87.7 mm with 43 HRC. The hardenability trends that happened in EN-3 (~1015) also manifested in EN-24 (~4340). At the initial position where the quench started which is at 3. 8 mm, the hardness value was 74 HRC and this decreased down the column as the distance from the start of quench is farther apart. At 103.2 mm the hardness value was seen to be 66 HRC. We can infer from Table 1 that the results obtained followed the theoretical assumption of the hardenability of steel.

Table 1: Rockwell values and corresponding impact position.

EN-3 (~1015)		EN-8 (~1040)		EN-24 (~4340)	
Position (mm)	Rockwell value	Position (mm)	Rockwell value	Position (mm)	Rockwell value
9.0	87.0	3.0	64.0	3.8	74
13.5	71.0	4.6	67.5	8.0	71
24.3	59.0	6.8	66.0	13.8	73
36.0	59.0	9.3	69.0	19.0	75
45.7	54.5	17.0	58.0	36.7	70
58.0	55.0	32.6	62.0	49.2	65
68.6	52.0	41.0	62.0	63.4	68
85.0	53.0	53.1	59.0	77.5	67
96.4	50.0	66.6	59.0	90.4	63
107.0	50.0	87.7	43.0	103.2	66

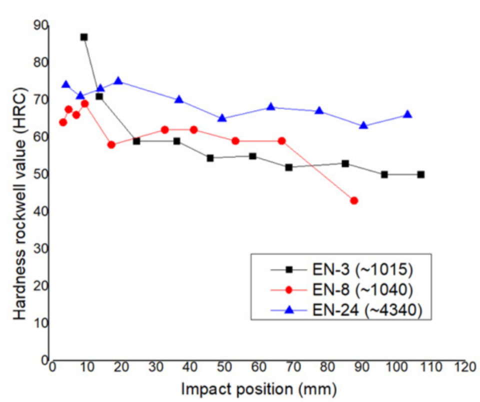


Fig. 9. Comparison of the hardness values of all the three tested samples.

The Rockwell value decreases as the impact position increases as evidence in Fig. 9, deviating from the initial position of the immediate cooling, EN24 has a higher hardenability, followed by EN8 and then EN3. A higher hardenability means that the martensite process is high, and it occurs even at a slow rate of cooling. The other factor which may have affected the hardenability of the different steels is the different grain sizes, the bigger the grain size, the higher the hardenability [5]. The Rockwell number for EN 24 is overall much higher than the Rockwell numbers for the EN-3 and EN 8 samples. The hardness at the quenched end of EN 24 is much higher than that of EN-3 and EN-8, demonstrating the hardening effects of the alloying element. The increase in the rate of cooling increases the hardness of steel. This is because of the effect the rate cooling has on the microstructure of the element. The expansion in the cooling rate results in better grains and brings down the changing temperature of ferrite and pearlite. Ferrite and pearlite structure at lower temperatures, bringing about better ferrite and pearlite grains. Littler grains result in harder steel [21-22].

The Jominy test was done in the correct setup using the prepared samples of steel with the various combinations of carbon content. The samples were heated in the furnace and quenched with water; the hardenability of the samples was measured as the function of the distance from the quenched end of the specimen. To show the different hardenability of the three steel a Rockwell machine was used. Varying hardness was measured along the length of the samples starting at the quenched end, the results were recorded in Table 1 and can be observed on the figures above for the individual samples.

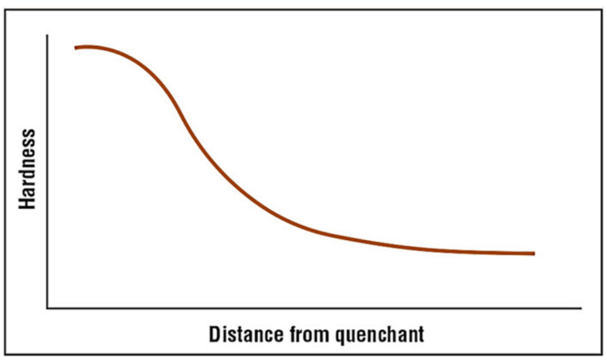


Fig. 10. Trend between hardness and depth.

Theoretically, as the distance from the quenched end increases, the hardness decreases as shown in Fig. 10, and this assertion is also demonstrated in Fig. 9. This shows that the percentage of martensite is decreasing due to the differences in the cooling rate.

IV. CONCLUSION

In this paper an experiment was carried out to observe the hardenability of steel, this showed the importance of the Jominy end quench technique. It showed that there is a change in the hardenability of steel due to the difference in carbon content. This change is as a result of the change of crystal structural grains. The data collected from a Jominy test can be used to determine if a material can be hardened.

The Jominy end quench test experiment was successful as the theoretical graph and the experimental graphs correlated, although it was not an exact match, this was due to experimental errors such as approximation of values, not fully preparing the specimens and also the quench time was almost half the standard time of the ideal. However, the experiment was able to determine the specimen which had a higher hardenability and other factors such as cooling rates and grain sizes were able to be deduced from the experiment.

Conflict of Interest. The authors declared that they have no conflicts of interest.

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