Comparative Study of Hardenability of Ferrous Alloys

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ABSTRACT

The ability of a ferrous alloy to partially transform from austenite to martensite at a specified depth when cooled under a given condition below the end surface is termed hardenability. Hardenability varies significantly in ferrous alloys due to carbon content, grain size, alloying elements and mass effect. Mild steel, cast iron and stainless steel have been selected in this study for hardenability tests using locally developed End-Quenched Test equipment. The coupons for hardenability tests were prepared in accordance with ASTM A 225. Each coupon was heated to 950 ^oC and soaked for 30 minutes for complete autenization after which they were quenched with preheated water at 25^oC using the End-Quenched machine. The results revealed that all material specimens responded to the heat treatment. As the slope of the Jominy curve increases, the ability to harden the ferrous alloys (hardenability) decreases. The maximum hardness is achieved at the tip of all specimens with value of 60.82 HRA, 71.30 HRA and 46.30 HRA for cast iron, mild steel and stainless steel respectively. The minimum hardness at 45 mm depth is found to be 41.87 HRA, 61.60 HRA and 42.70 HRA for cast iron, mild steel and stainless steel respectively which is a sign of tendency to pearlitic microstructure. Cast iron and mild steel responded better to heat treatment by Jominy End-Quenched method while the response is very low in stainless steel when the hardness at 0 mm depth is compared with the as-cast ferrous alloys. It can be concluded that Jominy End-Quenched test is not a suitable method to harden stainless steel like cast iron and mild steel.

Keywords: Hardenability, Ferrous Alloy, Martensite, Austenite, Pearlite, Jominy End-Quench Test

1. INTRODUCTION

Hardening has been an operation very popular in use among the early Greeks. Dated back to when the Greeks and Roman smith knew how to control the properties of the steel by quenching. The lack of understanding of the procedure did not stop the artisans to test different quenching conditions and quenching agents.

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The use of visual control of the surface colours was a method very common in the early stage of the century to predict the quenching temperature. The use of using urine, biological liquids and other organic nostrums as quenching agents during the Middle Ages and even thereafter seems to be preferred, . Such quenchants have since been replaced with water, oil, brine and other liquids (Vanpaemel, 1982).

Ferrous alloys are those of which iron is the prime constituent and they include all varieties of iron, cast iron and steels. They are extremely versatile due to the fact that it is possible to tailor them to have a wide-range of mechanical and physical properties. Examples of ferrous alloys include carbon steels, alloy steels, stainless steels, tool steels, cast iron, cast steel, maraging steel, and specialty or proprietary iron-based alloys (Yekinni, 2019).

Ferrous alloys constitute majorly a mixture of iron, carbon (ranging between 0.3 to about 4 percent) and some alloying elements. Carbon provides the hardness, and the alloying elements provide how deep this hardness will occur. This concept simply explains term “hardenability.” However, hardenability should not be confused with the maximum hardness attained by a metal after quenching. Maximum hardness is only depending on the amount of carbon present and the percentage of martensite in such metal after hardening. Rather, hardenability as to do with how deep a ferrous alloy can be hardened. For example, steels that deeply harden are called high hardenability steels, while steels that do not harden deeply are called low hardenability steels (Balasubramaniam (2010).

According to mass effect of heat treatment, it will be difficult for carbon steel of heavy cross-section to cool quickly to produce a uniformly martensitic structure throughout, even if the most severe quenchant is used. Heat must be transferred to the surface of the specimen before it can be dissipated into the quenching medium during quenching process. Thereafter, the rate at which the inner part of the specimen cools is dependent on its surface area to volume ratio. The larger the ratio, the more the rate the specimen will cool and therefore the deeper the hardening effect (Digges and Rosenberg, 1960).

When quenching a hot metal workpiece, the area in contact with water will instantly cools and its temperature balances with the quenching medium. The interior part of the metal however will not experience such rapid cooling, and if the workpiece is large, the rate of cooling may be low to allow the austenite to transform fully into a structure other than martensite and bainite. This will lead to a workpiece that does not have the same crystal structure throughout its entire structure rather a structure with a softer core and harder ‘shell’ will form (Mass effect, 2007).

However, the major factors influencing hardenability and the rate of austenite transformation in ferrous alloys are carbon content, grain size, mass effect and alloying elements (Mackenzie, 2017). Hardenability is therefore, used to determine improvement in hardness during a hardening process when a rapid/sudden cooling is taking place on austenite region (ASTM A370, 1999; Callister, 2002; Hadi *et al.,* 2013). Hardenability is believed to be a complex property that varies depending on an alloy’s arrangement of microstructural and chemical content. Knowledge about the hardenability of metals is necessary to select the appropriate combination of alloy steel and heat treatment to minimize thermal stresses and distortion in manufacturing components of different sizes.

It also plays a significant role in deciding a heat treatment process in metals/alloys for product and component. Grossman's Critical Diameter Method, Jominy End Quench Test, Use of chemical composition for hardenability, Boegehold L-bar hardenability test and Wuerfel bomb hardenability test are different types of hardenabilty tests available. The most common technique to determine hardenability of ferrous alloys is through Jominy test ASTM A-225 (Fond, 1993 and Hadi *et al.,* 2013). This test is now one of the cheapest and reliable methods to carry out hardenability test. The method can also be used in deriving Continuous Cooling Transformation (CCT) diagram for metals and alloys (ASTM A225, 1999, Jatczak *et al.,* 2011).

With modification, the result of the Jominy test can be used as a basis in estimating the "ruling section" of particular steel. Worth noting is that, there is no simple mathematical relationship between the two, but it is often more satisfactory to find by trial and error how a particular section will harden, after an initial Jominy test has been conducted.

Yekinni *et al.,* (2014) redesigned and produced a Jominy-End Quench machine. The modified machine was tested to determine the hardenability of manganese steel. Hardenability test was conducted on the as cast manganese steels which were quenched in water at different austenizing temperature. Microstructures of the cut samples were investigated using optical microscope. The results revealed that decomposition of the chromium carbide was hindered due to the extremely rapid cooling of the samples. The hardness values of the samples decreased with increase in the depth from the quenched surface. The chromium carbide content in the steel also increased with austenitic temperatures thus reduction in hardness values at higher austenitic temperatures.

Yazdi *et al.,* (2008); Knap *et al.,* (2009); Yue-Peng *et al., (*2007) studied the mathematical model of transition phase of eutectoid carbon steel. However, the mathematical model can further be developed into numerical models to simulate Jominy test from which thermal cycles can be predicted to derive CCT diagram. Hence, hardenability of cold work tool steels can be predicted from the cooling rate of heat treatment by using computer simulation of the Jominy results.

Yahdi *et al.,* (2008) predicted the hardness values on several points of a Jominy specimen using Quench Factor Analysis (QFA) method from the cooling curve and hardness test results.. The modification of the Jominy test (JMC-test) method was also used by Smoljan *et al.,* 2009 by combining cooling curve with various cooling medium which to determine hardenability of tool steels. The neural network method based on chemical composition was applied by Knap *et al*., 2009 to predict hardenability of steels.

Ke-Jian, (2007) suggested that hardenability results can be used to predict possible distortion in steels during rapid cooling using Cooling Rate Band (CRB) method.

Comparative study of case-hardening and water-quenching of mild steel rod on its mechanical properties was investigated by Adetunji *et al.,* 2015. Mild steel rod samples of diameter 50 mm were prepared and heat treated. 12 out of the 15 samples were subjected to tensile test. Some specimens were heated to 950 ^{o}C and soaked for 40 minutes and later quenched in water. Other specimens for case-hardened were heated to 950 ^{o}C and for a period of 40 minutes and then quenched in salt solution.

The results showed that the case-hardened specimens had more ductility than the water-quenched. On the other hand, the water quenched samples had better hardness than the case-hardened samples. The case-hardened specimens strained better than the water quenched samples.

Sujata *et al.,* (2020) carried out comparative analysis on four different types of steel grade: namely SAE/AISI 1015, 1040, 1045 and 4140. Jominy test method was used in the analysis. The results revealed that martensite formation varies along the length of the specimen for any chemical composition of the steel. The hardness value is decreased gradually from the quenched end due to decrease in cooling rate. Steel grades with low carbon are less susceptible to martensite formation because a minimum of 0.3% carbon is required to for martensitic formation. Constant cooling rate still results in various grades of steel have different hardness values. However, formation of matensite gradually increases for the same Jominy distance with an increase in carbon percentage. For the same level of carbon %, alloy steel shows additional improvement in the hardenability rather than plain carbon steel.

In view of the above, it is quite promising to carry out a comparative study of hardenability of ferrous alloys having different chemical compositions but the same mass effect. This study is aimed at comparing the hardenability of cast iron, mild steel and stainless steel using the modified End-Quench Machine developed by Yekinni *et al.,* 2014

2. METHODOLOGY

2.1 Materials

The materials used for the tests are cast iron, mild steel, and stainless steel. They were machined in accordance with ASTM A 225 which can fit properly into the testing profile.
A heat treatment furnace was used to heat the specimens for complete austenization. Quenching for the purpose of hardenability test was carried out in the locally fabricated End-Quench machine.

2.1.1 Cast iron

Cast iron is a group of iron-carbon alloys with a carbon content not more than 2%. It has more compressive strength and has the ability to resist abrasion and indentation (Cast Iron, 2021). Due to its hardness, cast iron is used in manufacturing automotive parts, machine parts, and ship anchor etc.

2.1.2 Mild steel

Mild steel is a type of carbon steel with low amount of carbon, the amount of carbon typically found in mild steel is 0.05% to 0.25% by weight, whereas higher carbon are typically described as having a carbon content from 0.30% to 2.0%. Mild steel can be used for automobile body parts, plates and wire products.

2.1.3 Stainless steel

Stainless steel is a group of ferrous alloys that contains a minimum of approximately11% chromium, a composition that prevents iron from rusting and also provides heat-resistant properties. Stainless steel can be rolled into sheets, plates, bars, wire, and tubing. Compared to low-carbon steel, stainless steel offers a massive upgrade in strength, hardness, and mostly important it is corrosion-resistant.

2.2 Methods

2.2.1 Preparation of Specimens and Heating

The Jominy bar end-quench test is the most familiar and commonly used procedure for measuring steel hardenability. Each of the specimens was machined in accordance with ASTM A 255, SAE J406, DIN 50191, and ISO 642. ISO, (Figure 1) (IS0642 Steel, 1999). Each of the ferrous alloy specimens was heated to austenizing temperature of 950 °C and are left to soak in this temperature for about 30 minutes for complete austenization.

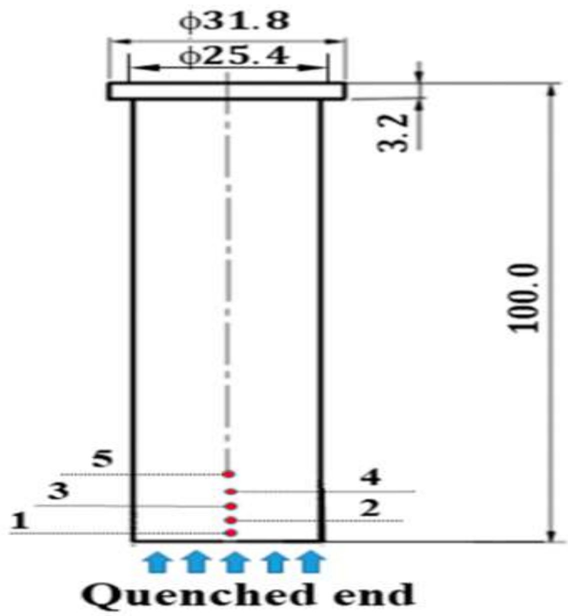
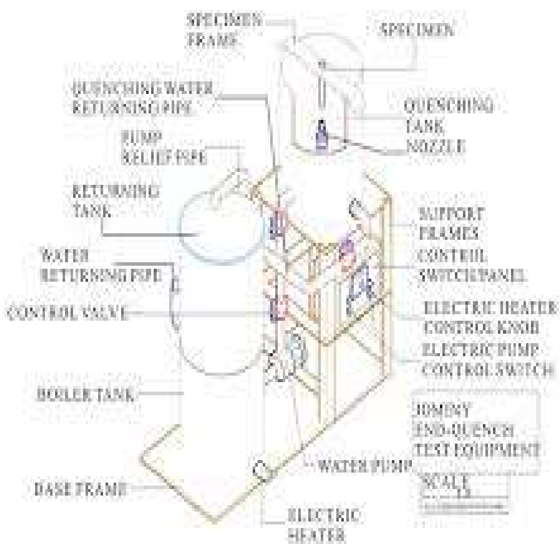


Figure 1: ASTM A 225 Jominy specimen for hardenability test

2.2.2 Quenching on the End-Quenched machine

Each of the Jominy specimens was then dropped into position in a frame of the End-Quenched machine (Figure 2a and b), and quenched at its end only by means of a pre-set standard jet of water at 25°C. Thus, different rates of cooling were obtained along the length of the bar until the specimen cooled to room temperature. After the cooling a "flat", 0.4 mm deep, was ground along the side of the bar while parallel flats at every 5 mm were ground on opposite side of the bar. Hardness values of each flat were obtained to investigate the hardenability of each material and for comparative study.



(a) (b)

Figures 2: Modified Jominy End-Quenched Machine (a) Exploded view (b) Picture (Yekinni *et al.,* 2014)

2.2.3 Hardness measurement

The Rockwell hardness machine was used to determine the hardness of each specimen. All specimens were prepared with fine-grained emery polishing papers. The specimen was mounted on a Rockwell hardness testing machine using phenolic powder, ground and then polished to produce a hardness specimen with a smooth surface finish. During the test, the indenter of the equipment was forced to make a residual depth on the specimen. This is called an indent and its depth was measured. The results of each sample were presented in tabular form.

3. RESULTS AND DISCUSSION OF FINDINGS

3.1 RESULTS

Hardness value of the ferrous alloy before heat treatment (as-cast ferrous alloys) is as follows:
Cast Iron = 56.10 HRA
Mild steel = 68.42 HRA
Stainless Steel = 46.16 HRA

Hardness as a function of distance from the quenched end is measured and presented in Table1.

Table 1: Hardness Values of Cast Iron, Mild Steel and Stainless Steel

Distance (mm)	Cast Iron (HRA)	Mild Steel (HRA)	Stainless Steel (HRA)
0	60.82	71.30	46.30
5	56.61	71.00	46.01
10	54.00	70.70	44.96
15	52.36	70.00	44.36
20	48.57	69.20	43.60
25	43.80	67.70	43.60
30	43.21	66.10	43.32
35	43.01	63.80	43.01
40	42.56	62.00	42.70
45	41.87	61.60	42.70

Hardenability of cast iron, mild steel and stainless steel are compared using Jominy curves shown in Figure 3.

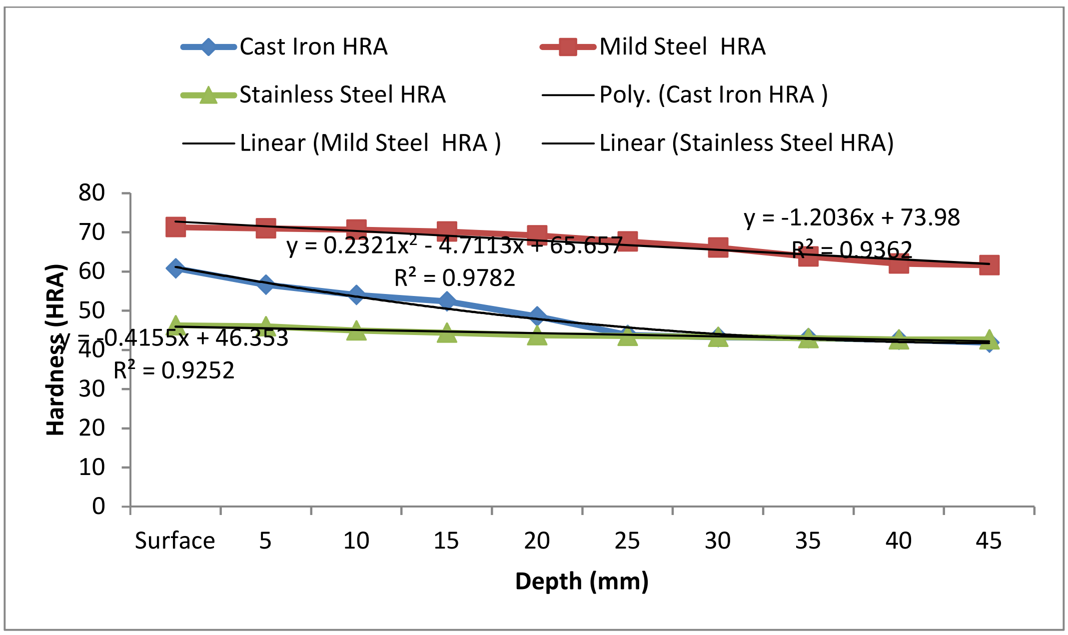


Figure 3: Rockwell Hardness values versus depth of Jominy specimen bar.

3.2 Discussion

For all ferrous alloys, cooling velocity of the test bar decreases with increasing distance from the quenched end.

It is typical of hardenability curves that as the distance from the quenched end increases, the cooling rate decreases. Hardenability curves are dependent on carbon content. A greater percentage of carbon present in steel will increase its hardness. It should be noted that all the three ferrous alloys will contain different amount of carbon and are expected to varying hardenability behaviour. It should be known that carbon is not the only alloying element that can have an effect on hardenability. The disparity in hardenability behaviuor between these three ferrous alloys will depend more on their alloying elements.

It can be observed for all samples that as the slope of the Jominy curve increases, the ability to harden the steel (hardenability) decreases. With a diminishing cooling rate (steeper drop in hardness over a short distance), more time is allowed for carbon diffusion and the formation of a greater proportion of softer pearlite. This means less martensite and a lower hardenability. A material that retains higher hardness values over relatively long distances is considered highly hardenable. Also, the greater the difference in hardness between the two ends, the lower the hardenability.

Maximum hardness is achieved at the tip of each ferrous alloy specimen with hardness value of 60.82 HRA, 71.30 HRA and 46.30 HRA for cast iron, mild steel and stainless steel respectively. For all ferrous alloys tested, this hardness decreases with depth as a result of slower cooling rate. The minimum hardness at 45 mm depth is found to be 41.87 HRA, 61.60 HRA and 42.70 HRA for cast iron, mild steel and stainless steel respectively.

Cast iron sample has total decrease in hardness at 0 mm depth to 45 mm depth by 32 percent. Average decrease in hardness across the length of the bar is 3.68 percent .the highest of the three samples. This is an indication of poor hardenability. Therefore, degree of transformation of microstructure from austenite to martensite as the depth increases is very low. However, comparing the hardness of the as cast specimen to heat treated cast iron at 0 mm depth, the percent increase of 8.41 shows the degree of transformation of pearlite to austenite to be very high, and the highest of all the ferrous alloys. This is because of the effect of percentage of carbon in cast iron. Carbon content can raise the hardness of steel because it can resist the formation of ferrite-pearlite phase thereby accelerating the formation of martensite on the slow cooling rate but cannot increase the hardenability.

Total percent decrease in hardness of mild steel from the tip (0 mm depth) to end of the bar (45 mm depth) is 13.6. Average reduction of 1.52 % in hardness between 0 mm to 45 mm is also an indication of better hardenability of mild steel when compared with cast iron. This shows that the degree of transformation of microstructure from austenite to martensite at varying depth is relatively high. The 4.2 % increase in hardness of the as cast mild steel when compared with the highest hardness obtained at the 0 mm end of the bar is an indication of a material showing good response to hardness by Jominy End-Quench method.

Stainless steel on the other hand has a total percent decrease in hardness from the quenched end to the other end of the bar of 9.94 % with average reduction in hardness between the two ends (0 mm to 45 mm) of 0.86 %. This appears to be a material with hardenable propertyby the the poor improvement in hardness value of the as cast stainless steel (pearlitic microstructure) when compared with heat treated (austenitic microstructure) is an indication of a material showing reluctance to hardening by heat treatment. 0.3 % increase in hardness between the as cast stainless steel and the quenched end of the sample does not show a material yielding to hardness by heat treatment. The gentle slope of the stainless steel confirms the general knowledge that Austenitic stainless steel cannot be harden via heat treatment.

Generally, in a slow cooling, there is tendency for austenite phase transformed into ferrite and pearlite phase. This transformation is bound to occur because of longer diffusion of heat time. Hardening capability describes the hardest surfaces that can be achieved by rapid cooling process (quenching) which can only be achieved if there is 100% martensitic microstructure.

Hardenability and hardness are tools that allow the heat treaters to determine whether a product can meet a specific need in welding, machining, fabrication and metal forming process.

4. CONCLUSION

Based on the testing results on ferrous alloys using Jominy End-Quenched method, the following conclusions can be drawn:

1. Cast iron, mild steel and stainless steel were machined in accordance with ASTM A 225 All ferrous alloys showed maximum hardness on the cooling tip.
2. Mild steel has the highest rate of conversion of austenitic to martensitic microstructure at the tip, followed by cast iron while stainless steel has the least conversion.
3. Cast iron showed average percent reduction in hardness between the tip (0 mm) and end (45 mm) of the specimen by 3.68 %. This is an indication of poor hardenability. Therefore, degree of transformation of microstructure from austenite to martensite at varying depth is very low.
4. Mild steel showed average reduction in hardness between 0 mm to 45 mm of the specimen by 1.52 %, an indication of better hardenability when compared with cast iron. The degree of transformation of microstructure from austenite to martensite at varying depth is relatively high.
5. Stainless steel showed average reduction in hardness between 0 mm to 45 mm of the specimen by 0.86 %. The poor improvement in hardness value of the austenized specimen at the tip when compared with pearlitic form of the specimen is an indication of reluctance to hardening of stainless steel by heat treatment.
6. Mild steel has the highest hardenability, next is cast iron and stainless steel has the least.
7. The results will guide in knowing which of the ferrous alloys require pre and post heating during welding. It will also be a guide to machinist to know the type of coolant to use for these classes of ferrous alloys. Ferrous alloys most suitable for cold and hot working processes in metal forming can be decided from the results.

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