Development and Performance Evaluation of Jominy End-Quench Apparatus.

Jacob O. Aweda, Ph.D.[*1]; Sunday O. Abegunde, B.Eng.[2]; and Raheedat M. Mahamood, Ph.D.[1]

[1]University of Ilorin, Faculty of Engineering and Technology, Department of Mechanical Engineering, PMB 1515, Ilorin, Nigeria.
[2]The Federal Polytechnic, Physical Planning Unit, Ado Ekkiti, Nigeria.

E-mail: jacobaweda@gmail.com

ABSTRACT

This study was on the development and performance evaluation of a Jominy end-quench apparatus used for the determination of the hardenability of metals. The fabrication of the apparatus was undertaken bearing in mind the availability of the materials and cost implications of the apparatus. Stainless steel was used for the water prone areas to avoid corrosion while mild steel was used for other areas that are not exposed to water or other quenching fluids during operation. Fifty-four samples were prepared for the performance evaluation on the developed Jominy apparatus and were heated to temperatures of 850°C, 900°C, and 950°C before quenching in the apparatus.

Water and brine (pH values 6.5 and 5.6, respectively) were used as quenchants in the determination of hardenability of the specimens. The results obtained from the tests showed that Brinell hardness values reduced as distance from the quenched surface increases. Water quenched samples produced higher hardness value at lower quenching temperature while brine quenched specimens had higher Brinell hardness value at higher heating temperatures. When compared with the standard, the results obtained were very close which make the developed apparatus suitable for hardenability test of metals.

(Keywords: Jominy end-quench apparatus, hardenability, Brinell hardness, water, brine)

INTRODUCTION

In many research centers and tertiary institutions, appropriate testing equipment are either not available or, where present, are obsolete. In places where they are available, the cost of material evaluation becomes prohibitive with high charges placed on them. This may probably due to the high initial cost of procurement or the high cost of maintenance of such equipment. If access to testing equipment is readily available and at affordable cost, the risk of traveling long distances and paying much for material evaluation will be eliminated. Currently, due to non-availability of appropriate laboratory equipment, many researchers have resorted to reducing the number of samples prepared for testing which may result in poor representative of the samples or overall results.

Hardenability is the property of material that determines the depth of hardness when cooled in a desirable quenchant from its austenizing temperature. This is measured quantitatively through the determination of the depth of hardness of a standard size and shape of steel in a controlled/standardized environment (Pietrzyk and Kuziak, 2011). Steels and its alloys are a few of the engineering materials that can be heat treated by varying their mechanical properties in order to achieve desired mechanical properties (Bain and Paxton, 1966; Kutz, 2002). Heat treatment is applied to steel not only to harden it but sometimes to improve or relieve its strength, toughness or ductility (Grossmann and Bain, 1964; Prabhudav, 1988).

The knowledge of steel hardenability is very necessary because it aids in the selection of appropriate grade of steel or its alloys for various engineering applications (Higgins, 1893). Most structural failures which occur during service arise due to poor choice of the correct materials for service purposes. A good understanding of steel hardenability helps to reduce failure while in service (Yekini, *et al*., 2014).

Hardenability of steel increases with increase in carbon content and the alloy elements of steel to be tested. The mass of steel to be quenched also influences the hardenability because in a small material, the heat is extracted very quickly therefore exceeding the critical cooling rate of the steel making that portion to become martensitic.

Bhaskar, *et al.* (2011) studied the effect of alloying elements on steel hardenability using Jominy end-quench apparatus to determine their hardenability. They discovered from their results that alloy steel has higher hardenability forming martensite to a greater depth than plain carbon steel thereby making hardenability test very important.

There were various Jominy end-quench apparatus that have been developed in time past that are in existence. Yekini *et al.,* (2014) developed Jominy end-quench machine that has a short processing time consequently reducing the volume of quenchant used for cooling. They affirmed that it is necessary to have the knowledge of steel hardenability because it helps in the selection of appropriate alloy-steel combinations for any engineering applications. From the experiment performed, they found out that hardness of the quenched sample is not uniform throughout the entire volume of the sample. Therefore, hardness decreases with the distance from the quenched surface.

Pietrzyk and Kuziak (2002) used computer-aided design to interpret Jominy end-quench tests by comparing the hardenability of two bianitic steels with different compositions using finite element simulations. Kutz (2002) proffered the use of similar equipment other than Jominy end-quench tester to study the sensitivity of non-ferrous aluminum alloy (Al 7050) to quenching and got similar results.

Attempts have been made, as in Matthew (2010) and Marrow (2001), to fabricate Jominy end-quench apparatus, but despite this, accessibility to the apparatus remains worrisome. This now gives rise to the present work. This Jominy end-quench apparatus can be conveniently used to test for steel hardenability, if readily available in research centers, higher institutions and other research laboratories within Nigeria. It is in the light of this that the development of Jominy end-quench apparatus becomes necessary. This equipment helps to determine the hardenability of metallic materials and guide the end users not only in the selection of the right materials for various engineering applications but determine their behavior characteristics. Therefore, the design and performance evaluation of the Jominy end-quench apparatus was undertaken to make it more available and cost effective in research centers and tertiary institutions for use.

The materials used for the fabrication were sourced locally and very cost effective. The maintenance of the developed apparatus is simple and requires no high level trained personnel to operate.

MATERIALS AND METHODS

Material Selection

The materials used for the development of this apparatus were stainless steel for the fabrication of the parts prone to corrosion such as the cooling chamber and specimen holder. The connecting pipe to the nozzle was of PVC material for easy connection and maintenance. Mild steel was used as the stand and galvanized steel for the quenchant recirculating tank. This combination was selected due to the fact that water which may be used as quenchant is corrosive. These materials as selected are readily available locally and relatively cheap.

Design Methods

The design criteria used was based on the rigidity and strength of the apparatus to withstand the heat and weight that might be applied on it during operation. Each of the component parts were designed based on the applied criteria of operation.

Design for Tanks Containing Quenchant

Tanks containing fresh quenchant and that for spent quenchant were made from galvanized stainless sheet.

Volume of each tank is calculated using Equations 1 and 2.

$$V = \frac{\pi {d_t}^2 h_t}{4} \qquad \textbf{(1)}$$

Where,

d_t = tank diameter and
h_t = tank height.

$$V = \frac{\pi h}{3}(R^2 + Rr + r^2) \qquad \textbf{(2)}$$

Where,

R = the bigger diameter and
r = smaller diameter

The pressure difference between the quenchant supply tank and nozzle is given by:

$$\Delta P = \rho g h \text{ (tank)} - \rho g h \text{ (nozzle)} \quad \textbf{(3)}$$

Where,

ρ = density of water,
$g = accelaration\ due\ to\ gravity$
h = head height

From the law of conservation of mass:

$$A_1V_1 = A_2V_2 \quad \textbf{(4)}$$

And from Bernoulli's equation:

$$P_1 + {}^1/_2\, \rho V_1^{\,2} + \rho g h_1 = P_2 + {}^1/_2\, \rho V_2^{\,2} + \rho g h_2 \quad \textbf{(5)}$$

Where,

P_1, P_2 = nozzle and tank pressures, respectively,
ρ = quenchant density,
V_1, V_2 = Velocities of nozzle and tank respectively
h_1, h_2 = nozzle and tank heights, respectively,
g = acceleration due to gravity

The volumetric flow rate, Q through the pipe was determined thus,

$$Q = AV \quad \textbf{(6)}$$

Where,

A = pipe cross sectional area (m^2)
V = flow velocity (m/s)

Nozzle Design

Nozzle of 12.5 mm diameter as specified from ASTM standard was selected for the measurement of hardenability of steel using tester. The nozzle was made of stainless steel to avoid corrosion.

Flow rate, Q through the nozzles was determined using Equation 7,

$$Q = A_n V_n \quad \textbf{(7)}$$

Where,

A_n = nozzle area (m^2)
V_n = nozzle flow velocity

Pump Design

Selection of the hydraulic power to drive the pump depends on the main flow rate, the fluid density and differential height.

The determination of the theoretical power of the pump is given by:

$$P_h = Q\rho g h \quad \textbf{(8)}$$

Where,

P_h = hydraulic power (W),
Q = Volumetric flow rate (m^3/s),
ρ = density of fluid (kg/m^3),
g = acceleration due to gravity,
h = differential head (m)

The shaft power is given by:

$$P_s = {}^{P_h}/_{\eta} \quad \textbf{(9)}$$

Where,

η=pump efficiency

EXPERIMENTAL PROCEDURE

The Fabrication of the Apparatus

The apparatus was fabricated on the floor of the Machine shop of the Federal Polytechnic, Ado Ekiti, Nigeria. The apparatus after fabrication is as shown in Figure 1. Figure 1a shows the full view with the upper compartment housing the specimen and the lower half the spent quenchants. Figure 1b is the top view of the same apparatus where the specimen undergoing quenching is shown.

Sample preparation

Medium carbon steel rod of 15 mm diameter and 900 mm long was used for the performance evaluation of the designed device. The rod was further machined to 12.5 mm diameter and 810 mm in length. They were cut into 8 pieces of 100 mm length each. These samples were heat treated in an electric furnace of maximum temperature of 1200 ^{0}C following ASM criteria. The furnace temperature was monitored using Chromium-Alumel thermocouple, K type with temperature range of -210 to 1260 ^{0}C. Table 1 shows the samples and the heat treatment given.

(a)

(b)

Figure 1: Fabricated Jominy Apparatus, a) -full view, b) -top view.

Table 1: Samples Temperatures and Quenchants.

S/No	Sample	Treatments	Quenching Temperature (°C)
1	Sample A	Water quenched	850
2	Sample A1	Brine quenched	850
3	Sample A2	Thermocouple implanted. Water quenched	850
4	Sample B	Water quenched	900
5	Sample B1	Brine quenched	900
6	Sample C	Water quenched	950
7	Sample C1	Brine quenched	950
8	Sample D	Control	No heat treatment

Samples' Heat Treatment Procedure

The samples were heat treated in an electric furnace where the specimens' temperatures were monitored with thermocouple. The furnace temperature was initially set at 350^{0}C. After achieving this temperature, the furnace temperature was increased afterwards by 150^{0}C in circles until the desired quenching temperature for each specimen was reached.

The prepared samples were removed from the furnace and quickly placed gently in the developed Jominy end apparatus where quenchant was directed to one end for rapid cooling (see Figure 2a). The quenchant, water was directed to the lower end of the sample continuously for 90 seconds in such a way that there was no splashing to the side of the specimen. This process was repeated for the situation when brine was the quenchant.

The quenching temperatures adopted were 850, 900 and 950 ^{0}C for different samples. After quenching, the specimens were then sliced into ten equal parts and taken for Brinell hardness test on Universal Testometric Machine (M500-100AT).

RESULTS AND DISCUSSION

The results obtained from the performance evaluation of the developed apparatus are presented in Figures 3 to 7. Figure 3 shows the results of hardness values against distance from the quenched end of the specimen when water and brine were used as quenchants at 850^{0}C. As the distance from the quenched end increases, there is a drop in the hardness values of the material as indicated in the figure. This trend was the same when water and brine were used with the values obtained for water been higher.

(a)

(b)

Figure 2: (a) Heated sample, (b) Sample after cooling.

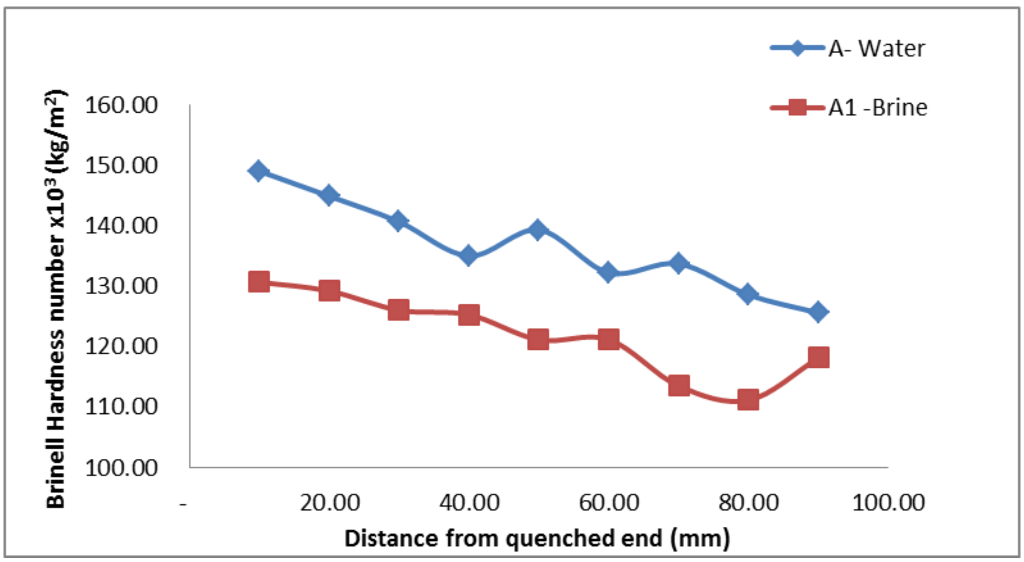

Figure 3: Brinell Hardness Curve of Samples cooled at 850°C.

The water cooled was higher for all the hardness values obtained at all distances from the quenched end. At the quenched end the water cooled was 14.08 % higher than the brine cooled while at the farthest end the difference was reduced to 6.31 %. For the situation when the quenching temperature was 900 °C and 950 °C as in Figures 4 and 5, respectively, the same trend was equally observed.

From Figure 6, when the apparatus was tested for Brinell hardness and quenched with water at temperatures 850, 900 and 950 °C, the hardness values fall as distance progressed from the quenched end. This same pattern was observed when brine was used as quenchant as seen in Figure 7. For both situations, the higher the quenching temperature the higher the value of Brinell hardness obtained.

CONCLUSION

The fabricated Jominy end-quench test apparatus was constructed with locally sourced materials. The preliminary tests carried out showed that the apparatus can be used for hardenability test of steel and other metallic objects. Through this effort, the apparatus can be readily made available to needing institutions or agencies thereby minimizing the cost of procurement of same from other countries.

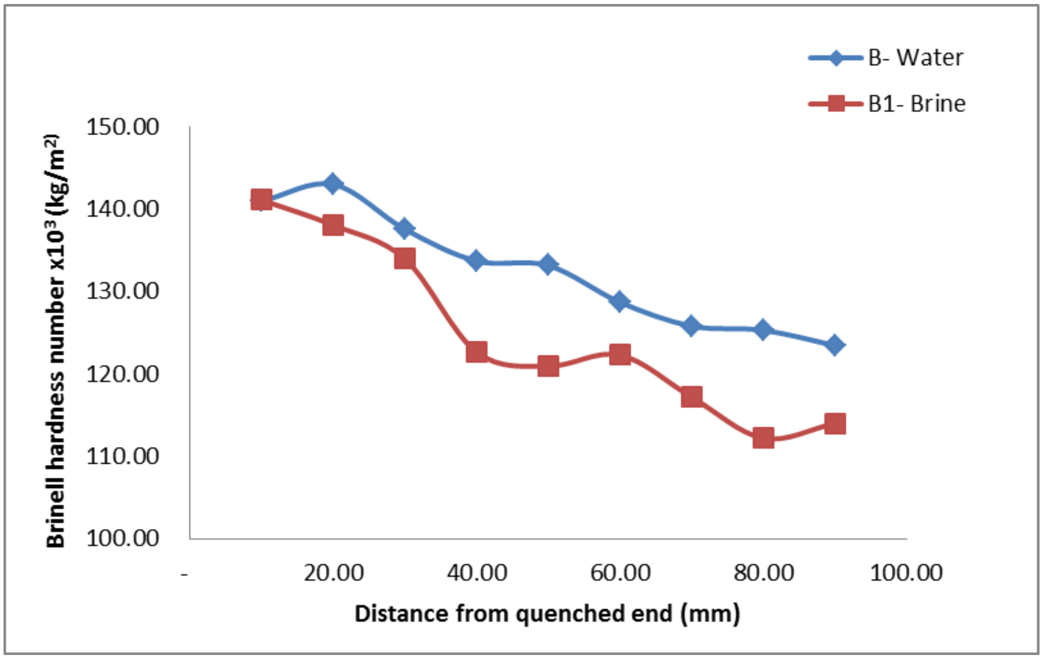

Figure 4: Brinell Hardness Curve of Samples cooled @ 900^{o}C.

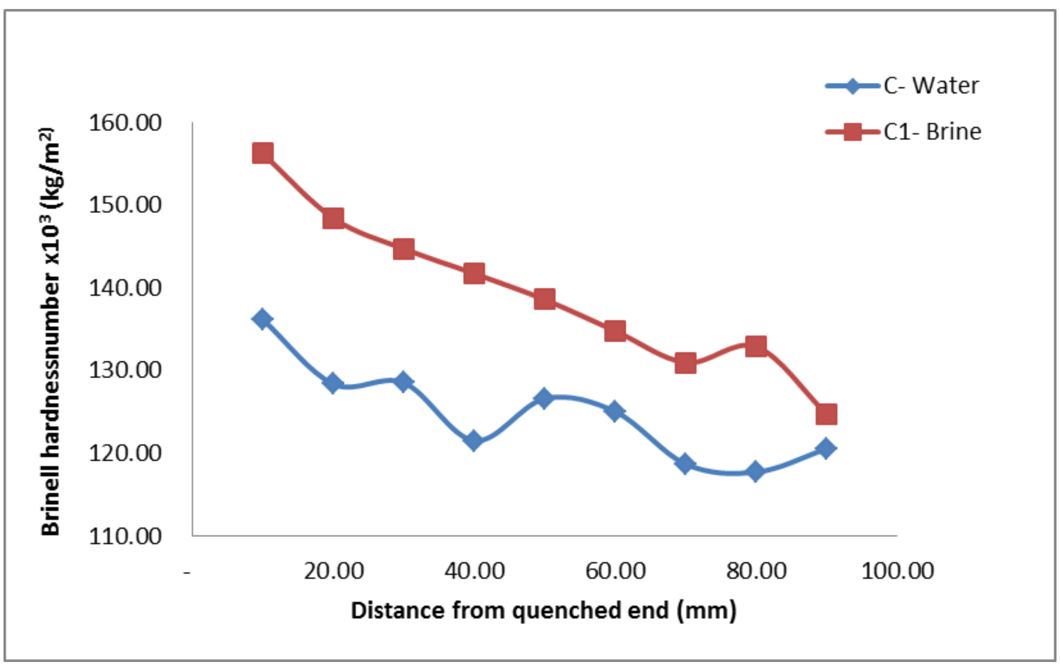

Figure 5: Brinell Hardness Curve of Samples cooled @ 950^{o}C.

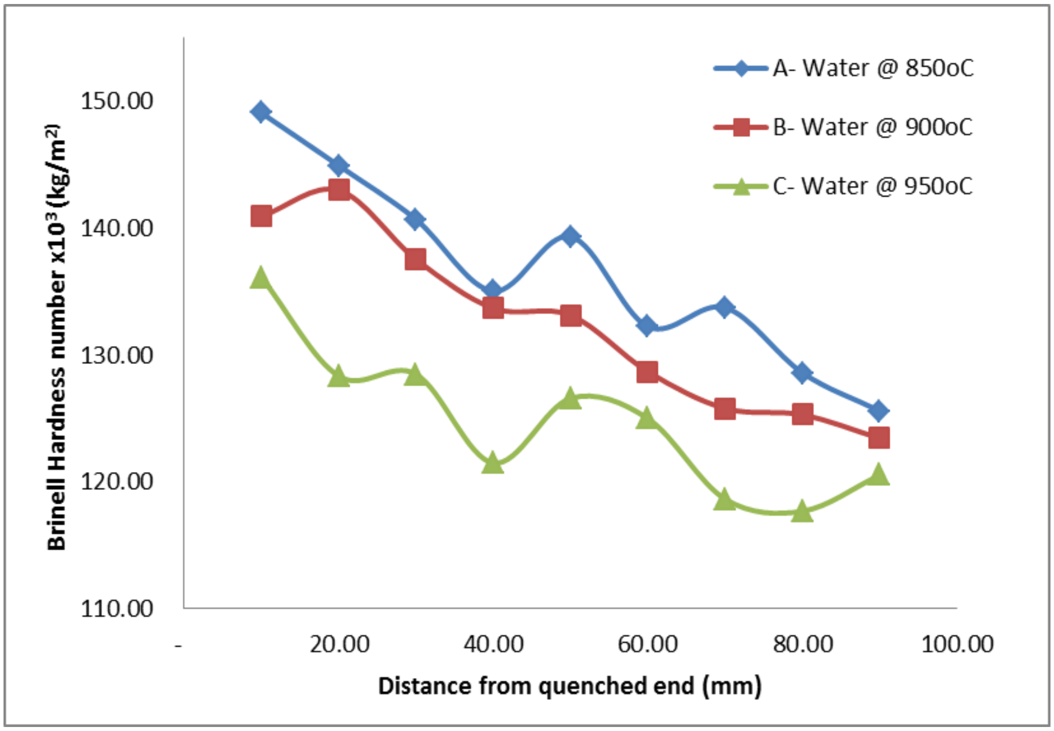

Figure 6: Brinell Hardness Curves of Samples cooled with Water at different Temperatures.

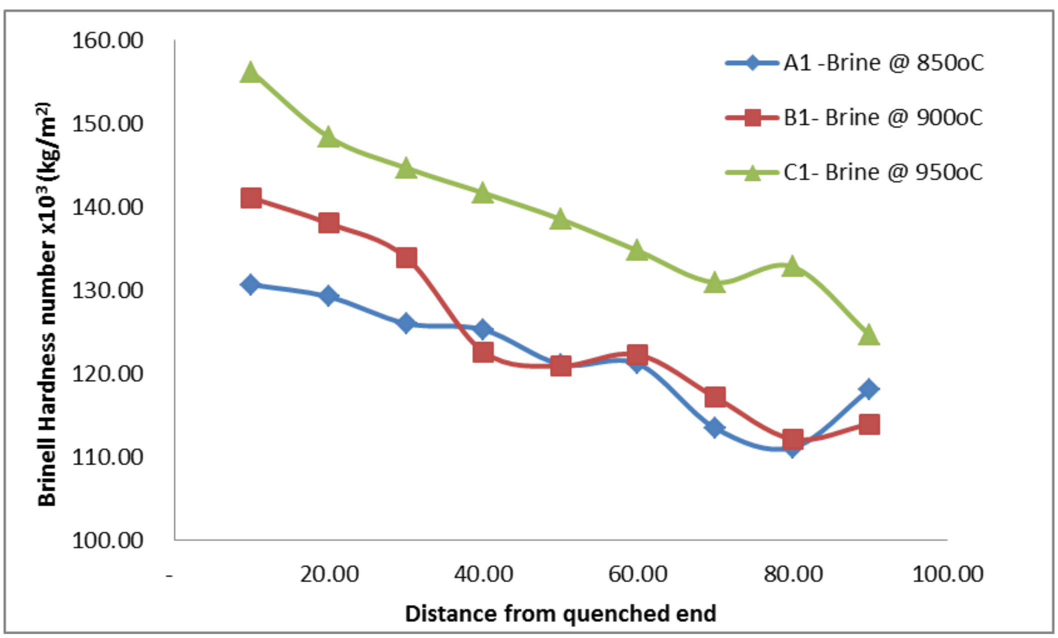

Figure 7: Brinell Hardness Curves of Samples cooled with Brine at different Temperatures.

The developed apparatus is functional and the results obtained from it are reliable and credible. The results showed high hardening effect was obtained with water-quenched samples which were in agreement with the results of Altaweel and Tolouei (2014). This indicated that the developed apparatus could be used for hardenability test of metals. There was insignificant difference between the results of this Jominy end-quench test apparatus and the imported one.

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ABOUT THE AUTHORS

Dr. Jacob O. Aweda, is Senior Lecturer in the Department of Mechanical Engineering, University of Ilorin. He holds a Ph.D. in Mechanical Engineering from the same University. His areas of research include material engineering, metallurgical engineering, mechanics and casting technology.

Engr. Sunday O. Abegunde is an Engineer with the Federal Polytechnic, Ado Ekiti, Nigeria. He graduated from the Federal University of Technology, Minna, Nigeria and is currently a Post graduate candidate with the University of Ilorin, Nigeria.

Dr. (Mrs.) Rasheedat M. Mahamood is a Lecturer with the University of Ilorin, Department of Mechanical Engineering who holds a Ph.D. from South Africa University. Her research areas include mechanics, manufacturing and materials engineering.

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