Design and Development of a Jominy End-Quench Apparatus

[1]Zainab Muhammad-Bako, [2]Oyebamiji Muideen Oladele, *[3]Yusuf Aliyu and [4]Ahmed Abiola Abdullateef
[1,2,3,4] Department of Mechanical Engineering, School of Infrastructure, Process Engineering, and Technology, Federal University of Technology Minna, Niger State, Nigeria.
muhammad.m1700273@st.futminna.edu.ng|oyebamijimuideenoladele@gmail.com|aliyu.m1702870@st.futminna.edu.ng|abdullateef.m1702864@st.futminna.edu.ng

Received: 12-MAY-2024; Reviewed: 21-SEPT-2024; Accepted: 25-SEPT-2024
https://dx.doi.org/10.4314/fuoyejet.v9i3.1

ORIGINAL RESEARCH

Abstract— This study describes the design, fabrication, and testing of an end-quench apparatus for Jominy hardenability testing of steel according to ASTM A255-10 standards. This design aims to improve on previous designs which are heavy resulting in difficulty in mobility of the apparatus, inadequate water circulation, less compact of the entire system and unreliable power supply. This apparatus design incorporates a quenching chamber, frame, reservoir, drainage tanks, quenchant channel, pump, and battery. Material selection prioritized performance and cost-effectiveness. Each component was built to standard specifications, assembled, and painted for corrosion resistance. Testing employed a Leeb testing machine and three identical steel specimens quenched with water, 3.5% brine, and 5% brine. Hardness measurements were taken at designated distances from the quenched ends. The specimen quenched with 3.5% brine exhibited the highest hardenability, with hardness values decreasing with depth for all specimens. The apparatus achieved an estimated efficiency of 77.5%. Notably, the design incorporates a DC power source to mitigate potential disruptions during quenching caused by power failures.

Keywords— hardness, hardenability, Jominy specimen, quenchants, quench test,

1 Introduction

Metals are widely employed in manufacturing a wide range of engineering applications, including construction components, automotive components, and aeronautical structures, (Muhammad, *et al.*, 2018 & kumar, 2012). Achievement of the requisite hardness profile across diverse applications necessitates the selection of a material with appropriate hardenability. Hardenability is a critical property of steel that governs the depth of the zone exhibiting enhanced hardness following quenching from the austenitizing temperature. (Yekinni, *et al.*, 2014; Landgraf, *et al.*, 2021 and Colla, *et al.*, 2023). In-depth understanding of steel hardenability is paramount for selecting optimal alloy-steel combinations. This knowledge facilitates the mitigation of thermal stresses and distortions that may arise during and after the heat treatment processes employed in manufacturing components. Furthermore, it is crucial to recognize the influence of section size on hardenability (Yekinni, *et al.*, 2014). It is imperative to distinguish between hardness and hardenability of steel. Hardness represents a material's resistance to permanent deformation, such as scratching or indentation. Conversely, hardenability reflects the steel's inherent potential to achieve increased hardness through quenching processes. The Jominy end quench test serves as a well-established technique for evaluating the hardenability of steel and other materials.

Steel's unique properties and versatility have driven its ever-increasing demand in the face of technological advancements and ever-evolving human needs. This enduring material has demonstrably exerted a profound influence on the course of human history (Ikumapayi, *et al.*, 2018 & Akinlabi, *et al*. 2020) The Jominy end quench test, developed by metallurgists Walter E. Jominy and A. L. Boegehold, is a standardized experimental method for evaluating the hardenability of materials. This technique is based on the principle that during the quenching of a heated specimen, the region in direct contact with the quenching medium (typically water) experiences a rapid temperature decrease, with a gradual progression towards a more uniform temperature distribution throughout the material as the distance from the quench interface increases. (Akinlabi, *et al*. 2020; Kandpal, *et al.*, 2011 & Yazdi, *et al.* 2008). The Jominy end quench test offers significant advantages within the manufacturing sector. This standardized technique facilitates the selection of steels with optimal hardenability characteristics for various industrial applications. Through the evaluation of hardenability, manufacturers can identify steels that are best suited for processes like drilling and machining, ensuring the production of components with the requisite mechanical properties (Akinlabi, *et al.* 2020).

Mechanical properties can be manipulated to leave desired properties in particular steel through heat treatment. Hardness of a steel is one of the mechanical properties that can be manipulated and for that to take place, the hardenability of a steel has to be known. Hardenability is a very useful and important property of steel which can be measured using the Jominy curve. The Jominy curve is plotted after the Jominy end-quench test is done. During the testing process, ~~a~~ steel is heated to its

*Corresponding Author

Section C- MECHANICAL/MECHATRONICS ENGINEERING & RELATED SCIENCES
Can be cited as:
Muhammed-Bako, Z., Oladele, M. O., Aliyu, Y., and Abdullateef, A. A. (2024). Design and Development of a Jominy End-Quench Apparatus, FUOYE Journal of Engineering and Technology (FUOYE**JET), 9(3), 464-469.**
https://dx.doi.org/10.4314/fuoyejet.v9i3.1

austenitizing temperature in a furnace and then moved for quenching in an apparatus and the apparatus is known as the Jominy end-quench test apparatus. This design aims to improve on previous designs which are: heavy weight resulting in difficulty in mobility of the apparatus, inadequate water circulation, some lack compact of the entire system, and unreliable power supply (Yekinni, *et al.*, 2014). Thus, this design was made smaller, more compact, and less weighty compared to previous designs. This research focused on the design and fabrication of an environmentally friendly, portable, friendly user-interface, easy mobility, and cost-effective Jominy end-quench testing machine which will enable the engineer, technician, or student to have an easy and stress-free experience using it.

2 Materials and Methods

2.1 *Design Considerations*

The materials for each component were selected based on their reliability, ease of fabrication, ease of joining, mechanical properties and cost.

Stainless steel was the material selected for the quenching chamber and all the parts attached to it as a result of its resistance to high temperature which it will be subjected to after the specimen to be quenched is austenitized and placed on it for quenching. It can be easily fabricated to the desired shape and cost less compared to other materials that can serve the same purpose. It was painted to prevent corrosion and elongate its lifespan.

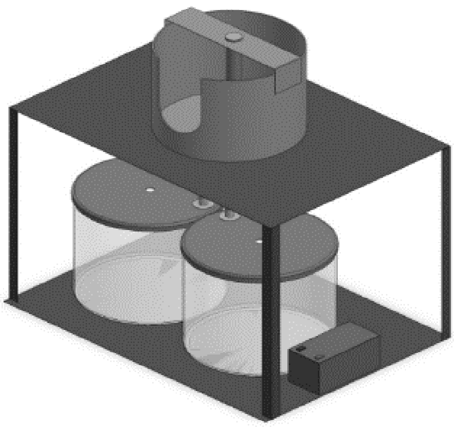
Carbon Steel was used for the frame due to its high strength to withstand the load of the quenching chamber and specimen. It is less costly compared to other metals that can serve a similar purpose. It was also painted to prevent corrosion.

The reservoir tank and drainage tank will be used to store quenchants in them and place the DC pump. Therefore, corrosion resistance and electrical resistance are the properties we sought out for. As a result, Plastic tanks were selected due to their resistance to corrosion, electricity and their cost.

2.2 Design calculation for the development of Jominy End-Quench Apparatus

Table 1: Summary of the Design calculation

QUANTITY	INITIAL DATA	FORMULA/CALCULATIONS	RESULTS
Area of the legs of the specimen holder	F=3.855, l = 0.62m, ϵ=190GPa, $\delta = 10^{-6}$	$A = \frac{F\ l}{\epsilon\ \delta}$ $A = \frac{3.855 \times 0.62}{190 \times 10^9 \times 1 \times 10^{-6}}$	1.26×10^{-5} m²
Volume of Tanks	r=0.125, h=0.245	$V = \pi r^2 h$ $V = \pi \times 0.125^2 \times 0.245$	0.012m³
Area of plates	l = 0.535, b=0.41	$Ap = l \times b$ $Ap = 0.535 \times 0.41$	0.22m²
Area of frame columns	F=7.55, l = 0.45, ϵ=190GPa, $\delta = 10^{-6}$	$Ac = \frac{F.l}{\epsilon.\delta}$ $Ac = \frac{7.55 \times 0.45}{190 \times 10^9 \times 1 \times 10^{-6}}$	1.79×10^{-5} m²
Flow rate of the pump	V=3L, t=1min	$Q = \frac{volume\ of\ water\ delivered}{time\ taken}$ $Q = \frac{10.5L}{3.39min}$	3.1L/min
Diameter of pipe	Q=2.61, v= 12981	$d = \sqrt{\frac{4Q}{\pi v}}$ $d = \sqrt{\frac{4 \times 3}{\pi \times 14920.78}}$	0.016m
Pressure of water		$p = \rho g h$ $p = 977 \times 9.81 \times 0.4$	3912.23N/m²
Delivery pressure of pump	p=3912.23, L=0.115, $p_l = -32.976$	$\Delta p = p + Lpl$ $= 3912.23 + (0.115 \times -32.976)$	120N/m²
Efficiency of pump		$\eta = \frac{actual\ flow\ rate\ of\ pump}{expected\ flow\ rate} \times 100\%$ $\eta = \frac{3.1}{4} \times 100\%$	77.5%
Power required by pump	Q=3, ΔP = 120, η =75	$P = \frac{Q\ \Delta P}{\eta}$ $= \frac{3 \times 120}{75}$	4.8W



http://dx.doi.org/10.46792/fuoyejet.v9i2.C engineering.fuoye.edu.ng/journal

Figure 1: The isometric view of the Jominy end quench apparatus model

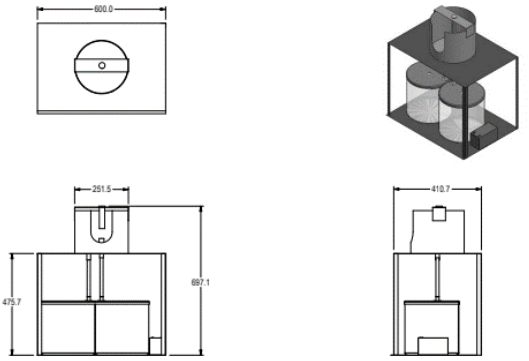


Figure 2: Orthogonal view of the Apparatus

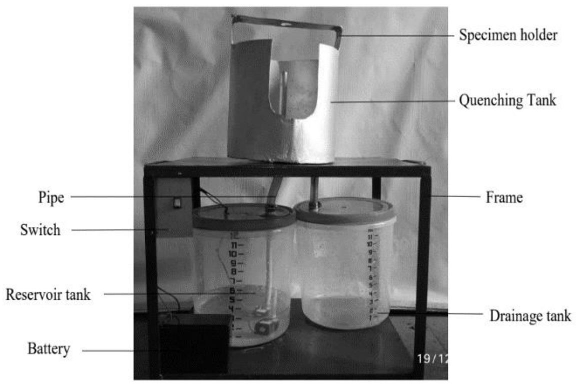
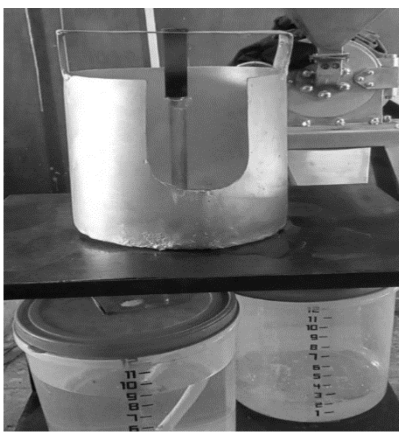


Figure 3: The Jominy end quench apparatus model develop

3 RESULTS AND DISCUSSION

The results obtained after testing the apparatus are shown in Table 2.



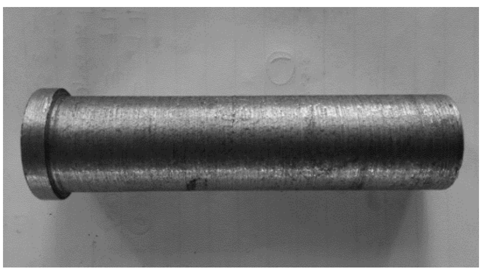
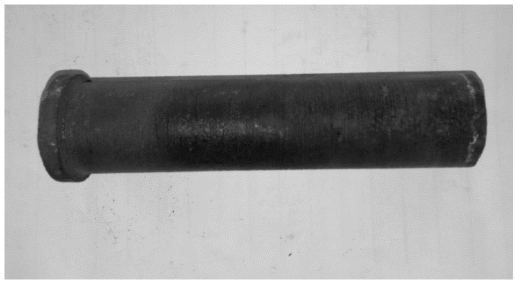
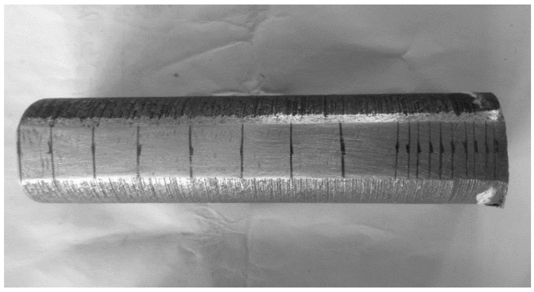


Figure 4:

Quenching process





(5a)

(b)

(c)

Figure 5a, b, c: Prepared specimen, Quenched specimen, marked dimensions where the hardness is to be tested.

Table 2: Summary of information obtained from the quenching processes.

Data	Quenchants used		
	Water (^{0}c)	Brine solution of 3.5% salt	Brine solution of 5% salt
Temperature of specimen before quenching (T_1)	700	700	700
Temperature of specimen after quenching (T_2)	170.2	172.6	175.1
Temperature loss by specimen (T_5= T_1- T_2)	529.8	527.4	524.9

Temperature of quenchant before quenching (T_3)	28.8	28.8	28.8
Temperature of quenchant after quenching (T_4)	30.6	30.3	30.4
Temperature gained by quenchant (T_6= T_4 - T_3)	1.8	1.5	1.6
Temperature loss to environment (T_5 - T_6)	528	525.9	523.3
Volume of quenchant before quenching (V_1) L	11	11	11
Volume of quenchant after quenching (V_2) L	1	0.3	0.2
Volume of quenchant used (V_1 - V_2) L	10	10.7	10.8
Time before quenching (t_1)	0.00	0.00	0.00
Time after quenching (t_2) mins	3.29	3.42	3.46
Time taken to quench (t_2 - t_1) mins	3.29	3.42	3.46

Average temperature loss by the specimen $= \frac{529.8+527.4+524.9}{3} = 527.37°C$

Average temperature gained by quenchants $= \frac{1.8+1.5+1.6}{3} = 1.63°C$

Average temperature loss to the environment $= \frac{528+525.9+523.3}{3} = 525.73°C$

The average volume of quenchant used $= \frac{10+10.7+10.8}{3} = 10.5L$

Average time taken to quench the specimen $= \frac{3.29+3.42+3.46}{3} = 3.39\ mins$

Table 3: Average hardness values of different distances from the quenched end with different quenchants.

Distance from the Quenched end (mm)	Average Hardness Values (HL)		
	Water	Brine Solution of 3.5% Salt	Brine Solution of 5% Salt
2	465	578	448
4	436	569	446
6	433	507	445
8	431	492	444
10	429	489	442
12	429	486	440
14	424	486	438
16	421	474	438
18	420	469	432
20	414	469	432
30	412	455	423
40	409	434	421
50	397	434	419
60	396	429	408
70	395	428	406
80	393	418	405
90	383	398	399
100	373	376	395

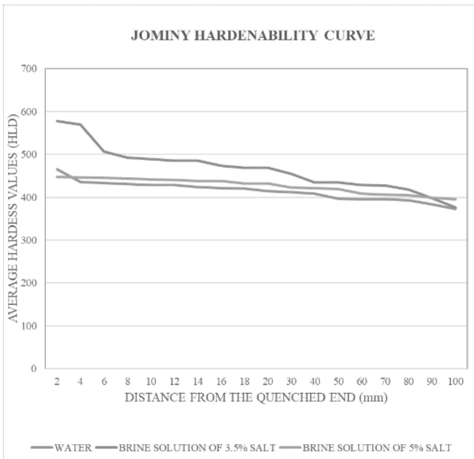


Figure 1: Jominy hardenability curve of different quenchants used for quenching specimens of the same compositions.

From the Jominy hardenability curve shown in Figure 1, the specimen quenched with brine solution with 3.5% salt content has the highest hardness from the quenched end, while, the specimen quenched with brine solution with 5% salt content has the lowest hardness from the quenched end, but as the distance from the quenched end increases, specimen quenched with water had the lowest hardness from a distance of 4mm to 100mm where the hardness of both water and brine solution of 3.5%

quenched specimen coincides. The brine solution of 5% salt content quenched specimen has a little variation of hardness from the quenched end to the top.

3.1 DISCUSSION

From the result of the quenching process shown in Table 2, the average temperature loss during quenching is 527.37°C, while losing the majority of the heat to the environment and losing a negligible temperature to the quenchant, an average of 1.63°C. The average volume of quenchant used for quenching was 10.5L for an average time of 3.39 minutes. As a result of this analysis, we can calculate the flow rate of the pump, the pump efficiency and the cooling rate as:

$$\text{Flowrate} = \frac{\textit{volume in liter delivered}}{\textit{time taten in minutes to deliver the volume}} = \frac{10.5\,L}{3.39mins} = 3.1L/min \quad (1)$$

$$\text{Efficiency of pump } \eta = \frac{\textit{actual flow rate of pump}}{\textit{expected flow rate}} \times 100\% = \frac{3.1}{4} \times 100\% = 77.5\,\% \quad (2)$$

$$\text{Cooling rate} = \frac{\textit{temperature loss}}{\textit{time taten in minutes to loss the temperature}} = \frac{527.37°C}{3.39mins} = 155.57°C/\text{min} \quad (3)$$

The efficiency of the pump defines the efficiency of the apparatus, since the pump is the main component for quenching in the apparatus. Therefore, the efficiency of the apparatus can be said to be 77.5%.

Specimen quenched with water had a Leeb hardness of 465 HL and 373 HL from a distance of 2 mm and 100 mm respectively from its quenched end; the specimen quenched with a brine solution of 3.5% of salt content had a hardness of 578 HL and 376 HL from a distance of 2 mm and 100 mm respectively from its quenched end and specimen quenched with a brine solution of 5% of salt content had a hardness of 448 HL and 395 HL from a distance of 2 mm and 100 mm respectively from the quenched end. From the analysis, it appeared that specimen quenched with 3.5% of salt contend had the highest hardenability. (Abdullah, *et al.*, 2023), had a similar evaluation in their research with a quenched medium of normal and cold water using the Brinell hardness test having 218 HB and 136 HB. The solution of salt content of 25 and 100% were 176 HB and 148 HB respectively. Their best performing medium was a salt solution containing 50% with 187 HB.

4.0 CONCLUSIONS

The design and fabrication of a Jominy end-quenching apparatus was done successfully according to the standard of ASTM A255-10. The incorporation of a DC power source has helped tackled power failures that may occur during quenching process. The hardenability of mild steel using different quenchants was characterized during the apparatus testing stage; this enabled the calculation of the efficiency of the apparatus which is 77.5%. Hardness values were highest at the quenched end and decreased along the depth of the specimens. The apparatus was tested using mild steel, water and brine solutions as quenchants, but other types of steel and quenchants (having viscosity similar to water) can be tested on it as it will enable the determination of their hardenability. Jominy end-quench testing is a very important test in the determination of the hardenability of steels to be used for designs in different engineering applications.

Hardenability requirements are dependent on the specific application of a component. High hardenability is not always required, but this apparatus did not provide the necessary means to determine low hardenability. The low hardenability can be determined using a quenchant of high temperature, which can be obtained by varying quenchant temperature. The apparatus was designed for less viscous quenchants influenced by the type of pump used in the design. It also lacks pressure variation. For improvement of this design, a temperature and pressure varying means should be added. The developed apparatus works in a short time cycle and with a shorter processing time, the amount of water used was enhanced, similar result was reported by (Yekinni, et al., 2014).

4.1 RECOMMENDATION

Hardenability requirements are dependent on the specific application of a component. High hardenability is not always required, but this apparatus did not provide the necessary means to determine low hardenability. Low hardenability can be determined using quenchant of high temperature, which can be obtained by varying quenchant temperature. The apparatus was designed for less viscous quenchants influenced by the type of pump used in the design. It also lacks pressure variation. For improvement of this design, the following solutions were proposed.

1. Temperature Control: Implement a system that allows for precise control and adjustment of the quenchant temperature. This will enable the determination of hardenability across a wider range of conditions, including those requiring low hardenability.
2. Quenchant Viscosity Flexibility: Consider using a pump or other mechanisms that can handle a broader range of quenchant viscosities. This will increase the apparatus' compatibility with various materials and quenching processes.
3. Pressure Variation: Incorporate a means to vary the quenching pressure. This will provide greater control over the cooling rate and allow for more accurate hardenability testing.

REFERENCES

Abdullah, T., Abdulhakeem B. M., & Mohammed, A., A. M. (2023). The Effect of Quenching Media on the Hardness of Low Carbon Steel. Sabha University Journal of Pure & Applied Sciences vol.21 no.4 http://dx.doi.org/10.51984/jopas.v21i4.2152

Akinlabi, E. T., Ikumapayi, O. M., Bodunde, O. P., Adaramola, B. A., Uchegbu, I. D. & Fatoba, S. O. (2020). Impact of Quenching on the Hardenability of Steels EN-3 (~1015), EN-8 (~1040) and EN-24 (~4340) during Jominy End Quench Technique. International Journal on Emerging Technologies, 11(5): 290–297.

ASTM A255-10. (2014). Standard specification for carbon steel bars for forging and heat treatment. ASTM International.

Colla, V. Vannucci, M., Matino, I. & Valentini, R. (2023). A deep learning-based approach to estimation of Jominy profile of medium Carbon quench hardenable steels. steel research international. 95. http://dx.doi.org/10.1002/srin.202300374

Hwang, J. K. (2021) Effects of Water Jet Height and End Dipping on the Cooling Rate and Hardenability in the Jominy End Quench Test. Processes 2021, 9, 607. https://doi.org/10.3390/pr9040607

Ikumapayi O. M., Okokpujie I. P., Afolalu S. A., Ajayi O. O., Akilabi E. T., Bodunde O. P (2018). Effects of Quenchants on Impact Strength of Single-Vee Butt Welded Joint of Mild Steel. IOP Conf. Series: Materials Science and Engineering, 391, 012007 http://dx.doi.org/10.1088/1757-899X/391/1/012007

Kandpal, B. C., Chutani, A, Harsimran, A. G., Sadanna, C. (2011). A review on Jominy test and determination of the effect of alloying elements on the hardenability of steel using the Jominy end quench test. International Journal of Advances in Engineering & Technology, 1(3): 65-71

Kumar, S. (2013). Design and analysis of aerospace structures using advanced materials. In Aerospace Structures and Materials (pp. 3-74). Springer, Dordrecht.

Landgraf, P., Birnbaum, P., Meza-García, E., Grund, T., Kräusel, V., Lampke, T. (2021) Jominy End Quench Test of Martensitic Stainless Steel X30Cr13. Metals 2021, 11, 1071. https://doi.org/10.3390/met11071071

Muhammad, A. H., Muhammad, M., Muhammad, O., Muhammad, N., & Syed M. K. H. (2018), Design and Fabrication of Jominy End-Quench Testing Machine: Hardenability Evaluation of AISI-8620 Case-Hardening Steel, Journal of Testing and Evaluation, http://dx.doi.org/10.1520/JTE20170185

Yazdi A.Z., Sajjadi S. A., Zebarjad S. M., & Nezhad M. (2008). Prediction of hardness at different points of Jominy specimen using quench factor analysis method. Journal of Materials processing technology, 199(1-3): 124-129 http://dx.doi.org/10.1016/j.jmatprotec.2007.08.035

Yekinni, A. A., Agunsoye, J. O., Bello, S. A., Awe, I. O. & Talabi, S.I. (2014) Fabrication of End Quenched Machine: Hardenability Evaluation. Journal of Minerals and Materials Characterization and Engineering, 2, 107-113. http://dx.doi.org/10.4236/jmmce.2014.22014

