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The Effect of Quenching on High-temperature Heat Treated Mild Steel and Its Corrosion Resistance

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ABSTRACT

Steel is extensively used in many applications that include construction because of its unique properties and the ease with which its properties can be enhanced for improved performance. Due to its high malleability and strength, it can be easily machined and welded compared to other types of steel. However, the susceptibility to low performance has been associated with its low resistance to environmental degradation when exposed to corrosive or polluted environments. This study focuses on mild steel heat treatment quenched in four mediums of engine oil, water, palm oil, and air, along with its properties and corrosion susceptibility. The high temperature used for the procedure is 800 °C, 900 °C, and 1000 °C, respectively. After the heat treatment procedure, the test samples undergo corrosion testing in the sodium chloride solution for two weeks to observe the presence of corrosion products rust on its surface. The tensile machine was utilized to obtain the mechanical properties, including yield strength, tensile strength, and percentage elongation. The hardness values were obtained using the Rockwell hardness machine, and the optical microscope (OM) was used to observe the effect of the corrosion activity on the sample surface. The results obtained indicate an

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increase in the hardness, yield, and tensile strength, but the elongation reduces as the temperature increases.

Keywords: Heat treatment, mechanical properties, mild steel, quenching, sodium chloride

INTRODUCTION

Carbon steel, due to its extensive use, can be classified into three different categories based on its carbon content: low carbon steel (mild steel); medium carbon steel; and high carbon steel (Fadara et al., 2011). Mild steel is a type of low-carbon steel, which is cheap and easy to alter its mechanical properties (Hassan, 2016). The low carbon content of this steel gives lower tensile strength when compared with high carbon alloy steel (Alves et al., 2013; Ahaneku et al., 2013; Xiaohui et al., 2018; Roland et al., 2018; Kazeem & Esther, 2018; Elewa et al., 2021; Joseph & Alo, 2014).

Mild steel is produced in millions of tonnes around the world yearly for different engineering applications. Mild steel has been used to produce automobile panels, structural beams, and other engineering applications as they are readily available and easy to fabricate (Samuel et al., 2021; Melchers, 2005; Burstein & Pistorius, 1995). Heat treatment procedure, which involves a controlled heating temperature; cooling or quenching of the metals improves the material properties without distorting its shape have been researched and documented (Nkhoma et al., 2014; Araoyinbo et al., 2018; Ismail et al., 2016; Bhateja et al., 2012). The heat treatment methods often used to obtain this desired microstructure include the annealing process, normalizing, and tempering (Tukur et al., 2014). The quenching approach is often used to improve steel properties by inducing a martensite transformation, which requires the steel to be cooled rapidly through the eutectoid point, at which the austenite phase becomes unstable (Ismail et al., 2016). Quenching, which is an important process in material property alteration, involves a carefully selected hardening temperature, which is essential before the rapid cooling in water, oil, or other cooling mediums to attain a certain level of hardness or tensile strength, which develops the final mechanical properties and at the same time provides stress relieve in the material.

The carbon and other elements present in the steel composition during the quenching process are trapped within the crystal grain, reducing the dislocation movement and contributing to the improved hardness of the steel (Sharma & Roy, 2014). In this research, low carbon steel is used, which is heat-treated and quenched in four different mediums to observe the effects on the hardness, percentage elongation, yield, and tensile strength. In addition, the heat-treated samples are further subjected to corrosion test by immersion in an aqueous solution of sodium chloride (NaCl) to observe the effect of the heat treatment procedure and subsequently the different quenching mediums on its surface morphology and corrosion behavior.

MATERIALS AND METHODS

Preparation of Raw Materials

The low carbon steel plate was locally purchased for the research, was cut into 85 mm x 18 mm x 3 mm. The samples are cleaned and polished to remove any rust and unevenness on the surface using sandpaper.

Heat Treatment Procedure

For this research, the procedure for the heat treatment process was in three stages, the heating of the samples at specified temperatures; soaking of the heat-treated samples; and cooling or quenching of the samples in water, air, engine oil, and palm oil. First, the tube furnace was utilized as the heating medium in which the cut samples were placed inside, and the temperatures adjusted to 800 °C, 900 °C, and 1000 °C respectively for 1 hour with a soaking time of 30 minutes. Next, the samples were quenched in four mediums of water, air, engine oil, and palm oil.

Testing and Characterization

The testing and characterization of the samples were by XRF to determine the chemical composition, the tensile machine for the percentage elongation, yield, and tensile strength. In contrast, for the hardness values, a Rockwell machine was used. In addition, the morphology of the corrosion test in sodium chloride solution was observed with the use of an optical microscope.

For the tensile testing, the samples were tested using Shimadzu tensile testing machine model AG-XD plus on the heat-treated mild steel with an average of five samples tested for each temperature quenched in water, air, engine oil, and palm oil. The samples were subjected to uniaxial load at a gauge length of 37 mm, and a fixed crosshead speed of 10 mm/min, and the average result of the specimens were recorded. This test method provides readings for the yield strength, tensile strength, and percentage elongation at the break-off for the samples. In addition, for the Rockwell hardness testing, five readings at different positions on the samples were obtained, with a Rockwell hardness machine for all the quenched samples.

The heat-treated mild steel specimens were immersed in sodium chloride solution for two weeks. The solution was prepared by adding 35 grams of sodium chloride to 1 liter of water. After two weeks of immersion, the samples were taken out and dried in an oven at 90 °C for 12 minutes. The morphology of the samples was observed with an optical microscope after the corrosion testing using an optical microscope with a magnification of 40x.

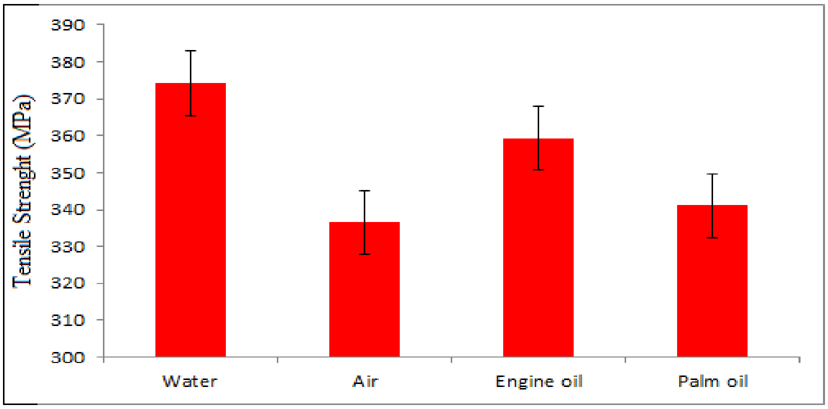
RESULTS AND DISCUSSION

In this study, X-Ray Fluorescence (XRF) was used to characterize the chemical composition of the mild steel. Mild steel consists of many elements, and the main elements present in mild steel are Carbon, Copper, Iron, and Manganese. These elements have a significant effect on the microstructure and the mechanical properties of mild steel. The composition of the mild steel is shown in Table 1, and it shows that the main constituents of the mild steel, which is iron (Fe), has a weight percentage of 98 %, Carbon (C) with a percentage of 0.25 %, Copper (Cu) 0.20 %, Manganese (Mn) 1.03 %, and others 0.52 %.

Table 1
Chemical composition of the as-received material

Element	Content (Weight %)
Carbon, C	0.25
Copper, Cu	0.20
Iron, Fe	98.0
Manganese, Mn	1.03
Others	0.52

The tensile strength of the quenched steel samples in water, air, engine oil, and palm oil are shown in Figures 1(a), 1(b), and 1(c) at 800 ^oC, 900 ^oC, and 1000 ^oC. There was an improvement in the tensile properties, and the tensile strength results at 800 ^oC reveal that the sample quenched in water has the highest value of tensile strength of 374.16 MPa, while the sample quenched in the air has the least tensile strength of 336.49 MPa. The samples heat-treated at 900 ^oC and 1000 ^oC records the highest tensile strength in both cases to be water quenched samples, which record the tensile strength of 408.42 MPa and 421.80 MPa. The sample quenched in the air still records the lowest tensile strength for both temperatures, which was 352.84 MPa for 900 ^oC, and 368.5 MPa for 1000 ^oC. It was observed that as the temperature is increased, all the quenched sample records increased in their tensile strength, including the engine oil and palm oil. The heat treatment process that involves quenching in different mediums provides a means of obtaining certain desirable conditions in mild steel (Tukur et al., 2014). Quenching in the four media allows steel hardening of the mild steel during this process by controlling the heat flow, which also improves the reduction of cracks and distortion that are likely to be obtained from the cooling process (Burstein & Pistorius, 1995).



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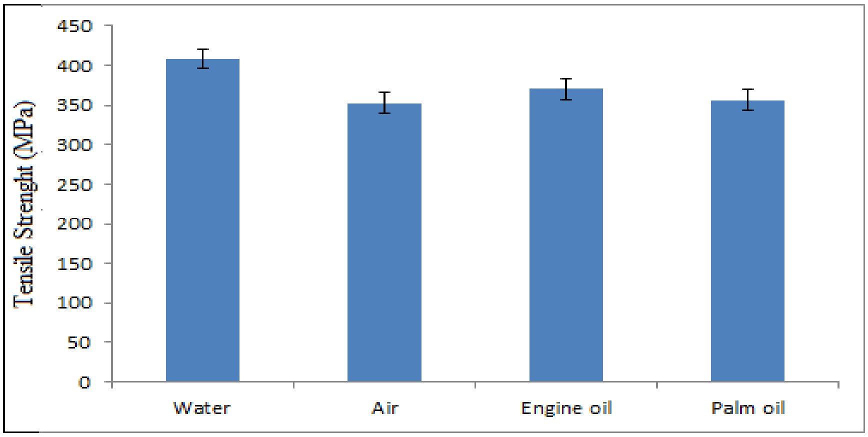

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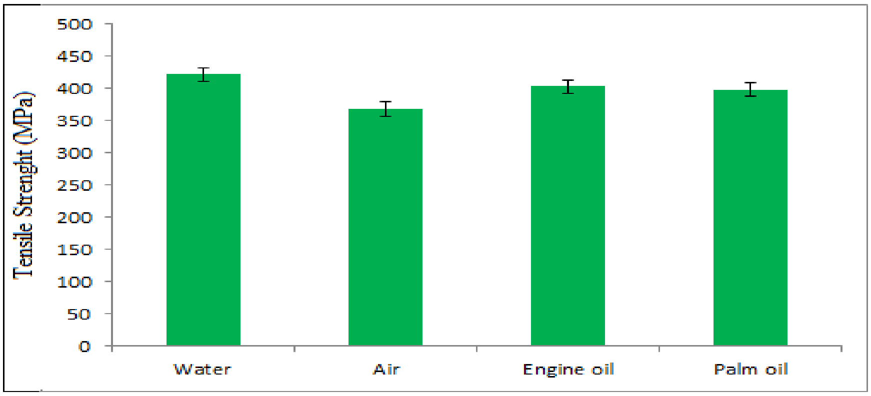

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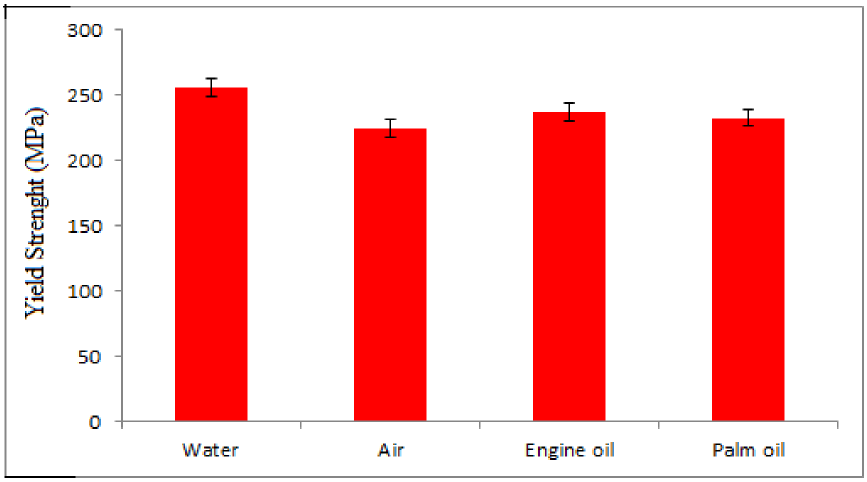
Figure 1. (a) Tensile strength of samples heat-treated at 800 ^{o}C and quenched in four mediums; (b) Tensile strength of samples heat-treated at 900 ^{o}C and quenched in four mediums; (c) Tensile strength of samples heat-treated at 1000 ^{o}C and quenched in four mediums

Figures 2(a), 2(b), and 2(c) shows the yield strength of the samples heat-treated at 800 °C, 900 °C, and 1000 °C, respectively. The yield strength records the highest strength of 256.31 MPa for 800 °C water quenched sample and 224.70 MPa for 800 °C air quenched sample. The samples heat-treated at 900 °C and 1000 °C records the highest yield strength in both cases to be water quenched samples, which records the yield strength of 275.70 MPa and 286.33 MPa. The sample quenched in the air still records the lowest yield strength for both temperatures, 228.63 MPa for 900 °C and 232.65 MPa for 1000 °C. The values obtained from the three temperatures are indicative of the yield point of the samples, which is indicative of the materials returning to their initial shape or undergoing permanent deformation (Xiaohui et al., 2018).



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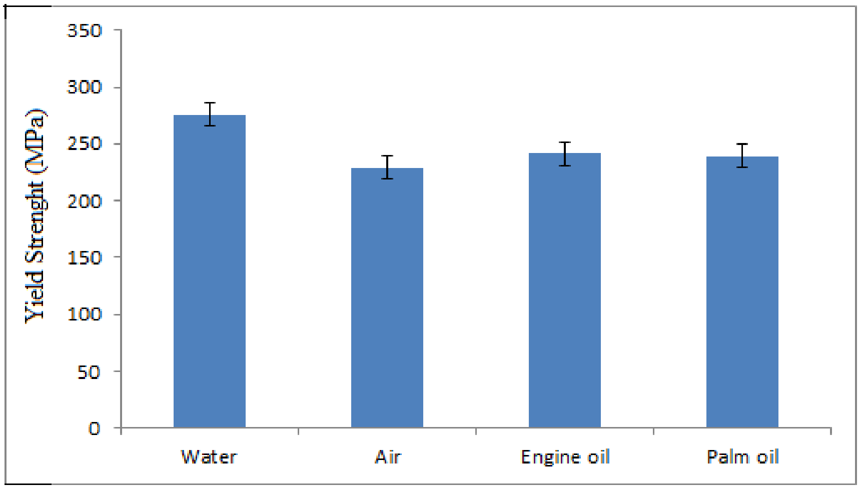

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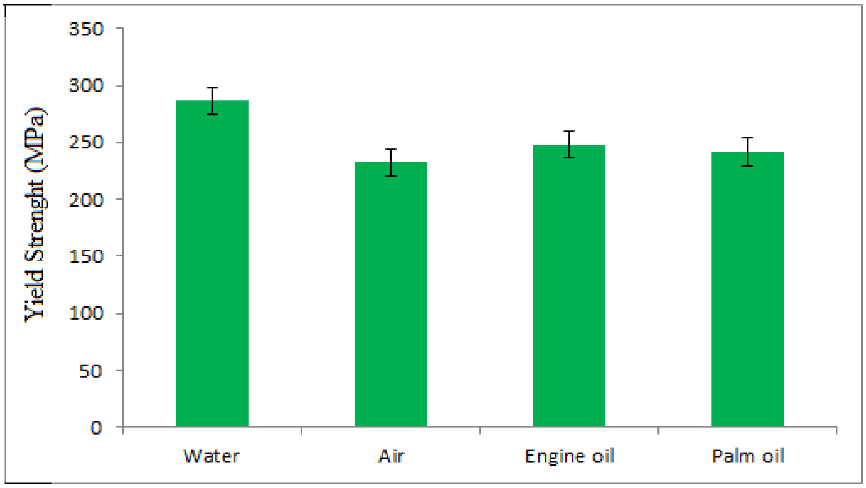

(c)

Figure 2. (a) Yield strength of samples at 800 °C and quenched in four mediums; (b) Yield strength of samples at 900 °C and quenched in four mediums; (c) Yield strength of samples at 1000 °C and quenched in four mediums

Figure 3 shows the percentage elongation of heated specimens at 800 °C, 900 °C, and 1000 °C and water quenched, air-cooled, engine oil quenched, and palm oil quenched. Percentage elongation in gauge length measures the ductility of the material, the sample heat-treated at 800 °C in Figure 3, and air-cooled or quenched records the highest elongation of 42.4 %, and water quenched sample records the lowest of 30.2 %. At temperatures of 900 °C and 1000 °C shown in Figure 3, the percentage elongation reduces with increasing temperatures and records 40.48 % at 900 °C and 38.5 % for 1000 °C for air quenched; and 27.4 % at 900 °C and 20.2 % at 1000 °C for water quenched samples. All the quenched samples from the four-quench medium show a significant reduction in percentage elongation as the temperature is increased, which implies that there will be a reduction in its ductility and the ease of machining for the different applications.

The Rockwell hardness machine was used to measure the hardness of the mild steel samples produced from different temperatures of 800 °C, 900 °C, and 1000 °C, and quenched in water, air, engine oil, and palm oil as shown in Tables 2, 3, and 4. This method used to obtain the hardness values offers a less expensive route and is easy to use the approach in relation to other methods (Pillay & Lin, 2014). Tables 2, 3, and 4 show the result of the hardness test obtained from the different specimens quenched in the cooling mediums. Moreover, at 800 °C the water quenched sample records the highest hardness of 22.4 HRA, and the air-cooled records the lowest hardness of 11.2 HRA. At 900 °C and 1000 °C, it was observed that the hardness values increase with increasing temperature. Water quenched samples records the highest in both cases of 24.3 and 28.6 HRA, respectively, while air

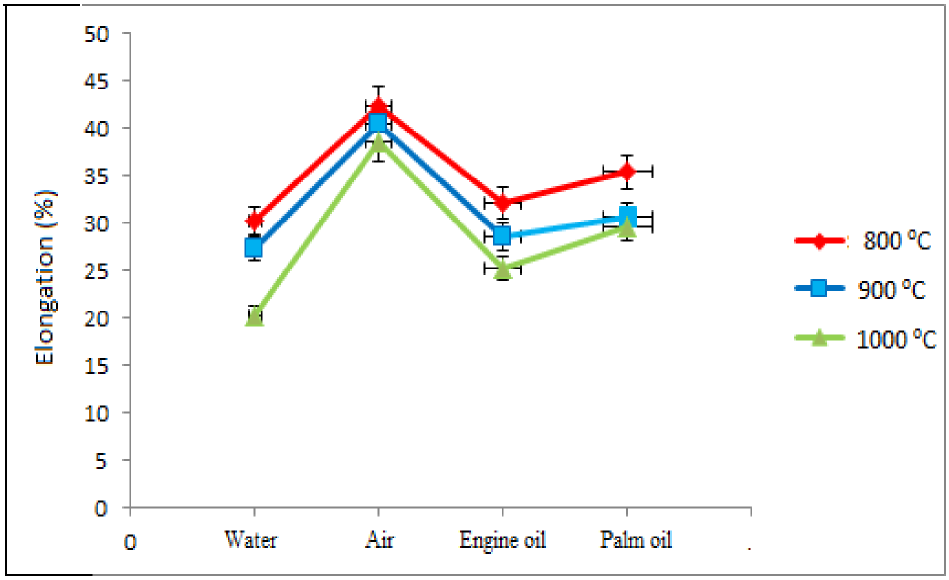

Figure 3. Percentage elongation of samples quenched in four mediums at 800 °C, 900 °C, and 1000 °C.

quenched record the lowest for both temperatures at 16.1 and 20.8 HRA. The higher the hardness, the less ductile the material will be and the likely difficulty to the machine. It was observed that water quenched samples have a higher hardness value when compared with air, engine oil, and palm oil. It may be attributed to the fact that water has a higher cooling rate than the other quenching mediums (Shi et al., 2017).

Table 2

Rockwell hardness values at 800 °C and quenched in four mediums

Sample	Rockwell Hardness (HRA)
800 °C (Water quench)	22.4
800 °C (Air cool)	11.2
800 °C (Engine oil quench)	17.8
800 °C (Palm oil quench)	14.5

Table 3

Rockwell hardness values at 900 °C and quenched in four mediums

Sample	Rockwell Hardness (HRA)
900 °C (Water quench)	24.3
900 °C (Air cool)	16.1
900 °C (Engine oil quench)	20.1
900 °C (Palm oil quench)	18.5

Table 4
Rockwell hardness values at 1000 °C and quenched in four mediums

Sample	Rockwell Hardness (HRA)
1000 °C (Water quench)	28.6
1000 °C (Air cool)	20.8
1000 °C (Engine oil quench)	25.4
1000 °C (Palm oil quench)	23.7

Corrosion is known to be a rapid deterioration of materials into a more stable oxide form as a result of exposure to corrosive mediums. This corrosion process involves reducing material thickness which results in a gradual reduction in both tensile and hardness properties. In addition, the presence of pits, which is one form of corrosion, is responsible for stress concentration in the material, which reduces the load-carrying capacity of the steel and further degrades the material until failure occurs (Dauda et al., 2015). Low carbon steel has low resistance to corrosion attacks, and one of the main properties often demanded of steel products is that they should not corrode. A few types of steel provide some form of resistance to corrosion by forming an oxide layer at the surface; the process is called passivation to reduce the corrosion attack on its surface. Figures 4(a), 4(b), 4(c), and 4(d) show the surface morphology of samples heat-treated at 1000 °C and quenched in water, air, engine oil, and palm oil as observed by the optical microscope. Samples heat-treated at 1000 °C are shown only since the 800 °C and 900 °C sample micrographs are similar, and only one temperature is illustrated here. The samples quenched in water, air, engine oil, and palm oil, as shown in Figure 4, shows corrosion attack to be present as the dark pots located on all the metal surfaces due to exposure to the corrosive medium. The corrosion attack spreads over the microstructural surface and is aided by the surface imperfections where the surface has deformities, unevenness, and roughness.

The result shows that when the temperature increases, at the surface of the four quenching mediums, surface corrosion is observed as the pitting spots on the material surface; this might be due to the strong bonding existing in the samples when heat-treated and quenched. The type of corrosion commonly observed on all of these micrographs is the pitting form because the metal is pitted by aerated sodium chloride solution (Seidu & Kutelu, 2013). The different areas on the surface of the mild steel become unstable when a pit is created on the metal surface, and the mild steel samples start to oxidize, and where the pit is created, the corrosion will continue to propagate, and the pits continue to grow (Marlon et al., 2018). The corrosion rate is the rate at which materials deteriorate when in contact with the environment for a known duration of time. The speed or rate of deterioration depends on the environmental conditions and the type and condition of the metal under consideration. The corrosion rate for the samples heat-treated at 1000 °C shows a marginal difference for all the four quenched samples. Samples quenched in the water had a corrosion rate of 0.142 mmpy, air quenched 0.135 mmpy, engine oil quenched 0.140 mmpy, and palm oil quenched 0.138 mmpy.

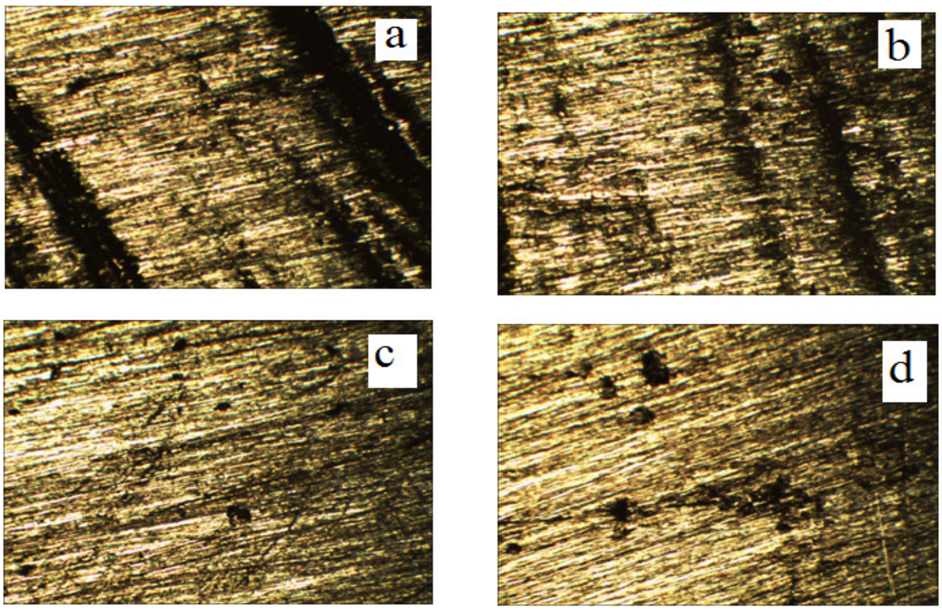

Figure 4. Shows optical microscope (10x) morphology of the samples heats-treated at 1000 ^{o}C after immersion test in NaCl (a) Water quench, (b) Air quench, (c) Engine oil quench, and (d) Palm oil quench.

CONCLUSIONS

The research highlights the impact of high temperature on mild steel's mechanical properties when quenched in water, air, engine oil, and palm oil. It was observed that the samples quenched in engine oil and palm oil produce mechanical properties inferior to water quenched samples. It is a result of water having a faster cooling effect on the mild steel. The results recorded for the tensile strength, yield strength, and hardness show a significant increase when the temperature increases. The water quenched results records the highest tensile strength, yield strength, and hardness, while air quenched indicate the lowest tensile strength, yield strength, and hardness values. The reverse was observed for the percentage elongation as the air quenched samples records the highest percentage elongation and water quenched the lowest percentage elongation. This study further showed that the heat treatment and quenching methods significantly improve the mechanical properties of the material. However, when exposed to corrosive medium, the presence of pitting form of corrosion was observed as a result of the chloride attack on the surface of the metal.

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REFERENCES

Ahaneku, I. E., Kamal, A. R., & Ogunjirin, O. A. (2013). Effects of heat treatment on the properties of mild steel using different quenchants. *Frontiers in Science, 2*(6), 153-158. https://doi.org/10.5923/j.fs.20120206.04.

Alves, V. A., Brett, C. M. A., & Cavaleiro, A. (2013). Influence of heat treatment on the corrosion of high speed steel. *Journal of Applied Electrochemistry, 31*, 65-72. https://doi.org/10.1023/a:1004157623466

Araoyinbo, A. O., Salleh, M. A. A. M., & Jusof, M. Z. (2018). Corrosion protection of mild steel in sea water using chemical inhibitor. In *IOP Conference Series: Materials Science and Engineering* (Vol. 343, No. 1, p. 012012). IOP Publishing. https://doi.org/10.1088/1757-899x/343/1/012012.

Bhateja, A., Varma, A., Kashyap, A., & Singh, B. (2012). Study the effect on the hardness of the three sample grades of tool steel ie EN-31, EN-8 and D3 after heat treatment processes such as annealing, normalizing and hardening and tempering. *The International Journal of Engineering and Science, 1*(2), 253-259. http:// http://www.theijes.com/papers/v1-i2/AL01202530259

Burstein, G. T., & Pistorius, P. C. (1995). Surface roughness and the metastable pitting of stainless steel in chloride solutions. *Corrosion, 51*(5), 380-385. https://doi.org/10.5006/1.3293603.

Dauda, M., Kuburi, L. S., Obada, D. O., & Mustapha, R. I. (2015). Effects of various quenching media on mechanical properties of annealed 0.509wt%C - 0.178wt%Mn steel. *Nigerian Journal of Technology, 34*(3), 506-512. https://doi.org/10.4314/njt.v34i3.12

Elewa, R. R., Araoyinbo, A. O., Fayomi, O. S. I., Samuel, A. U., & Biodun, M. B. (2021). Effect of machining on stainless steel: A review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1107, No. 1, p. 012084). IOP Publishing. https://doi.org/10.1088/1757-899x/1107/1/012084.

Fadara, T. G., Akanbi, O. Y., & Fadare, D. A. (2011). Effect of heat treatment on mechanical properties and microstructure of NST 37-2 steel. *Journal of Minerals and Materials Characterization and Engineering, 10*(3), 299-308. https://doi.org/10.4236/jmmce.2011.103020.

Hassan, M. F. (2016). Analysis of mechanical behavior and microstructural characteristics change of ASTM A-36 steel applying various heat treatment. *Journal of Material Science & Engineering, 5*(2), 1-6. https:// doi.org/ 10.4172/2169-0022.1000227

Ismail, N. M., Khatif, N. A. A., Kecik, M. A. K. A., & Shaharudin, M. A. H. (2016). The effect of heat treatment on the hardness and impact properties of medium carbon steel. In *IOP Conference Series: Materials Science and Engineering* (Vol. 114, No. 1, p. 012108). IOP Publishing. https://doi.org/10.1088/1757-899x/114/1/012108.

Joseph, O. O., & Alo, F. I. (2014). An assessment of the microstructure and mechanical properties of 0.26% low carbon steel under different cooling media: Analysis by one-way anova. *Industrial Engineering Letters, 4*(7), 39-45.

Kazeem, O. S., & Esther, T. A. (2018). Experiment on effect of heat treatment on mechanical and microstructure properties of AISI steel. *Materials Today: Proceedings, 5*, 17996-18001. https://doi.org/10.1016/j.matpr.2018.06.132.

Marlon, M. N., Eduardo, M. S., Reny, A. R., & Tarcisio, G. B. (2018). Analysis of quenching parameters in AISI 4340 steel by using design of experiments. *Materials Research, 4*(1), 133-135. https://doi.org/10.1590/1980-5373-mr-2018-0315

Melchers, R. E. (2005). The effect of corrosion on the structural reliability of steel offshore structures. *Corrosion Science, 47*(10), 2391-2410. https://doi.org/10.1016/j.corsci.2005.04.004

Nkhoma, R. K. C, Siyasiya, C. W., & Stump, W. E. (2014). Hot workability of AISI 321 and AISI 304 austenitic stainless steels. *Journal of Alloys and Compounds, 595*, 103-112. https://doi.org/10.1016/j.jallcom.2014.01.157.

Pillay, C., & Lin, J. (2014). The impact of additional nitrates in mild steel corrosion in a seawater / sediment system. *Corrosion Science, 80*, 416-426. https://doi.org/10.1016/j.corsci.2013.11.047.

Roland, T. L., Cleophas, A. L., & Idehai, O. (2018). Effect of heat treatment processes on the localized corrosion resistance of austenitic stainless steel type 301 in chloride/sulphate solution. *Results in Physics, 11*, 570-576. https://doi.org/10.1016/j.rinp.2018.09.056

Samuel, A. U., Araoyinbo, A. O., Elewa, R. R., & Biodun, M. B. (2021). Effect of machining of aluminium alloys with emphasis on aluminium 6061 alloy - A review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1107, No. 1, p. 012157). IOP Publishing. https://doi.org/10.1088/1757-899x/1107/1/012157.

Seidu, S. O., & Kutelu, B. J. (2013). Effect of heat treatments on corrosion of welded low-carbon steel in acid and salt environments. *Journal of Minerals and Materials Characterization and Engineering, 1*(3), 95-100. https://doi.org/10.4236/jmmce.2013.13018

Sharma, P., & Roy, H. (2014). Pitting corrosion failure of an AISI stainless steel pointer rod. *Engineering Failure Analysis, 44*, 400-407. ttps://doi.org/10.1016/j.engfailanal.2014.06.001

Shi, D., Kang, K., & Gao, G. (2017). Effect of quenching parameters on the mechanical properties of the 7A04 aluminium alloy. *Materials and Technology, 51*(1), 95-99. https://doi.org/10.17222/mit.2015.267

Tukur, S. A., Dambatta, M. S., Ahmed, A., & Muaz, N. M. (2014). Effect of heat treatment temperature on mechanical properties of the AISI 304 stainless steel. *International Journal of Innovative Research in Science Engineering and Technology, 3*, 9516-9520.

Xiaohui, C., Jia, L., Xu, C., Huaming, W., & Zheng, H. (2018). Effect of heat treatment on microstructure, mechanical and corrosion properties of austenitic stainless steel 316L using arc additive manufacturing. *Materials Science and Engineering: A, 715*, 307-314. https://doi.org/10.1016/j.msea.2017.10.002.