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Effects of Different Holding Time and Quenchants on the Hardness and Corrosion rate of Medium Carbon Steel

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Abstract

The heat treatment of steels is majorly aimed at improving the mechanical and physical properties of the material and to understand factors that can influence these properties such as soaking time and quenching media etc. This research investigated the effects of different holding time and quenchants on the hardness and corrosion rate of medium carbon steel, after austenising at a temperature of 750^{o}C and soaking for a varied time of 1hr and 3hrs, the samples were quenched using three quenching media water, brine and condemned engine oil, and after which a hardness and corrosion test were conducted. The corrosion test was done in a 25%wt NaCl solution using Potentiodynamic method. The experimental result obtained revealed a hardness value of 43.7, 37.4, 36.1 and 26.9 HRC for condemned engine oil, water, brine and As-received respectively for 1hr holding time and those of 3hrs holding time were of hardness value of 40.1, 33.3, and 31.7 HRC respectively. It was therefore observed that the corrosion rate for the sample quenched in water after 1hr soaking time had the highest value with 1.523e^{002} mil/yr and a lowest value in the sample quenched in water after 3 hours with a value of 1.941e^{-003} mil/yr. The corrosion rate of the As-received sample had the highest value with 4.331e^{+002} mil/yr and a smallest value in water quenched sample at 1.213e^{+001} mil/yr. Therefore, it is believed that the results obtained will contribute immensely to the knowledge required for the processing and applications of medium carbon steel in the industry.

1. Introduction

Steel is so important because it is the most widely used alloy and for a very good reason [1]. Steel is majorly an alloy of iron and carbon though not in the exclusion of other alloying elements. Carbon steel is a major type of material that is commonly used in the industrial field for various applications. Carbon steel consists of low carbon, medium carbon and high carbon steel. In this research work, medium carbon steel is being investigated. Literature has proved that medium carbon steel usually fail in the industry due to corrosion and as well as heat treatment which generates gaseous molecules, irregular grain size and internal stresses in the heat affected zone. However, medium carbon steel is an iron alloy with carbon composition more than 0.25% to 0.5% [2]–[5]. It is a known fact that medium carbon steel provides an excellent tradeoff between strength and ductility, and it is used in many types of steel parts. Iron is relatively soft and the carbon in steel reduces this softness thereby making medium carbon steel harder than the conventional iron [6], [7]. Alloying elements like manganese, chromium, tungsten, and vanadium have always acted as hardening agents when added in steel. Though the accuracy in the proportion of these elements decides the specific properties that will be achieved in the steel. Medium carbon steel has been virtually and economically used in all aspects of human endeavor such as in oil and gas, manufacturing, construction, medical, transport, textile and aerospace industries etc., [4], [7], [8]. The failure of parts produced from engineering materials such as medium carbon steel in various industries by corrosion has become a major problem today. Corrosive processes are mostly directly and indirectly connected to our everyday lives. Corrosion also means the physicochemical degradation of a metal in a given environment, by looking at how it wears away the material, different types of corrosion can be classified. Corrosion problem is observable in numerous places, such as buildings, industries, viaducts, ancient and modern works of art are also not left out. Corrosion can as well emanate from the cross section losses of materials that have lower ductility, yield strength and ultimate strength. It reduces the life span of structures leading into structural vulnerability which usually results to structural failure. Corrosion is responsible for many catastrophes that have bedeviled operational materials in the engineering industries since the history of man. However, corrosion is the destruction or degradation of a material that results from the reaction of material with its [4], [9]–[12]. In another term, corrosion has also been stated as the chemical or electrochemical reaction of a metal with its environment which in some cases can lead to the failure of the entire structural component [13], [14]. Corrosion cause wastage of resources and it is practically not possible to mention a single branch of the national economy of any country, mostly nations that are highly developed technologically, where metals and its alloys are not used as materials in the construction of plants, equipment, machines, processes, transportation, and storage facilities, etc. [9]. Corrosion might not have instant negative consequences on the material but it attack the physical appearance, mechanical behavior and strength of the material leading into enormous operational difficulties [15]. The type and level of corrosion in a system relies on the composition and structure of the metal and its service environment.

Refinements have been mostly realized through controlling and applying novel casting, thermomechanical and heat treatment processes to influence the chemical composition of steels [16]–[18]. Through this means, reduction of the non-metallic inclusions and porosities, could result to increment in the homogeneity of chemical composition and microstructure, in particular prior austenite grain size, are usually controlled and achieved by casting and thermomechanical processing. As a further matter, a high strength martensitic structure of engineering components is manoeuvred by quenching-hardening and alloying additions [19]–[22]. The alloying additions are usually aimed to enhance the hardenability and final mechanical properties of steels. Nevertheless, in alloy steels, a subsequent tempering process is mainly employed to increase the toughness, uniformity of microstructure and mechanical properties and to regulate the amount of retained austenite and carbide precipitates and quenching-defects, and to reduce the amount of hydrogen embrittlement [18], [23]–[26]. The two main reasons for the remarkable flexibility of steel are heat alloying and heat treatment. Where heat treatment is a high heating operation applied to metals or their alloys in solid state above their recrystallization temperature and followed with cooling to impact the required properties to the metal and its alloy suitable for a particular application [4]. Heat treating of metals is a very useful operation in the final fabrication process of most engineering parts [27]. It is used to improve the mechanical properties of the metal alloys through manipulation of its microstructure. In the most essential respects, the product performance definitely will improve when the strength of metal is increased [28]. Heat treatment process includes; quenching, annealing and tempering. As a general rule, the procedure of heat treatment process consists of three stages [29]. First stage involves heating of the material. Second stage, hold the temperature for a specific period of time and cool down the material to room temperature. The heat treatment of medium carbon steel usually changes its mechanical properties, such as ductility, strength and hardness [29]. Finally, heat treatment of steel to a little degree affects other important properties such as its ability to conduct heat and electricity as well.

In austenitic carbon steel, it is a common practice to constantly revisit the choice of quenchant and austenitisation temperature, and soaking time. However, the challenge has still remained up to now, that there are only a handful of potentiodynamic corrosion test done on medium carbon steels using variant quenchants. Therefore, the effects of different holding time and quenchants on the hardness and corrosion rate of medium carbon steel after austenitizing at 750^0C will be investigated in 250 ml of simulated 25 w% brine at room temperature. This research is believed to be in the industrial interest in tackling the trade-off in the hardness and other mechanical properties so as to provide the designers and users in the steel industries with good and experimentally proven guidelines to select proper austenisation temperature and holding time for the heat treatment of medium carbon steel.

2. Materials and Methods

The medium carbon steels used in this work were in the form of forged bar measuring 10mm × 10mm × 0.5mm. The steel samples were purchased from Finke Steel Inc. (Sorel, QC, Canada). The chemical compositions of the medium carbon steel were determined using Spark Optical Emission Spectrometer model ARL Quanta Desk rating 350VA, are shown in Table 1 respectively. A total of 14 samples were cut from the material with hand sharer and washed in methylated spirit to remove dirt. Due to the smallness of samples, a steel pipe was cut opened and 12 out of samples were place into each half of the steel pipe to enable easy removal before placing them into a Muffle furnace model number LABC1210 for heat treat at a temperature of 750^oC and held for 1hr and 3hrs respectively. 150 ml was measured with beaker from each of the three quenching media comprising of water, brine, and condemned engine oil and poured into three stainless steel cups where that samples were quenched at the two different holding time intervals. Thereafter, a Leeb hardness testing machine model PRLH210 produced by Inspection Technology Co., Ltd was used to measure the hardness of the samples in HRC.

The heat-treated samples were sandpapered with SiC abrasion papers of about 600 grit, and again washed with methylated spirit to remove dirt and dried before corrosion test was done using electrochemical analyser model CH1604E. Potentiodynamic polarization test was done to assess the corrosion behaviour of the steel samples in the as-received, and in the austenitised and holding time of 1hr and 3hrs. This test was done in accordance with ASTM G8-96 standard. The potentiodynamic polarization test was performed using a 3-electrode cell, in which a saturated calomel electrode (SCE) was used as a reference electrode, a graphite electrode served as a counter electrode and whereas the steel sample was the working electrode. Each corrosion test were performed in 250 ml of simulated 25 w% brine at room temperature. The potentiodynamic polarization test was carried out at an applied potential in the range of -1500 mV (vs. SCE) to +1500 mV (vs. SCE) at a scanning rate of 2 mV/s. The corrosion parameters such as corrosion current density, corrosion rate and slopes were obtained from the computer controlled potentiostat. Prior to each corrosion test, the working electrode was allowed to stabilize in the sea water.

Table 1 Chemical composition of the medium carbon steel

Element	Percentage weight
Carbon (C)	0.47%
Iron (Fe)	98. %
Manganese (Mn)	0.5 - 0.8%
Phosphorous (P)	0.03%
Sulphur (S)	0.03%
Silicon	0.17 – 0.37%
Chromium	≤ 0.25%

2.1 Corrosion test calculation

The corrosion test as was carried out on the samples used the potentiodynamic method where electrochemical analyzer was used to read off the corrosion current (icorr) and the potential, which are information needed to determine the rate of corrosion of the material. The corrosion rate depends on the kinetics of both anodic (oxidation) and cathodic (reduction) reactions. According to Faraday's law, there is a linear relationship between the metal dissolution rate also known as the corrosion rate.

$$R_m = \frac{Mi_{corr}}{nF\rho} \qquad \textbf{Eqn. 1}$$

where R_m is rate of corrosion, i_{corr} is corrosion current, M is the atomic weight of the metal, ρ is the density, n is the charge number which indicates the number of electrons exchanged in the dissolution reaction and F is the Faraday constant, (96.485 C/mol). The ratio M/n is also sometimes referred to as equivalent weight.

3. Results and Discussion

3.1 Results

The results of the analysis showed that varying quenchants and holding time affects hardness and corrosion rate. Quenching produces a hardening effect on material as shown by this experiment when compared to the As-received samples. It can further be found from the experiment that waste oil produced a better hardening effect on the test samples than water and brine from **Table 2** above and that after soaking for an interval of 3hrs, the hardness values recorded a reduction in value but with an exception in the sample quenched in water (**Figure 1**), which recorded an impressively high value of 40.1 as against 37.4 HRC in 1hour. Brine had the lowest impact on the material hardness. It is a common knowledge that hardness of materials can be generally improved at the expense of the material’s ductility thereby making it brittle.

Table 2 describes the effects of the quenching media on the hardness over an interval of time and it is observed that in 1hr soaking time, the sample quenched in used engine oil has the highest hardness value of 43.7 HRC followed by the sample quenched in water with a hardness of 37.4 HRC, while the sample quenched in brine has a hardness of value of 36.1 HRC. The As-received samples quenched in brine after 3hrs of soaking at 750^0C acquired the highest hardness value as stated on **Table 2** above.

Again, after 3hrs soaking time, it was observed that the sample quenched in water has the highest hardness value of 40.1 HRC and the sample quenched in brine with the lowest value of 31.7 HRC.

The results obtained from **Figure 1** and **Figure 2** that shows the effects of different quenching media after a holding time of 1hr and 3hrs on the hardness of material respectively is in agreement with the study on the effect of quenching temperature and heating time on the quenched structure of a plain carbon steel by Takashi and Yoshio of Yamaguchi University (1967) [30] which proved that the longer the heating time, the lower quenching hardness for low carbon steels. Until heating time is 2 hours, the quenching hardness has not an effect on heating time at appropriate quenching temperature for high carbon steels.

Table 2 Result of hardness test on the heat-treated material carried out at different intervals of time.

Condition	Time(hr)	Average Hardness (HRC)
Quenched in brine	1 hour	36.1
Quenched in water	1 hour	37.4
Quenched in condemned engine oil	1 hour	43.7
As-received		26.9
Quenched in brine	3 hours	31.7
Quenched in water	3 hours	40.1
Quenched in condemned engine oil	3 hours	33.3

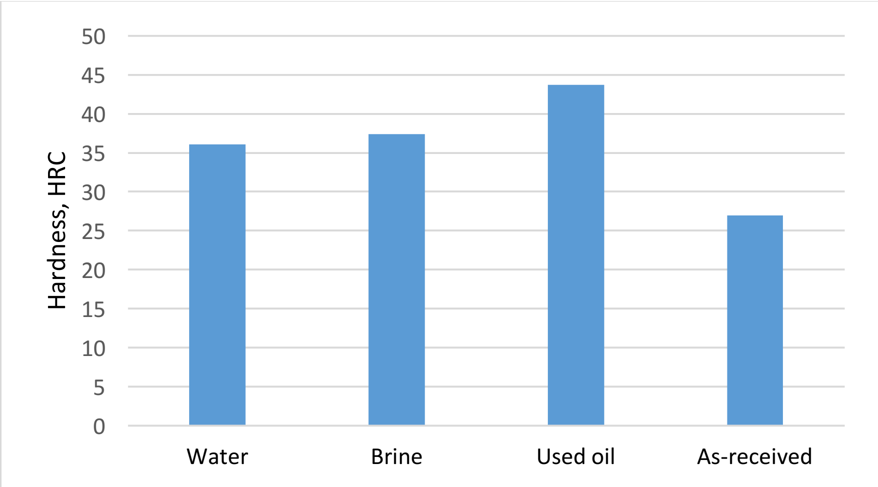

Figure 1. Graph of material hardness in different quenchants for 1hr holding time.

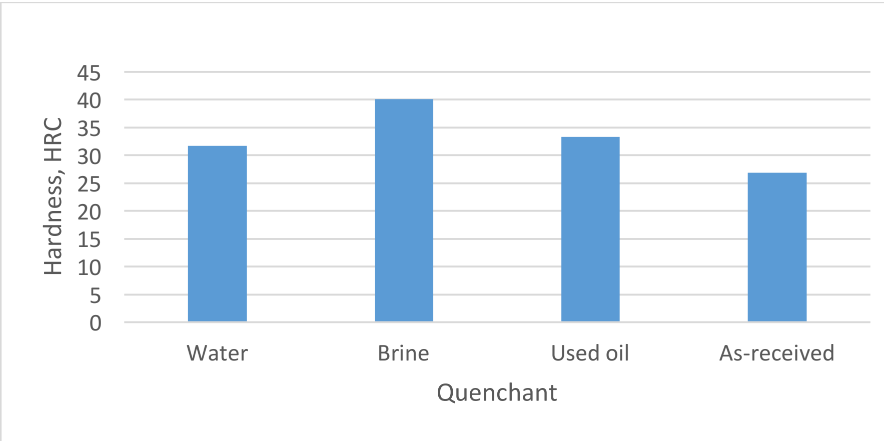

Figure 2. Hardness in the different quenching media after 3hrs holding time.

Figure 3 shows the comparison between the holding time of 1 hour and 3 hours after quenching in the three different media. **Table 3** is a table describing the values obtained from the corrosion rate of the As-received and all the samples quenched in different media. It was therefore observed that the corrosion rate for the sample quenched in water after 1hr soaking time had the highest value with 1.523e^{002} (mil/yr) and the lowest value was observed in the sample quenched in water after 3hrs with a value of 1.941e^{-003} (mil/yr). The corrosion rate of the As-received sample has the highest value of 4.331e^{+002} (mil/yr) and the lowest corrosion rate value of 1.213^{e+001} (mil/yr) was observed from the sample quenched in water.

Figure 4 is a graphical representation of the Tafel diagram of the As-received sample describing the rate of change of the log of current against the potential difference. **Figure 5** to **10** describes the Tafel diagram for the samples quenched in oil, water and brine respectively. Which is an exponential representation of the rapidly changing current through the electrode. **Figure 11** represents the comparison of the Tafel plot of all the samples of the experiment tends to describe the variation in logi/A as the potential difference changes from negative to positive values.

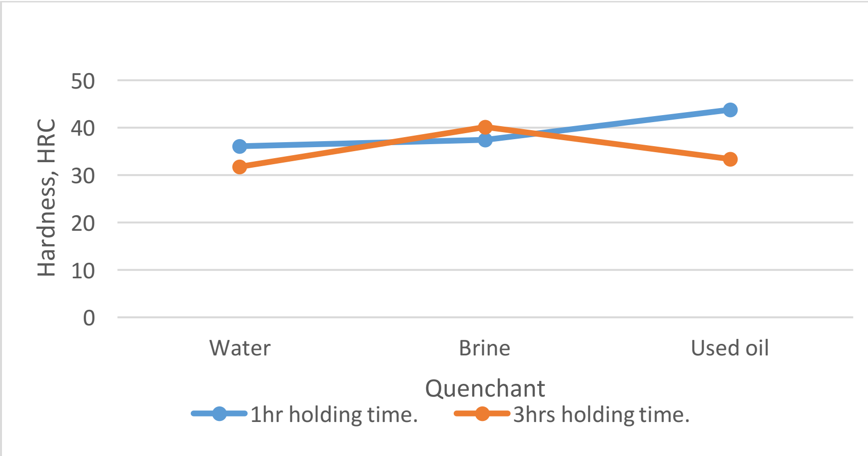

Figure 3. Comparison of variation in holding time.

Table 3: Corrosion rate and current of the samples

Samples	As-received	Oil quenched 1hr	water quenched 1hr	Brine quenched 1hr	Oil quenched 3hrs	water quenched 3hrs	Brine quenched 3hrs
Corrosion rate (mil/yr)	4.331e^{+002}	1.213e^{+001}	1.001e-^{003}	1.610e^{+002}	7.732e^{+000}	2.953e^{+002}	3.264e^{+001}

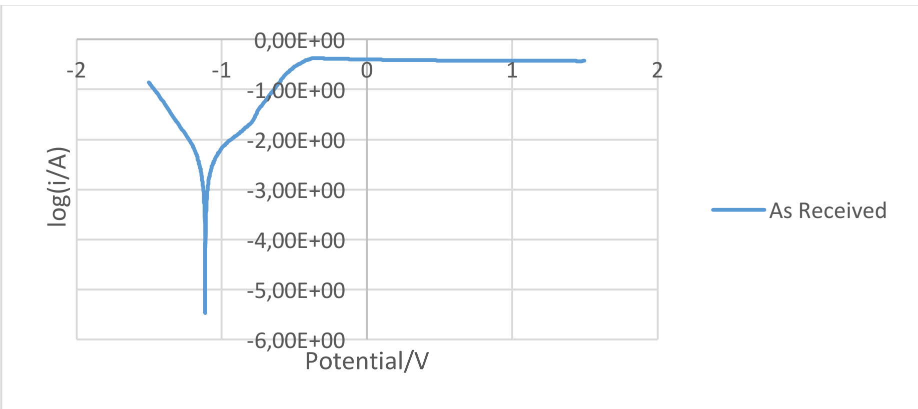

Figure 4. Electropotential plot for the As-recieved sample

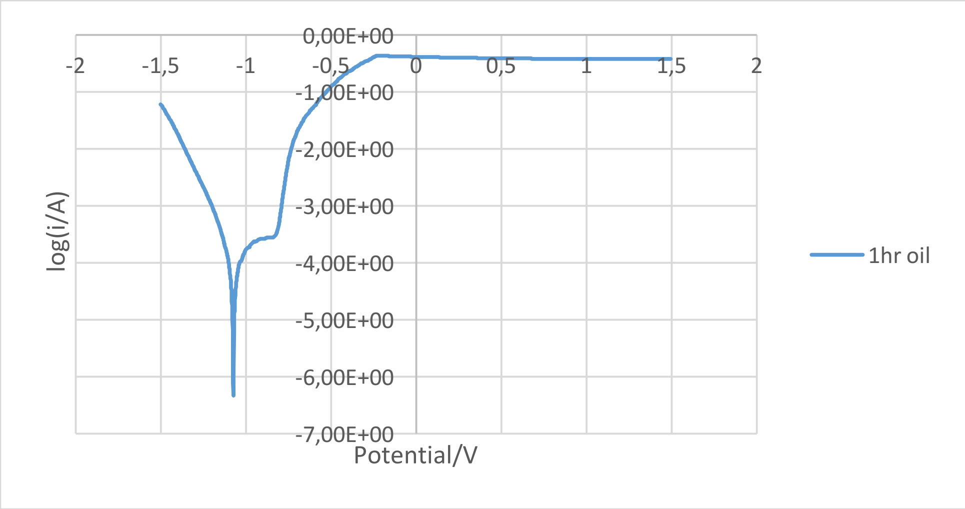

Figure 5. Electropotential plot for 1hr, quenched in oil sample

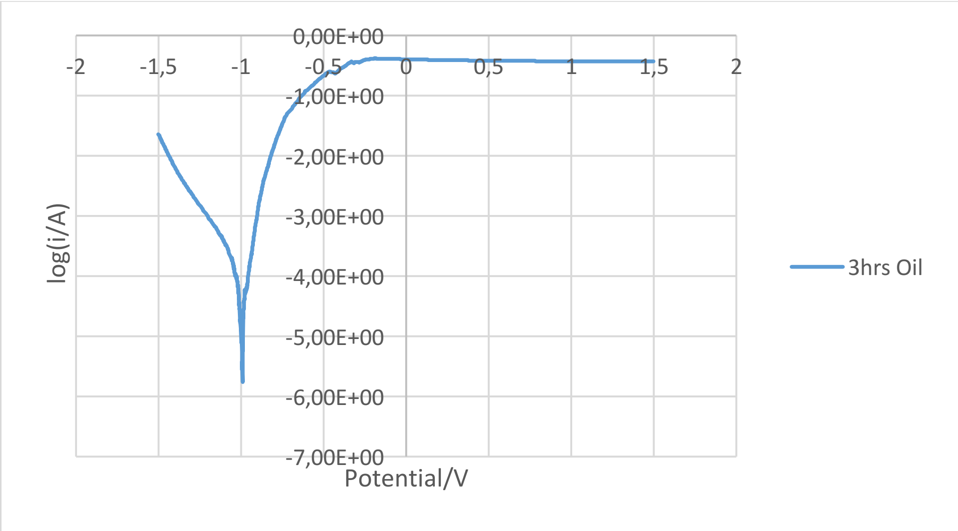

Figure 6. Electropotential plot for 3hrs quenched in used oil sample

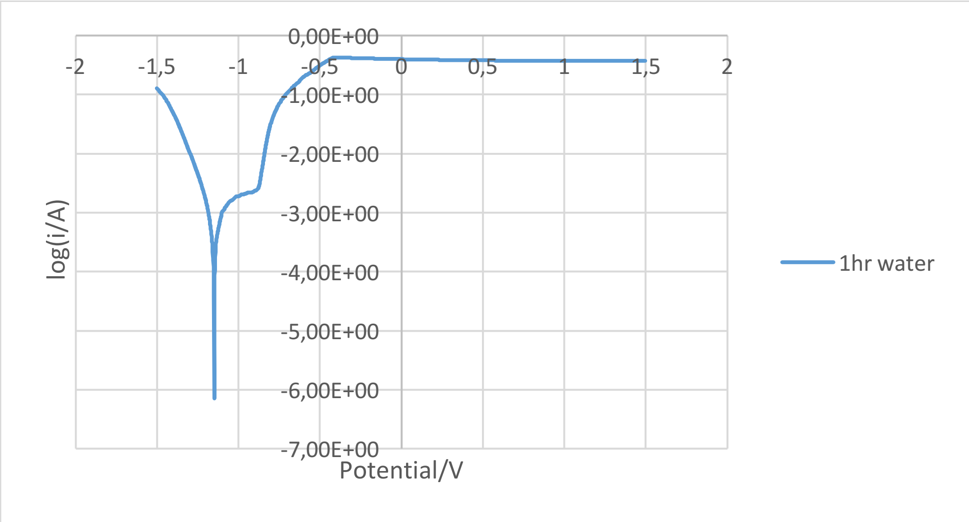

Figure.7. Electropotential plot for 1hr, quenched in water sample

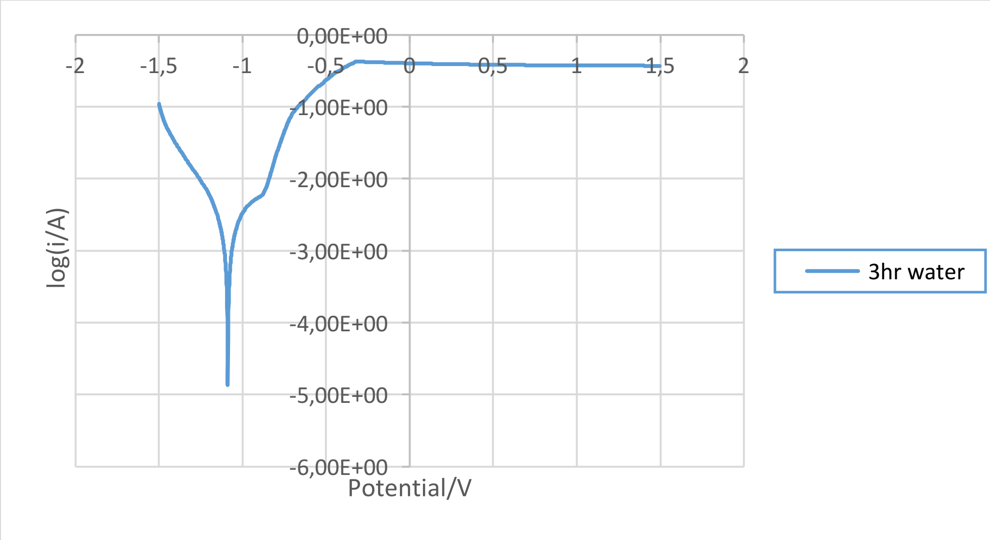

Figure 8. Electropotential plot for 3hrs, quenched in water sample

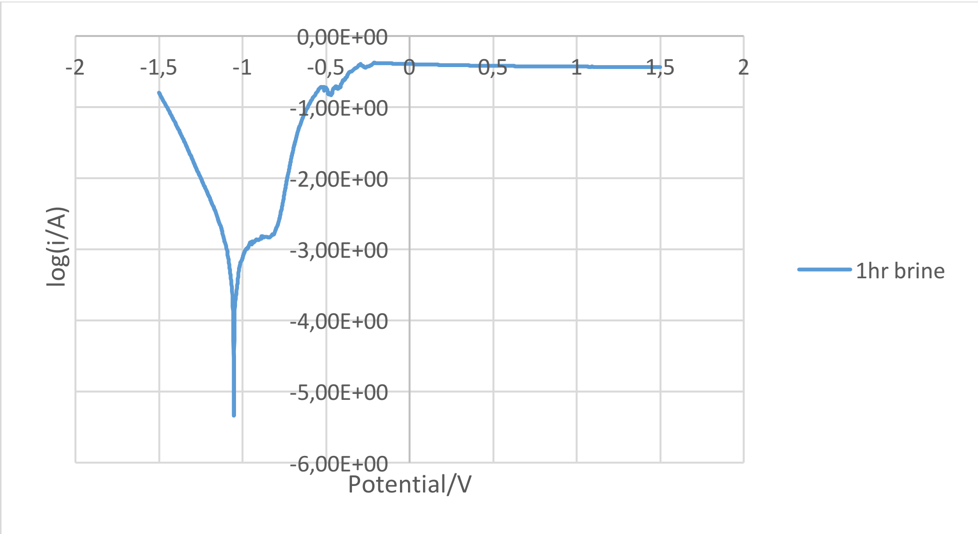

Figure.9. Electropotential plot for 1hr quenched in brine sample

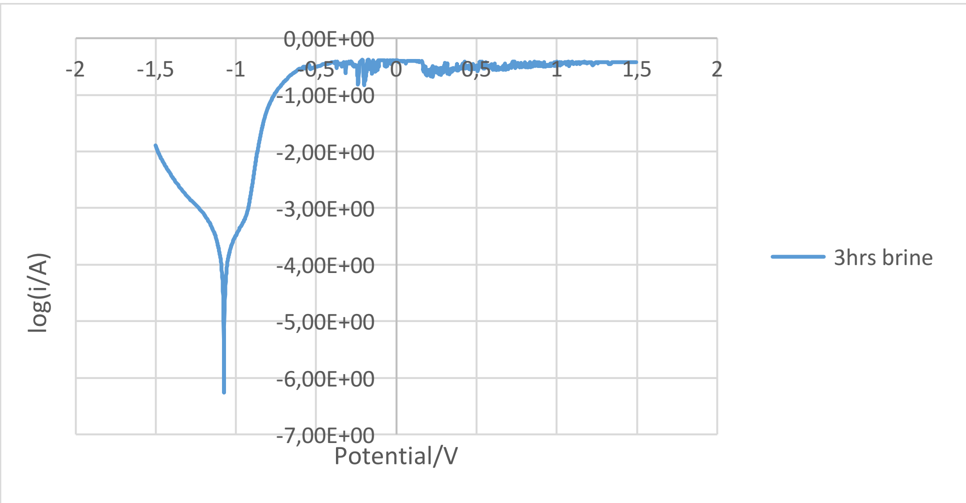

Figure 10. Electropotential plot for 3hrs, quenched in brine sample.

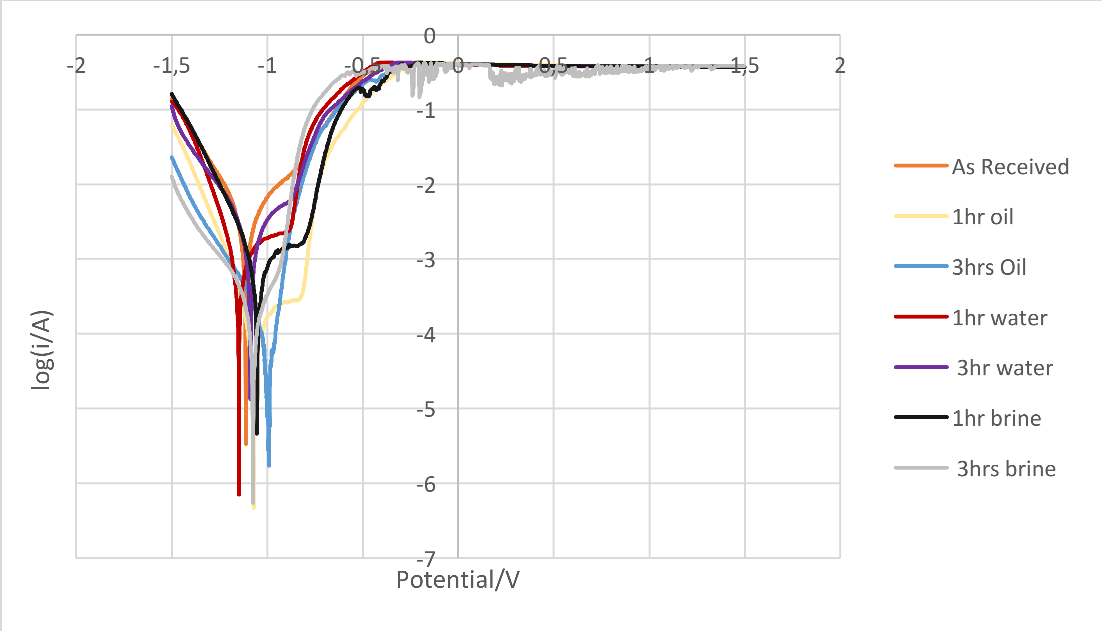

Figure 11. Comparison of the Electropotential plot all the sample.

Corrosion of materials are largely dependent on how corrosive is the environment. A 25 wt% of NaCl in 250ml of water produced a highly concentrated salt solution which was used as the corrosion medium to carry out the study as was observed from the potentiodynamic analysis with the aid of the Tafel plots (**Figure 4** to **11**). **Figure 11** also revealed that the potential values begins to remain steady and nearly constant at some point which is the point at which the current does not affect the material. The As-received material had the highest corrosion rate of $4.331e^{+002}$ (mil/yr) and the lowest corrosion was seen on the sample quenched in water with the value $1.001e\text{-}^{003}$ (Mil/yr) on table 3.2. But after soaking for 3hrs, the sample quenched in water increased in the rate of corrosion to $2.953e^{+002}$ (mil/yr). This shows that the As-received material corroded faster than any other sample and that austenisation temperature and soaking time adversely affected the material quenched in water as it tends to corrode more easily when compared to other samples. This investigation has proved beyond reasonable doubt that quenching samples in water can produce faster corrosion rate over a soaking time of 1hr, since an increase in holding time of 3hrs resulted to an increase in corrosion resistance.

Conclusion

The experiment as was conducted to determine the effect of the divers quenching media on the hardness and the corrosion rate of the medium carbon steel samples will contribute to the knowledge required for the processing and applications of medium carbon steel in the industry.

The results obtained from the experiment revealed a hardness value of 43.7, 37.4, 36.1 and 26.9 HRC for condemned engine oil, water, brine and As-received respectively for 1hr holding time and those of the 3hrs holding time were of hardness value of 40.1, 33.3, and 31.7 HRC respectively. It was therefore observed that the corrosion current for the sample quenched in water after 1hr soaking time had the highest value with $1.523e^{002}$ mil/yr and the lowest value was observed in the sample quenched in water after 3hrs with a value of $1.941e\text{-}^{003}$ mil/yr. The corrosion rate of the as received sample had the highest value with $4.331e+^{002}$ mil/yr and the smallest value observed in water quenched sample at $1.213e+^{001}$ mil/yr.

These observable differences in corrosion rates and hardness could be attributed to the effect of heat treatment and quenchants which is believed to have affected the material's microstructure thereby altering it. The waste oil produced a better hardening effect on the test samples than water and brine. Although increasing in holding time to 3hrs allowed the sample quenched in water to assume a better hardness. The As-received sample having been normalized, had the highest corrosion susceptibly. Therefore, heat treatment and quenching have impacted a reasonable hardness and corrosion resistance to the medium carbon steel.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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