

Effect of Furnace Heating Temperature on the Hardness and Corrosion Resistance of Plain Carbon Steel

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ABSTRACT

Microstructure modification of the plain carbon steel usually enhances hardness and corrosion resistance. Therefore, in the present research, the microstructure of plain carbon steel is modified by heating it in an electric furnace using various temperatures and then quenching it in engine oil to enhance corrosion resistance and hardness. Several characterizations were conducted, such as microstructure, hardness, and electrochemical behaviour. The microstructure evolution indicates a clear transformation of martensite morphology with decreasing austenitizing temperature. Decreasing the furnace's heating before quenching could increase the specimens' hardness and corrosion resistance, with values around 586.36 HV and 0.135 mmpy. Therefore, the optimal heat treatment condition for plain carbon steel components in marine environments was found at 800 °C based on the results of this study.

Keywords

Electric furnace, engine oil, quenching, holding time

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INTRODUCTION

Plain carbon steel is widely used in various industries because it has advantages such as higher tensile strength, ease of forming, and low production costs [1]. However, this material also has limitations, especially in terms of hardness and corrosion resistance, which can limit its use in certain working conditions [2]. In the marine environment, better hardness is needed to enhance the abrasion resistance; besides that, higher corrosion resistance in seawater is also required to reach a minimum cost of maintenance [3]. Therefore, various methods of modifying the structure and mechanical properties have been developed to improve the performance of plain carbon steel according to more specific application needs. Several methods have been implemented in plain carbon steel, such as heat treatment, carburizing, and hard facing [4][5][6].

One of the effective methods to modify the hardness value and corrosion resistance of plain carbon steel is by conducting the heat treatment process, such as quenching [7]. For the quenching process, the cooling medium significantly influences the properties of the sample. Commonly, water and engine oil were used as quenching media [8][9][10]. It should be noted that water and engine oil have different cooling rates, which would result in different hardness [11]. The faster the cooling rate, the higher the hardness value of the specimen, because more martensite is formed [4].

Unfortunately, higher cooling rates could result in a crack on the surface of the sample [12]. Moreover, besides increasing the hardness, heat treatment can also reduce the corrosion rate of steel [13][14][15].

Several researchers conducted heat treatment to increase the hardness and reduce the corrosion rate. Hermawan and Mochtar conducted heat treatment on tool steel with various temperatures (750-950 °C) held for 60 minutes, followed by quenching in oil, and found the highest hardness when the heat treatment was conducted for the sample at 800 °C [16]. Sekunowo et al. performed heat treatment on medium carbon steel using several temperatures between 750-900 °C held for 1 hour, then quenching in oil, and found the highest hardness on the sample when the heat treatment was at 850 °C [17]. Sutrisno et al. treated ST-60 at 800, 850, 900, 950, and 1000 °C in the electric furnace, held for around 30 minutes, and quickly immersed in waste oil, resulting in a continuous hardness increase with temperature increases [18]. Haryadi et al. quenching AISI 1045 in engine oil (SAE 20W-50) by using various heating temperatures (800, 850, and 900 °C) with a 25-minute holding time and found that hardness linearly depends on heating temperature [19]. Sopiyan et al. conducted quenching steel in air and engine oil, and found that engine oil as a quenching medium significantly reduces the corrosion rate from 0.2337 to 0.1870 mm/y [13]. Sholikhin et al. heating AISI 1045 steel until 860 °C (hold 15 minutes), then immediately quench in water, resulting in a reduction in corrosion rate from 0.069 to 0.049 mmpy in seawater [14]. Putratama et al. heating SKD-11 material at 1000 °C, hold for 15 minutes, then immediately immerses in water, resulting in a reduction in corrosion rate from 0.063 to 0.048 mmpy in 3% NaCl solution [15].

Based on what was mentioned above, limited studies have simultaneously investigated the hardness and corrosion resistance of plain carbon steel under different furnace heating conditions using engine oil as a quenching medium. Moreover, according to Hermawan and Mochtar, Sekunowo et al., and Haryadi et al., maximum hardness could be reached when the sample was heated at 800, 850, and 900 °C before quenching [16][17][19]. Therefore, the present study used a temperature range between 800 and 900 °C. Engine oil was selected due to having the slowest cooling rate than water to avoid cracking, while the holding time was chosen to be 25 minutes, adopted from Haryadi et al.'s study [19]. This study aims to find a sample with higher hardness and the lowest corrosion rate in a NaCl medium. Furthermore, several characterizations were conducted after quenching, such as optical microscope examination, hardness test on the top surface, open circuit potential (OCP) measurement, and linear sweep voltammetry (LSV) scans.

METHOD

Plain carbon steel was used in the present research, which has a composition of 0.39 wt.% C, 0.83 wt.% Mn, 0.25 wt.% Si, 0.007 wt.% S, 0.018 wt.% P, 0.19 wt.% Mo, 0.99 wt.% Cr, 0.04 wt.% Cu and the rest is Fe. The quenching media used was engine oil (SAE 10W-40). While corrosion media was used, it was analytical grade NaCl from Merck. Distilled water was prepared to dissolve NaCl. Plain carbon steel was cut with dimensions \varnothing 20× 20 mm. A total of nine specimens were cut for the heat treatment process (Figure 1).



Figure 1. Plain Carbon Steel After Cutting

Heat Treatment

Plain carbon steel was inserted into an electric furnace, and then the temperature was varied (See Figure 2). Temperatures were varied for each specimen (800, 850, and 900 °C). After reaching the temperature, hold for around 25 minutes and then quench in engine oil [19]. The engine oil volume used for quenching media is 500mL (Figure 3). All quenched specimens were prepared for microstructure investigation, hardness test, open circuit potential (OCP) scans, and linear sweep voltammetry investigation. The specimen after quenching is presented in Figure 4.



Figure 2. Set Up an Electric Furnace

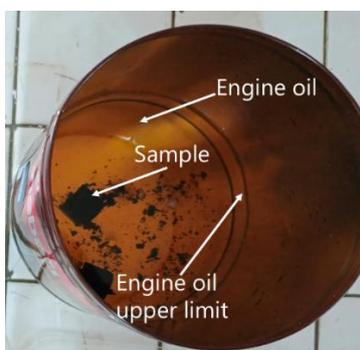


Figure 3. Engine Oil as Quenching Medium



Figure 4. Plain Carbon Steel After Quenching

Characterization

Specimens were polished and etched following standard metallographic techniques, then observed using Olympus BX51M optical microscopy. The specimens were investigated at 100x magnification. For hardness measurement, the surface of the sample was also polished up to #5000. Five repeatable measurements were performed on the polished surface using an FV 300e Vickers hardness tester (5kg of load).

Ossila potentiostat was used for OCP and LSV investigation. The investigations were conducted in 3.5% NaCl at room temperature. The sample's surface was polished up to #5000 for OCP and LSV investigation. Plain carbon steel as working electrode (3,14 cm² of exposure area), platinum as counter electrode, and Ag/AgCl as reference electrode. The OCP investigation was conducted for 600 seconds. After reaching 600 seconds of OCP measurement, LVS was performed. To analyze the LSV data, Tafel extrapolation was used. While the corrosion rate calculation is similar to the previous study [20].

RESULT AND DISCUSSION

Optical Microscope Observation

The optical micrographs of plain carbon steel after austenitizing at 800, 850, and 900 °C followed by quenching in engine oil, are presented in Figure 5. The microstructure evolution indicates a clear transformation of martensite morphology with increasing austenitizing temperature. Bakhshi and Mirak have found that microstructure evolution tends to be a straight line martensitic form, as the heating temperature increases (850 -1200 °C) prior to quenching [21].



Figure 5. Optical Microscope Observation Results of Various Heating Temperatures (a) 800°C, (b) 850°C, and (c) 900°C.

At 800 °C (Figure 5a), the microstructure reveals coarsely distributed needle-like martensite laths. This morphology suggests rapid martensitic transformation due to high undercooling, resulting in non-uniform, high-dislocation martensite. The coarse nature of the laths can be attributed to insufficient homogenization of austenite prior to quenching [22].

At 850 °C (Figure 5b), the martensitic structure appears more refined and closely packed. This refinement indicates enhanced diffusion of carbon and alloying elements during the austenitizing process. Those processes result in more uniform austenite and a smoother martensitic transformation. Such a refined martensitic microstructure is often associated with improved mechanical properties. Enhanced mechanical properties, including a favorable balance between hardness and toughness, due to the Hall–Petch strengthening effect [22][23].

At 900 °C (Figure 5c), the martensitic laths become even finer and more homogenous. However, the increased thermal energy promotes excessive grain growth, which can reduce the nucleation sites for martensite. Thus decreasing the martensite start (M_s) temperature and potentially increasing the fraction of retained austenite [24][25]. It has been demonstrated that higher austenitizing temperatures significantly promote grain coarsening,

leading to reduced hardness and less effective transformation to martensite [22]. In addition, larger austenite grain sizes tend to stabilize retained austenite, which may influence the mechanical strength of the steel [22][24][26].

Hardness Test Result

Figure 6 shows average hardness test results using the FV-300e Vickers hardness tester. The highest average hardness test result is found in 800 °C sample, while lower hardness test results are found in the 900 °C sample. Zhou et al. have found an increase in austenitizing temperature prior to quenching, leading to a decrease in the hardness [16]. It seems that a coarse martensite shape led to the resulting highest hardness. Higher hardness is closely related to the formation of a more dominant martensite structure in samples with lower austenitizing temperatures. This martensite phase has a significant effect on increasing the hardness value of the material [27]. Conversely, lower hardness values occur due to the growth of austenite grain size at higher austenitizing temperatures, which can reduce the level of martensite transformation and produce lower hardness values [28].

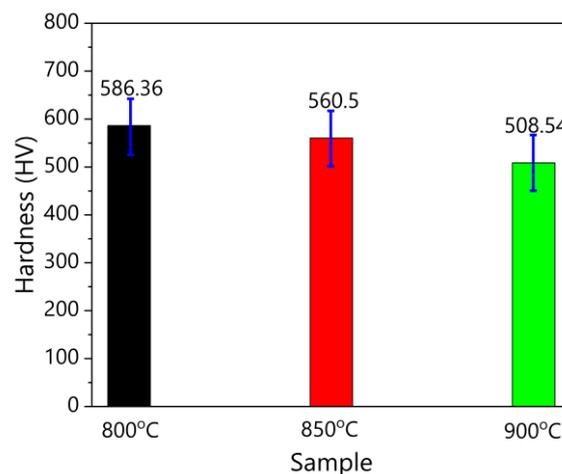


Figure 6. Average hardness test results

When compared with Figure 6 from another study, it can be seen that higher hardness values are also achieved when most of the structure consists of martensite formed at a lower austenitizing temperature [29]. This condition is in line with the findings of Basori et al., which also revealed that a finer martensite structure can increase the hardness value of the material [30]. In addition, the results of this study show differences when compared with the study by Haryadi et al., which showed that the highest hardness values were found in samples that underwent a heat treatment process at a temperature of 900 °C and then quenched in oil (SAE 20W-50) [19]. This difference is likely due to the microstructure formed in that study being different from the microstructure formed in this study. In the Haryadi et al. study, increasing the temperature of the heat treatment before quenching leads to an increase in the martensite formation; therefore, the hardness increased [19]. Similar to Haryadi et al.'s study, Sutrisno et al also found that increasing the heat treatment temperature before quenching in the engine oil leads to an increase in hardness due to C composition in the specimen, which was enhanced [18].

Open Circuit Potential (OCP) Result

Figure 7 shows the OCP investigation results. OCP investigation was conducted for 600 seconds in 3.5% NaCl at room temperature. OCP values of the 800, 850, and 900 °C samples at the end of measurement are -0.59, -0.59, and -0.64 V vs Ag/AgCl, respectively. At 900 °C, the

sample's initial measurement moved significantly in a negative direction. Indicating oxide on the top surface of the sample was easily released into the solution [31]. While the 850°C sample moves to a negative direction, it stabilizes until 600 seconds of measurement. Moreover, the 800 °C sample tends to be steady from the initial measurement to 600 seconds. Ahmadi et al. have found that the OCP curve decreases along the immersion time, indicating that the passive film on the top surface of the sample is not formed [32]. Commonly, FeO and Fe₃O₄ form on the surface of steel. Both oxide has low stability; therefore, they dissolve into the solution during the OCP measurement [20].

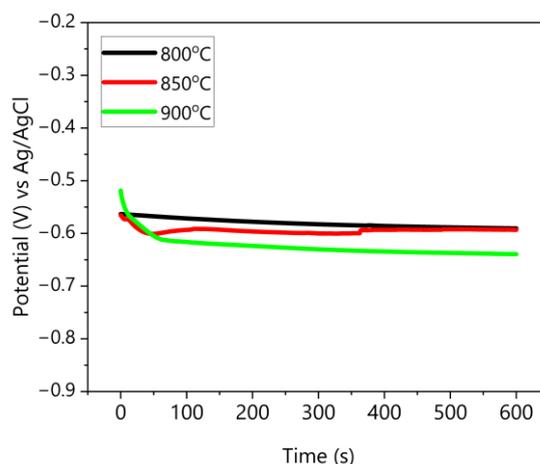


Figure 7. OCP Test Results

Generally, the 800 °C sample has a more positive potential value than the 850 and 900 °C samples, which means that it is relatively more resistant to initial corrosion. Conversely, the 900 °C sample has a more negative potential value, indicating that its condition is more active and potentially more easily corroded than the other samples. This would lead to more discussion in another section.

Linear Sweep Voltammetry (LSV) Result

Figure 8 shows the LSV investigation results in 3.5% NaCl at room temperature. Material testing in the 3.5 % NaCl is simulated closely to a seawater environment [33]. By using the Tafel extrapolation method, corrosion current and potential were found and summarized in Table 1. While the corrosion rate calculation is similar to the previous study [20]. The corrosion current of various samples is closely related to the corrosion rate. According to Hussien et al.'s study, corrosion current is linearly proportional to corrosion rate [34].

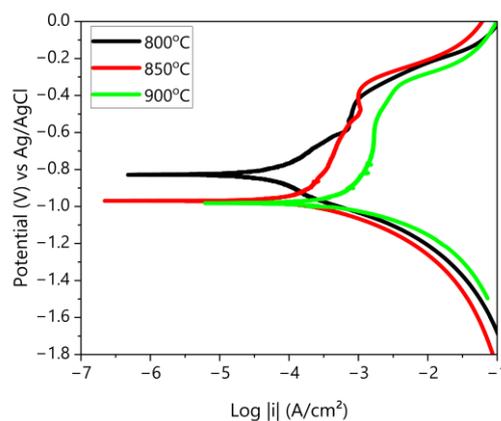


Figure 8. LSV Test Results

Based on Table 1, it can be seen that the sample with an austenitizing temperature of 800 °C shows the lowest corrosion current value compared to other samples, indicating better corrosion resistance. On the contrary, the sample with a temperature of 900 °C shows a higher corrosion current value, indicating a higher corrosion rate. This phenomenon is in accordance with changes in the material structure due to variations in the austenitizing temperature, where the formation of certain phases can affect the level of material resistance to corrosion [35][36].

Moreover, based on Table 1, it can also be observed that samples with higher heating temperatures tend to be more easily corroded. The 800 °C sample has the lowest corrosion rate value, which is 0.135 mmpy, while the 900 °C sample experiences the most significant corrosion rate with a value of 0.960 mmpy. Sopiyan et al. have found the corrosion rate of carbon steel in 3.5% NaCl around 0.3739 mmpy [13]. That value is higher than the present study due to having 0.128 wt.% of C. It should be noted that the C content value leads to the formation of the martensite phase [37].

Table 1. Corrosion parameters

Sample Name	Ecorr (V vs Ag/AgCl)	icorr (A/cm²)	Corrosion rate (mmpy)
800°C	-0.824	3.62×10^{-5}	0.135
850°C	-0.968	8.16×10^{-5}	0.303
900°C	-0.981	2.58×10^{-4}	0.960

The amount of martensite greatly influences the corrosion rate of the material in its microstructure [13]. Compared to the microstructure investigation, it is clearly seen that a higher level of corrosion rate is present in the sample with lower martensite. Therefore, the higher the martensite content, the corrosion rate tends to decrease. Parmita et al. have found that the martensite phase has more beneficial resistance to corrosion [38].

Moreover, compared to the OCP measurement, it can be seen that the 900 °C sample is experiencing a significant decrease in potential until it stabilizes at 600 seconds of measurement. Indicating that the oxide has poor protection and dissolves into the solution, making the samples easy to corrode [31]. Therefore, it has the highest corrosion rate among other samples.

CONCLUSION AND FUTURE WORK

The lowest temperature of the electric furnace before quenching results in a microstructure that reveals coarsely distributed needle-like martensite laths, whereas the higher temperature of the furnace results in smoother martensite. Coarsely distributed needle-like martensite laths microstructure would result in the highest hardness and corrosion resistance, while a smoother martensite would decrease the hardness and corrosion resistance. These findings indicate that controlling the austenitizing temperature plays an important role in optimizing plain carbon steel for engineering components that require a combination of strength and corrosion resistance. Moreover, when viewed from the hardness value and corrosion resistance level, the sample with an austenitizing temperature of 800°C can be said to be more ideal for application as a component material that requires high mechanical strength as well as good corrosion resistance. Recommendation for future work is to investigate different holding times and quench media viscosity.

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