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Effect of NaCl Concentration in Quenching Medium on Microstructure, Hardness, and Corrosion Behavior of AISI 4140 Steel

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Abstract: AISI 4140 steel is widely used in engineering and marine components due to its high strength and good hardenability. However, improving hardness through heat treatment may influence the corrosion behavior of the material in chloride containing environments. This study investigates the effect of NaCl concentration as a quenching medium on the microstructure, hardness, and corrosion behavior of AISI 4140 steel. The samples were austenitized at 1000 °C for 15 minutes and quenched in NaCl solutions with concentrations of 3.5%, 7%, and 10.5%. Microstructural observations were carried out using optical microscopy after etching with 3% Nital. Hardness testing was performed using the Vickers method with a 10 kg load, while corrosion behavior was evaluated using weight loss measurements and electrochemical tests in 3.5% NaCl solution. The results show that increasing NaCl concentration produces a finer martensitic structure and increases hardness from 673 VHN at 3.5% NaCl to 762 VHN at 10.5% NaCl. However, the corrosion rate also increases from 0.3688 mmpy to 0.3990 mmpy, indicating higher electrochemical activity at the material surface. These results demonstrate a trade-off between improved hardness and reduced corrosion resistance with increasing NaCl concentration.

Keywords: AISI-4140; hardness; corrosion; martensite; quenching

SDGs Problem Solving

The effect of different NaCl concentrations during quenching on the microstructure, hardness and corrosion resistance of AISI 4140 steel was studied. Results contribute to SDGs Chapter #9 by providing input into better heat treatment practices, assisting the development of more durable materials and fostering sustainable industrial innovation for long-lasting engineering solutions.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

Steel is one of the metals with good mechanical strength and utilized in marine vessel components. One type of steel used as a marine vessel component is AISI 4140 steel. Marine vessel components are required to exhibit good abrasion resistance to seawater, high hardness is required to achieve high abrasion resistance (Setiawan, Budiarto and Samuel, 2023). In that condition, marine vessel components are required to high corrosion resistance due to operation in environments with high salt concentrations (Zagkliveris, Mavropoulos and Triantafyllidis, 2023). Some steels, such as AISI 4140, have limited hardness and corrosion resistance. Therefore, efforts are required to improve the hardness and corrosion resistance (Keawhan *et al.*, 2012).

In marine environments, steel components are continuously exposed to aggressive service conditions involving chloride ions, high humidity, and fluctuating temperatures, all of which can simultaneously accelerate mechanical degradation and corrosion processes (Parangusan, Bhadra and Al-Thani, 2021). The presence of chloride ions (Cl^-) in seawater is particularly detrimental, as it promotes localized corrosion mechanisms such as pitting and crevice corrosion, which are often difficult to detect and can lead to sudden and premature material failure (Vargas *et al.*, 2010). These forms of localized attack significantly reduce the structural integrity and service life of marine components, especially when combined with cyclic mechanical loading and abrasive conditions (Shuai *et al.*, 2024). Consequently, marine structural materials are required not only to possess high mechanical strength and hardness to resist wear, but also to exhibit superior corrosion resistance to withstand prolonged exposure to saline environments. Achieving an optimal balance between these properties remains a critical challenge in materials engineering, particularly for medium-carbon low-alloy steels such as AISI 4140.

From a metallurgical perspective, the performance of AISI 4140 steel is strongly governed by its microstructural characteristics, which can be tailored through controlled thermal processing (Behrens *et al.*, 2020; Badaruddin *et al.*, 2024). Heat treatment followed by quenching is widely employed to enhance hardness and wear resistance by promoting the transformation of austenite into martensite, a supersaturated and hard phase (Sun *et al.*, 2022). However, the effectiveness of martensitic transformation is highly dependen on the cooling rate, which is influenced by the thermal properties of the quenching medium. Insufficient cooling rates may lead to incomplete transformation, resulting in the formation of softer phases such as ferrite or pearlite, thereby reducing hardness and wear resistance. On the other hand, excessively rapid cooling can generate high thermal gradients, leading to residual stresses, distortion, or even cracking (Mao *et al.*, 2023). Therefore, careful control of cooling conditions is essential to achieve a refined and homogeneous martensitic structure while minimizing undesirable defects.

Recent studies have emphasized that, the composition of the quenching medium plays a crucial role in determining heat transfer behavior during the quenching process (Narayan and Fritsching, 2024). In particular, the presence of dissolved salts such as sodium chloride (NaCl) can significantly modify the thermal conductivity, viscosity, and boiling characteristics of the medium. Increasing NaCl concentration has been reported to enhance cooling efficiency, leading to the formation of finer and more uniform martensitic structures, which contribute to improved hardness. However, higher salt concentrations may also introduce additional complexities, such as increased corrosivity of the medium and potential surface degradation during processing. Despite these findings, a comprehensive understanding of the combined effects of NaCl concentration on microstructure, hardness, and corrosion behavior in AISI 4140 steel remains limited, particularly under conditions that closely simulate real seawater environments (Puga-Patlán *et al.*, 2023). This gap highlights the need for systematic investigation to establish clear correlations between quenching medium composition and resulting material performance.

One method that can be used to improve the quality of steel is heat treatment (Sopiyan, Syamsuir and Nofendri, 2019; Sopiyan, Basori and Susetyo, 2020; Sopiyan *et al.*, 2025). The quenching process after heat treatment results in a significant increase in hardness value (Harmaji *et al.*, 2023). Various liquids, such as engine oil and vegetable oil are used as quenching medium to produce the desired microstructure. Quenching after heat treatment using water, oil and air as quenching medium can increase hardness value (Putri, Gunawan and Rizky, 2023). In particular, variations in cooling media affect hardness and phase transformation after heat treatment, indicating the importance of the quenching medium in obtaining desired property outcomes (Çoban, 2025). One method that can be used to improve the hardness and corrosion resistance of AISI 4140 steel is heat treatment followed by a quenching process.

AISI 4140 steel was heated to a temperature of 885 °C, held for 60 minutes, and then quenched in seawater at various temperatures (220–250 °C). AISI 4140 demonstrates high hardenability and responds significantly to heat treatment and quenching process (Mudda *et al.*, 2025). The results showed that quenching at 220 °C produced the highest hardness value, reaching 580 HV (Wijanarko *et al.*, 2016). Besides temperature, the NaCl concentration can also affect the hardness of the sample (Wijaya and Rasyid, 2023). The higher the NaCl concentration, the fine martensitic structure formed (Nishimoto *et al.*, 2023), and it can also increase hardness values. Some studies investigate the effect of various seawater concentrations on hardness, that the higher salt concentrations result in increased hardness values (Juliantika and Syofii, 2023; Simanjuntak, Budiarto and Mulyatno, 2024). Despite numerous studies investigating quenching media for medium carbon steels, most previous works primarily focused on hardness improvement and microstructural evolution without comprehensively correlating the resulting martensitic transformation with corrosion behavior under simulated marine environments. In addition, studies specifically examining the influence of NaCl concentration on the combined microstructure, hardness, weight loss behavior, and electrochemical corrosion characteristics of AISI 4140 steel remain limited. Therefore, this study aims to establish a comprehensive relationship between NaCl concentration, cooling severity, martensitic refinement, and corrosion susceptibility. The novelty of this research lies in the combined evaluation of mechanical and electrochemical behavior of AISI 4140 steel quenched in various NaCl concentrations to support the development of optimized heat treatment processes for marine engineering applications.

This study investigates the effect of NaCl concentration on the microstructure, hardness, and corrosion behavior of AISI 4140 steel. The material was heated to 1000 °C for 15 minutes and quenched in NaCl solutions with concentrations of 3.5%, 7%, and 10.5%. The heat treatment parameters were selected based on the phase transformation characteristics of AISI 4140 steel. The austenitizing temperature of 1000 °C and holding time of 15 minutes were applied to ensure complete dissolution of carbides and formation of a homogeneous austenitic phase prior to quenching. Meanwhile, NaCl concentrations of 3.5%, 7%, and 10.5% were used to produce different cooling severities, since increasing salt concentration enhances the heat transfer efficiency and cooling rate of the quenching medium. This accelerated cooling promotes more effective martensitic transformation, resulting in finer microstructures and changes in hardness and corrosion behavior (Gao et al., 2024). Microstructural analysis, Vickers hardness testing, and corrosion evaluation were conducted using optical microscopy, weight loss, and electrochemical methods.

2. METHODOLOGY

2.1. Material Preparation

The material used in this study was AISI 4140 steel, a medium-carbon low-alloy steel known for its good strength, toughness, and hardenability, with its chemical composition as presented in Table 1.

Table 1. Chemical composition of AISI 4140

C (wt.%)	Mn (wt.%)	Si (wt.%)	S (wt.%)	P (wt.%)	Mo (wt.%)	Cr (wt.%)	Cu (wt.%)	Fe (wt.%)
0.39	0.83	0.25	0.007	0.018	0.19	0.99	0.04	rest

Prior to heat treatment, the material was machined into samples with dimensions of 1 cm × 1 cm to ensure uniformity during testing. The machining process was conducted carefully to obtain consistent geometry and surface condition. The samples were subsequently cleaned to remove contaminants such as oil and debris that could influence heat transfer during quenching.

The solution preparation process was carried out by accurately weighing NaCl, followed by its dissolution in distilled water under continuous stirring to obtain a homogeneous solution. Each solution was prepared separately and used immediately to ensure consistency in experimental conditions. The NaCl concentrations of 3.5%, 7%, and 10.5% were selected to investigate their influence on the cooling characteristics of the quenching medium, particularly in terms of heat transfer behavior. Variations in salt concentration are known to affect thermal conductivity, viscosity, and boiling characteristics, which ultimately influence the cooling rate, as well as the resulting microstructural evolution and mechanical properties of the material.

2.2. Heat Treatment

The heat treatment process was carried out using a custom-built electric furnace to ensure controlled heating conditions. Prior to the heat treatment, all samples were inspected to confirm uniform dimensions and clean surface conditions. The furnace was preheated to the target temperature to minimize temperature fluctuations during the heating stage. In addition, the quenching media were prepared in advance in 500 ml containers for each NaCl concentration to ensure immediate immersion after heating.

The samples were heated to a temperature of 1000 °C and held at this temperature for 15 minutes to allow sufficient time for austenitization. This holding period ensured a homogeneous austenitic phase throughout the material. Temperature control during the heating process was carefully maintained to avoid overheating or uneven thermal distribution, which could affect phase transformation behavior. After the soaking period, the samples were rapidly removed from the furnace and immediately quenched into saline solutions with different NaCl concentrations (3.5%, 7%, and 10.5%). The quenching process was conducted for 15 minutes to ensure complete cooling to ambient temperature. Immediate transfer from furnace to quenching medium was critical to prevent premature cooling in air, which could alter the intended cooling rate and microstructural transformation. The overall heat treatment and quenching processes is illustrated in Figure 1.

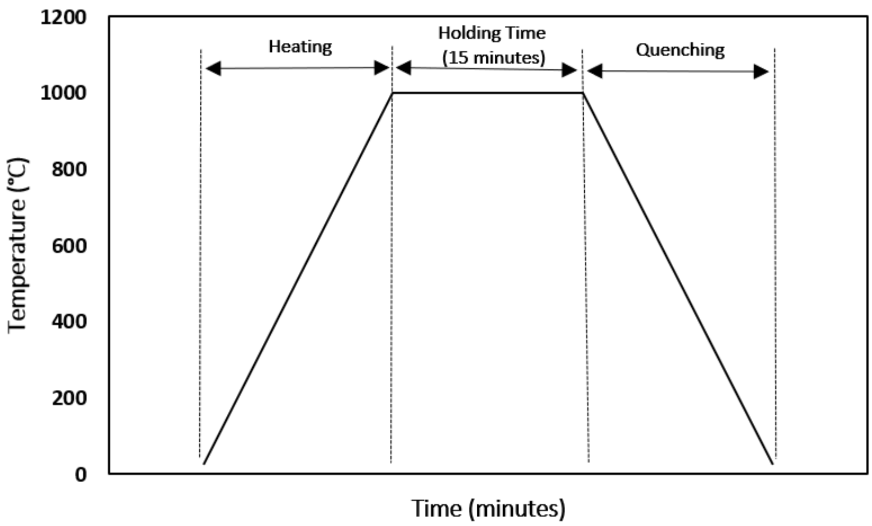


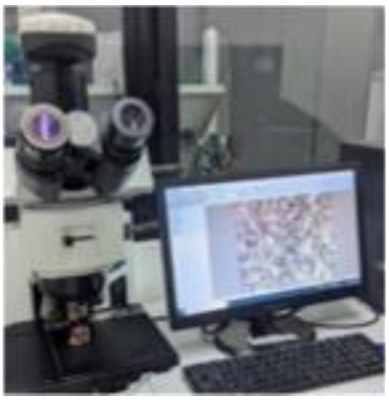
Figure 1. Schematic flowchart of the heat treatment process

The use of different NaCl concentrations in the quenching media was intended to evaluate the influence of solution composition on heat extraction efficiency during cooling. Variations in salt concentration affect boiling behavior and heat transfer characteristics, which in turn influence the cooling rate and the formation of martensitic structures.

2.3. Microstructure

All samples were prepared using standard metallographic procedures prior to microstructural analysis. Initially, the samples were mounted in epoxy resin to facilitate handling and to ensure edge retention during subsequent preparation steps. Mounting also provided a stable support, allowing uniform pressure distribution during grinding and polishing.

(a). The mounted samples



(b). Optical microscope

Figure 2. Microstructural observation

The mounted samples were then subjected to a sequential grinding process using silicon carbide sandpapers of increasing grit sizes, up to #5000, to obtain a smooth and scratch free surface. Each grinding stage was performed carefully to remove deformation layers introduced during machining and to minimize surface irregularities. Following grinding, the samples were polished to achieve a mirror-like finish, which is essential for accurate microstructural observation as illustrated in Figure 2(a).

After polishing, the samples were etched using a 3% Nital solution to reveal the microstructural features. The etching process was carried out for a controlled duration to ensure proper contrast between different phases without over-etching. Subsequently, the samples were rinsed thoroughly with distilled water, followed by drying to prevent oxidation or staining on the surface.

Microstructural observations were conducted using an optical microscope (Olympus BX51M) to examine phase distribution, grain morphology, and structural characteristics. Different magnifications were employed to obtain a comprehensive view of the microstructure. The observations focused on identifying key phases such as martensite, as well as any presence of ferrite or pearlite, depending on the cooling conditions. The prepared samples and the optical microscopy setup are illustrated in Figure 2(b).

The metallographic preparation and observation procedures were carefully controlled to ensure reproducibility and accuracy of the results, enabling a reliable evaluation of the influence of quenching conditions on the microstructural evolution of AISI 4140 steel.

2.4. Hardness Testing

The hardness of the samples was evaluated using a Vickers hardness tester (Future-Tech FV-300e), as illustrated in Figure 3(a). Prior to testing, the sample surfaces were carefully prepared to ensure flatness and smoothness, minimizing potential measurement errors caused by surface irregularities. Proper alignment of the sample on the testing stage was also ensured to obtain accurate and consistent indentation results.

(a). Hardness testing machine (b). Indentation points illustration

Figure 3. Hardness testing process

The Vickers hardness test was conducted by applying a load of 10 kgf through a diamond pyramid indenter with a square-based geometry. This load was selected to produce clear and measurable indentations without causing excessive deformation. For each sample, multiple indentations were performed to improve the reliability of the data. Specifically, five indentation points were made on different areas of the sample surface, as illustrated in Figure 3(b), to account for possible microstructural heterogeneity.

The diagonals of each indentation were measured using the built-in optical system of the hardness tester, and the corresponding Vickers hardness values (VHN) were calculated automatically by the instrument. Five Vickers indentations were performed for each sample condition (n = 5). The reported hardness values represent the mean value, while the error bars indicate the standard deviation. The relatively small standard deviation confirms the good repeatability and reliability of the hardness measurements.

The spacing between indentation points was maintained sufficiently large to avoid interaction effects between adjacent indentations, which could otherwise affect the accuracy of the measurements. All tests were conducted under consistent environmental and operational conditions to ensure repeatability. This testing procedure enables a reliable assessment of the hardness variation resulting from different quenching conditions and provides a quantitative basis for correlating microstructural changes with mechanical properties.

2.5. Corrosion testing

Corrosion testing was performed using a weight loss method in a 3.5% NaCl solution to simulate a marine environment. The samples were immersed for a total duration of 672 hours, with weight measurements taken at regular intervals of 168 hours. Prior to immersion, each sample was cleaned, dried, and weighed using a digital balance to obtain its initial mass. After each immersion interval, the samples were removed, rinsed to eliminate corrosion products, dried, and reweighed to determine the mass loss as illustrated in Figure 4. The corrosion rate was calculated based on the weight loss using the standard equation (Zeino *et al.*, 2018):

$$CR\left(\frac{mm}{year}\right) = 87.6\ \times W/(D\ \times A\ \times t) \tag{1}$$

where CR is the corrosion rate (mm/year), W represents the mass loss (g), D is the material density (g/cm^3), A is the exposed surface area (cm^2), and t is the exposure time (hours). This method provides a quantitative evaluation of material degradation over time due to corrosive exposure.

In addition to the weight loss method, electrochemical measurements were conducted using an Ossila potentiostat to further analyze the corrosion behavior. The tests included open circuit potential (OCP) monitoring and linear sweep voltammetry (LSV). A conventional three-electrode system was employed, consisting of an Ag/AgCl reference electrode, a platinum wire as the counter electrode, and the sample as the working electrode.

The LSV measurements were carried out at a scan rate of 5 mV/s within a potential range of −1.5 V to −0.4 V versus Ag/AgCl in a 3.5% NaCl solution. it was selected to obtain clear polarization responses within a shorter exposure time and to reduce surface changes during testing in chloride solution. Since the same scan rate was applied to all samples, the results remain valid for comparative analysis of corrosion behavior among the different quenching conditions. The corrosion current density was determined using the Tafel extrapolation method, which enables evaluation of corrosion kinetics. All experiments were conducted under controlled conditions to ensure reproducibility and accuracy of the corrosion data.

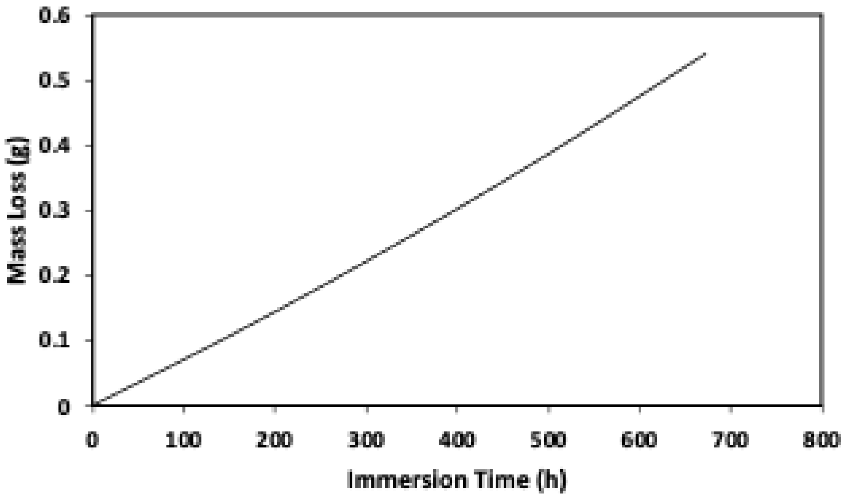


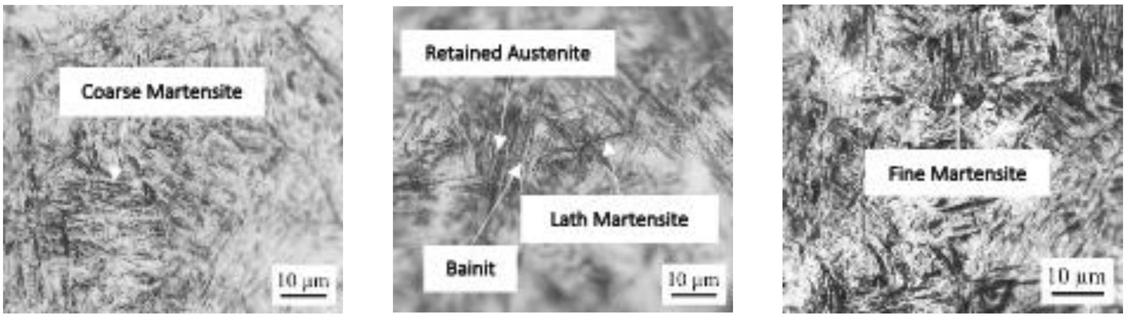
Figure 4. Schematic illustration of the relationship between immersion time and mass loss

3. RESULTS AND DISCUSSION

3.1. Velocity Distribution

Microstructural observations were performed using an Olympus BX51M optical microscope to evaluate the phase transformation behavior of the samples subjected to different quenching conditions. The analysis focused on identifying the morphology, distribution, and relative proportions of the phases formed as a function of NaCl concentration in the quenching medium. As shown in Figure 5(a), the sample quenched in 3.5% NaCl exhibits a non-uniform martensitic structure. The microstructure appears relatively coarse, and the grain boundaries are not clearly defined. This condition is attributed to the relatively low cooling rate associated with the lower NaCl concentration. Insufficient cooling severity limits the transformation of austenite into martensite, allowing the coexistence of other phases or incomplete transformation zones. As a result, the overall microstructure lacks uniformity and refinement, which may negatively influence the mechanical properties (Liu *et al.*, 2021).

The microstructure of the sample quenched in 7% NaCl, as presented in Figure 5(b), shows noticeable differences. The martensitic structure appears more developed, with larger and more distinguishable lath formations compared to the 3.5% NaCl sample. This indicates that the increased NaCl concentration enhances the cooling rate, thereby promoting a more effective transformation of austenite into martensite (Morawiec *et al.*, 2023). However, the presence of a small amount of bainite is also observed in this sample. The formation of bainite suggests that the cooling rate, although higher than that of the 3.5% NaCl condition, is still not sufficiently rapid to fully suppress diffusion-controlled transformations.



(a). Coarse martensite at 3.5% NaCl

(b). Bainite, retained austenite, and lath martensite at 7% NaCl

(c). Fine martensite at 10.5% NaCl

Figure 5. Microstructure of AISI 4140 steel quenched in different NaCl concentrations

The coexistence of bainite and martensite in the 7% NaCl sample indicates the presence of residual austenite during the transformation process. This phenomenon suggests that the cooling rate falls within an intermediate range, where both diffusion less and diffusion-controlled transformations can occur. Similar observations have been reported, who noted that partial bainitic transformation may occur when the cooling rate is not high enough to produce a fully martensitic structure (Babasafari *et al.*, 2020). These findings demonstrate that NaCl concentration plays a critical role in controlling the cooling rate and, consequently, the resulting microstructure. Higher concentrations lead to more refined and uniform martensitic structures, while lower concentrations result in heterogeneous microstructures with mixed phases.

As shown in Figure 5(c), a fine martensitic structure with relatively uniform morphology is clearly observed. This microstructural feature indicates that rapid cooling has effectively facilitated the transformation of austenite into martensite. The formation of martensite is strongly associated with high cooling rates, which suppress atomic diffusion and promote a diffusion less phase transformation. As a result, the microstructure becomes dominated by needle-like or lath martensite.

The use of higher NaCl concentrations in the quenching medium enhances the cooling capability of the solution. Increased salt content modifies the thermal properties of the medium, leading to improved heat extraction during quenching. This accelerated cooling promotes a more complete transformation of austenite into martensite, resulting in a finer and more homogeneous microstructure. Such conditions are consistent with previous findings, where enhanced cooling rates were shown to improve martensitic formation and refine the resulting microstructure (Purboputro, 2017; Sopiyan, Basori and Susetyo, 2020).

In contrast, samples quenched in lower NaCl concentrations exhibit relatively slower cooling rates. Under these conditions, the transformation of austenite is not fully completed, allowing the formation of softer phases such as ferrite and pearlite. These phases are typically associated with lower hardness values due to their more stable and equilibrium nature. The presence of mixed microstructures in lower concentration media indicates insufficient cooling severity to achieve full martensitic transformation. Similar observations were reported by Firdaus *et al.*, who observed that reduced cooling intensity promoted the coexistence of martensite with softer phases (Ms, Wiranata and Prasetyo, 2022).

Variations in NaCl concentration play a significant role in controlling the cooling rate and can influence the phase transformation behavior of the material. The results of this study are consistent with previous research, which has shown that variations in NaCl concentration during the quenching process significantly affect the resulting microstructure (Prabowo and Sunyoto, 2020). Therefore, increasing NaCl concentration can be considered an effective approach to enhance martensitic formation, thereby contributing to improved mechanical properties.

3.2. Hardness

The hardness test with five indentation points was conducted by Vickers method and the average hardness values of various concentrations as presented in Figure 6. The average hardness values increase from 673 VHN in 3.5% NaCl to 720 VHN in 7% NaCl, and the highest value of 762 VHN in 10.5% NaCl. The increase in hardness can be attributed to the greater formation of martensitic structures as the cooling rate increases. At 3.5% NaCl concentration can result in the presence of softer phases such as ferrite or pearlite along with martensite, leading to relatively lower hardness values. When the NaCl concentration increases to 7%, the hardness value rises to 720 VHN. This improvement indicates that the cooling intensity becomes higher, promoting a more significant transformation of austenite into martensite (Supriadi, Suka and Marjunus, 2025).

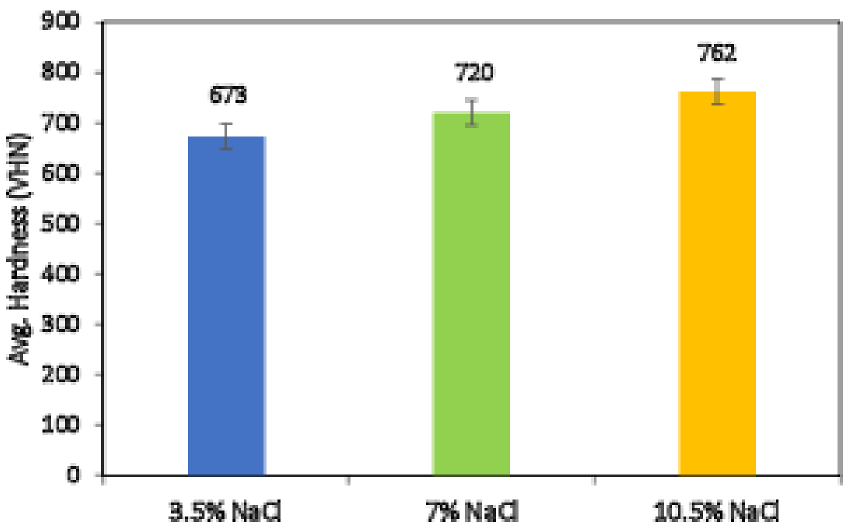


Figure 6. Avg. hardness of concentration NaCl

The highest hardness value is 762 VHN is obtained for the sample quenched in 10.5% NaCl. This result is consistent with the microstructural observation, where a finer and more densely distributed martensitic structure is formed. The higher NaCl concentration improves the heat extraction capability of the quenching medium, thereby accelerating the cooling rate and suppressing carbon diffusion, it can be a more complete martensitic transformation occurs, leading to a significant increase in hardness (Luo *et al.*, 2025).

The error bars presented on each bar of the graph represent the variability of the experimental data, which is typically expressed in terms of standard deviation or standard error (Mangiafico, Sauzéat and Di Benedetto, 2019).

The relatively small magnitude of the error bars across all concentration variations indicates that the experimental results exhibit a high level of consistency and repeatability (P. *et al.*, 2026). This suggests that the quenching process produces a stable material response with respect to changes in the concentration of the cooling medium (Narayan and Fritsching, 2024). Since hardness measurements inherently exhibit statistical dispersion, proper evaluation using variance and confidence intervals is required to distinguish systematic effects from random fluctuations (Schneider, Bigerelle and Iost, 1999). Therefore, the observed increase in hardness is unlikely to arise solely from experimental variability but instead reflects a systematic influence of NaCl concentration on the cooling characteristics of the quenching medium. This is consistent with previous studies indicating that hardness in quenched steels is strongly governed by cooling rate and heat transfer efficiency, where more effective cooling leads to higher hardness values (Armas *et al.*, 2026).

3.3. Weight Loss Measurement

Corrosion testing was conducted using the weight loss method to determine the corrosion rate based on the reduction in sample mass after the quenching treatment. The samples were performed in a 3.5% NaCl solution for 672 h and weighed periodically. The corrosion rate increased with increasing NaCl concentration. Table 2 shows the calculated corrosion rate.

Table 2. The corrosion rate of various samples

Samples	Corrosion Rate (mmpy)
NaCl 3.5%	0.3688
NaCl 7%	0.3964
NaCl 10.5%%	0.3990

The increase in corrosion rate observed at higher NaCl concentrations is associated with microstructural changes caused by the quenching process. Increasing the NaCl concentration in the quenching medium produces a finer and more uniform martensitic structure This condition can increase the electrochemical activity on the material surface which accelerates the corrosion process (Alcântara *et al.*, 2021). The results show that the corrosion rate increased from 0.3688 mmpy to 0.3990 mmpy. Similar findings have also been reported in recent studies, indicating that martensitic microstructures with a high defect density possess higher surface energy and greater susceptibility to corrosion due to intensified electrochemical reactions in chloride-containing environments (Gao *et al.*, 2024). The higher corrosion susceptibility of fine martensitic structures is associated with increased dislocation density and residual stress generated during rapid quenching. These defects increase surface electrochemical activity and promote localized corrosion in chloride environments. Therefore, although fine martensite improves hardness, it can also reduce corrosion resistance due to higher electrochemical reactivity

3.4. Electrochemical Test

Electrochemical measurements were conducted by immersing the samples in a 3.5% NaCl solution to simulate a seawater environment. The open circuit potential (OCP) results, as presented in Figure 7, were monitored over a duration of 1200 seconds. At the initial stage of immersion, a noticeable shift in potential toward more negative values was observed, indicating the breakdown of the protective oxide layer due to the aggressive attack of chloride ions (Peng *et al.*, 2024).

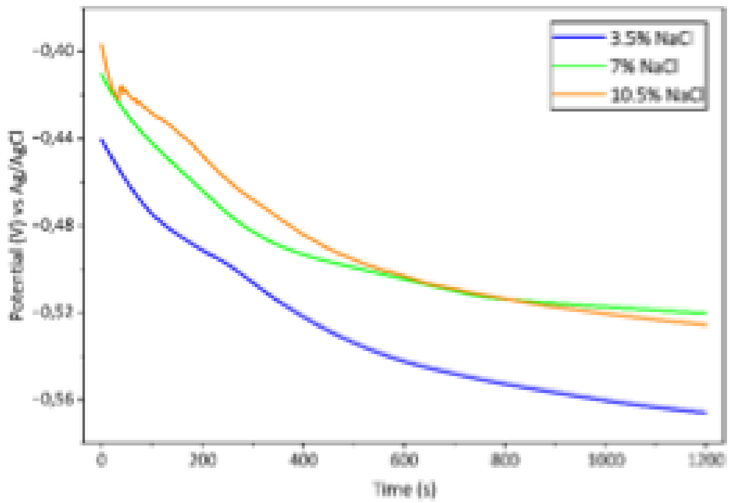


Figure 7. OCP measurement result

This negative shift reflects the initiation of active corrosion processes at the material surface, where localized dissolution begins to occur. As the immersion time progresses, the potential gradually stabilizes, suggesting the establishment of a dynamic equilibrium between anodic metal dissolution and cathodic reactions, such as oxygen reduction.

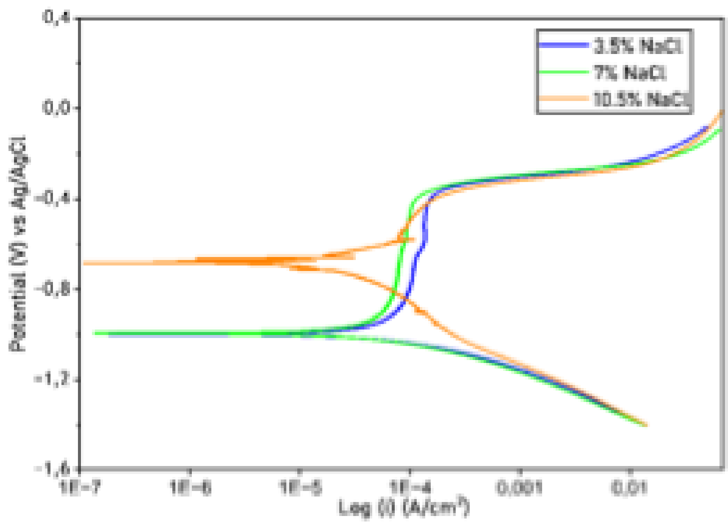


Figure 8. Polarization curve of various NaCl concentrations

The influence of NaCl concentration on electrochemical behavior is further demonstrated through the linear sweep voltammetry (LSV) results shown in Figure 8. The LSV curves reveal that higher NaCl concentrations correspond to increased current densities, which indicate a higher rate of electrochemical reactions at the metal surface. This behavior suggests that the presence of a greater number of chloride ions enhances the conductivity of the electrolyte and accelerates both anodic and cathodic processes (Xu *et al.*, 2022). Consequently, the material becomes more susceptible to corrosion due to intensified electrochemical activity.

These observations are quantitatively supported by the polarization test results presented in Table 3. The corrosion current density (Icorr) increases consistently with increasing NaCl concentration, rising from 1.75×10^{-5} A/cm² at 3.5% NaCl to 2.16×10^{-5} A/cm² at 7%, and further to 2.23×10^{-5} A/cm² at 10.5% NaCl. The increase in Icorr indicates a higher rate of metal dissolution, as corrosion current density is directly proportional to the corrosion rate. This trend confirms that increasing chloride concentration enhances the electrochemical kinetics of corrosion processes, as also reported in previous studies (Liu *et al.*, 2021; Shin and Kim, 2023).

Table 3. The potentiodynamic polarization test result

Sampels	Ecorr (V) vs Ag/AgCl	Icorr (A/Cm²)
3.5% NaCl	-0.679	1.75×10^{-5}
7% NaCl	-0.994	2.16×10^{-5}
10.5% NaCl	-0.683	2.23×10^{-5}

The electrochemical results are in strong agreement with the weight loss measurements obtained from long-term immersion testing. The corrosion rate calculated from mass loss data shows a similar increasing trend, rising from 0.3688 mmpy at lower NaCl concentration to 0.3990 mmpy at higher concentration. This consistency between electrochemical and gravimetric methods validates the reliability of the results and confirms that both approaches capture the same corrosion behavior. While electrochemical techniques provide rapid insight into corrosion kinetics, the weight loss method reflects the cumulative material degradation over time.

Overall, the combined analysis of OCP, LSV, polarization, and weight loss results clearly demonstrates that NaCl concentration plays a critical role in governing corrosion behavior. Higher NaCl concentrations not only accelerate electrochemical reactions but also increase the overall material degradation rate (Xu *et al.*, 2022). The presence of chloride ions contributes to the breakdown of protective films, enhances electrolyte conductivity, and promotes localized corrosion mechanisms. Therefore, increasing NaCl concentration significantly intensifies corrosion processes, leading to reduced durability of the material in simulated marine environments (Kokalj, 2021).

4. CONCLUSION

Increasing NaCl concentration in the quenching medium significantly affects the microstructure, hardness, and corrosion behavior of AISI 4140 steel. Higher NaCl concentrations enhance the cooling rate and promote the formation of finer and more homogeneous martensitic structures. Consequently, the hardness increased from 673 VHN at 3.5% NaCl to 762 VHN at 10.5% NaCl. However, the corrosion rate also increased from 0.3688 mmpy to 0.3990 mmpy due to higher dislocation density, residual stress, and electrochemical activity associated with fine martensitic structures. The results demonstrate a tradeoff between mechanical performance and corrosion resistance. This study contributes to the understanding of the relationship between quenching severity and electrochemical behavior, providing useful insights for optimizing heat treatment processes in marine engineering applications.

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