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The Effect of Quenching Methods Using Various Concentrations of Saltwater Solutions on the Hardness and Corrosion Rate of Low Carbon Steel After the Hardfacing Process

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Abstract: This study analyzes the effect of different saltwater (NaCl) concentrations in the quenching medium on the microstructure, hardness, and corrosion rate of low-carbon steel after the hardfacing process. Hardfacing was performed using a DF2A-450-R electrode, followed by rapid cooling in distilled water containing 3.5%, 7%, and 10.5% NaCl. Microstructure was observed using an Olympus BX51M optical microscope, hardness was tested by the Vickers method, and corrosion behavior was evaluated via electrochemical Open Circuit Potential (OCP) and Linear Sweep Voltammetry (LSV). The results show that higher NaCl concentrations accelerate cooling and promote a more dominant martensitic structure. The 10.5% NaCl specimen achieved the highest hardness of 582.1 HV and exhibited a more positive corrosion potential with the lowest corrosion current. Therefore, the 10.5% NaCl quenching medium provides the optimal balance between hardness improvement and corrosion resistance, making it suitable for post-hardfacing heat treatment of low-carbon steel in demanding industrial applications.

Keywords: quenching; NaCl; low-carbon; hardness; corrosion



SDGs Problem Solving

This study on hardfacing and quenching of low-carbon steel aligns with SDGs Chapter #9. The study improves material durability, reduces maintenance, and encourages sustainable industrial innovation by optimizing NaCl quenching to make materials harder and more resistant to corrosion. This leads to resilient infrastructure and more efficient use of resources in engineering applications.

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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Conflict of Interest STATEMENT
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1. INTRODUCTION

Low carbon steel is widely used in various construction and industrial applications due to its balanced mechanical properties; however, it remains susceptible to wear and corrosion under certain operational conditions (Triawan, Thohirin and Apriyanto, 2021). To enhance the surface resistance against wear, the hardfacing technique is often applied, followed by a heat treatment process such as quenching (Susetyo, Basori and Simanjuntak, 2021). Quenching is a rapid cooling process aimed at retaining the martensitic phase within the steel's microstructure, thereby significantly increasing the material's hardness (Basori *et al.*, 2024).

This process relies on the cooling rate from the austenitizing temperature to facilitate the transformation of phases into bainite and/or martensite, which directly correlates with the improvement in strength and hardness (Mulyadi *et al.*, 2022). The effectiveness of the quenching process is highly influenced by the cooling medium used, where saltwater becomes one of the most attractive options as it provides a faster cooling rate compared to plain water (Simanjuntak, Budiarto and Mulyatno, 2024).

The variation in salt concentration within the cooling medium potentially affects the cooling characteristics, which subsequently impacts the final hardness and corrosion resistance of low carbon steel after hardfacing (Syaifullah, Subhan and Juanda, 2021). The use of different quenching media has been proven to significantly influence the hardness variation in steels (Tasić *et al.*, 2018). Previous studies have demonstrated that cooling media such as water and oil result in notable differences in hardness for low-alloy steels, such as AISI 410 (Budi and Subagyo, 2021). Moreover, other research has indicated that rapid cooling methods, particularly those employing water as a medium, are highly effective in achieving superior hardness in high-carbon steels and chromium-coated tool steels (Koo, 2021). For instance, in Low Carbon steel, quenching using SAE 20W-50 oil as a cooling medium has been shown to produce a substantial increase in hardness, reaching up to 898.02 HV (Syaripuddin *et al.*, 2025). Previous studies have also indicated that the choice of cooling medium significantly affects the enhancement of strength and hardness in steels following the quenching heat treatment process (Susetyo and Syaripuddin, 2021).

The corrosion rate of low carbon steel after the quenching and hardfacing processes is particularly relevant to investigate, since heat treatment can modify both the microstructure and surface properties of the material, which in turn influence its resistance to environmental degradation (Mihajlović *et al.*, 2017). Therefore, it is crucial to understand how variations in saltwater concentration as the cooling medium affect the hardness and corrosion rate of low carbon steel after hardfacing (Abdulrazzaq, 2025).

Previous research has mainly focused on the influence of different cooling media such as water, oil, and polymer-based coolants on the mechanical and microstructural properties of medium carbon steels like AISI 1045, showing that the cooling rate strongly determines the final outcome of the heat treatment (Haryadi, Utomo and Ekaputra, 2021). Nevertheless, studies that specifically investigate the effect of varying saltwater concentrations as a cooling medium on the simultaneous behavior of hardness and corrosion rate in low carbon steel after hardfacing remain limited, thus opening opportunities for further exploration.

Although the influence of quenching media and salt solutions on steel properties has been widely reported, most studies focus on untreated steels or emphasize mechanical properties without comprehensive corrosion evaluation. This study investigates low-carbon steel subjected to a hardfacing process followed by quenching in saltwater with varying NaCl concentrations (3.5%, 7%, and 10.5%) to assess the combined effects on microstructure, hardness, and electrochemical corrosion behavior. The objective is to identify the quenching condition that provides the highest surface hardness with the lowest corrosion rate through microstructural observation, hardness testing, and electrochemical measurements (OCP and LSV).

2. METHODOLOGY

2.1. Experimental Setup

The material used in this study was low-carbon steel containing 0.2% carbon, with dimensions of 150 × 10 × 10 mm, as illustrated in Figure 1. Distilled water with the addition of NaCl at concentrations of 3.5%, 7%, and 10.5% was used as the quenching medium. The NaCl concentrations of 3.5%, 7%, and 10.5% were selected to represent different levels of corrosive environments. A concentration of 3.5% NaCl is commonly used to simulate seawater conditions (Kalisz, Haustein and Lieder, 2025), while higher concentrations of 7% and 10.5% were employed to model more aggressive saline environments and to accelerate corrosion processes for comparative evaluation of corrosion resistance (Brownlie *et al.*, 2022). The welding electrode used complied with JIS Z 3251 standards, classified as DF2A-450-R for HV 450 hardness. The chemical composition of the weld metal produced by this electrode is presented in Table 1.



Figure 1. Low carbon steel 150 x 10 x 10 mm

Table 1. Chemical composition of low carbon steel

	Element								
	C	Mn	Si	S	P	Cr	Mo	V	Fe
Amount (wt.%)	0.25	0.75	0.5	0.02	0.02	2.1	0.6	0.2	balance

2.2. Heat Treatment

The research procedure has several stages, starting from making test specimens, treating specimens, testing specimens, and taking test data. The hardfacing layer was deposited using a single pass surface welding technique. An HV450 electrode with a diameter of 3.2 mm was employed with a welding current of 110 A. In conventional quenching treatments, austenitizing is typically performed at temperatures above the critical transformation range with a specific holding time to obtain a fully austenitic structure prior to cooling (Field *et al.*, 2021). The specimens were then directly quenched in cooling media consisting of distilled water with the addition of NaCl at concentrations of 3.5%, 7%,

and 10.5%. Figure 2 shows the welded specimens that were directly quenched using NaCl medium with different concentration percentages.

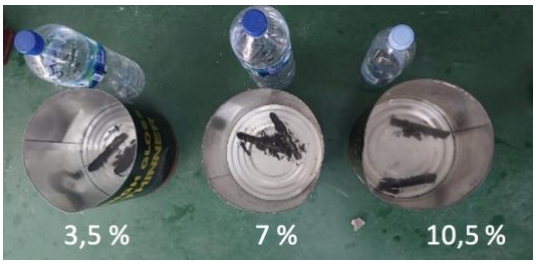


Figure 2. The welded and directly quenched specimen

2.3. Testing Methode

The quenched specimens were subsequently sectioned and mechanically polished using abrasive papers up to a #5000 grit size, followed by a drying process to ensure a clean surface. The samples were then chemically etched using a Nital solution and dried again prior to examination. The microstructural characterization was performed using an Olympus BX51M optical microscope to reveal the metallographic features of the specimens in this study, the hardness test was conducted using a Vickers hardness tester Future Tech (FV 300e) as shown in Figure 3. Five repeated indentation points were tested using a 5 kg load. The average value of these measurements was presented as the hardness value.

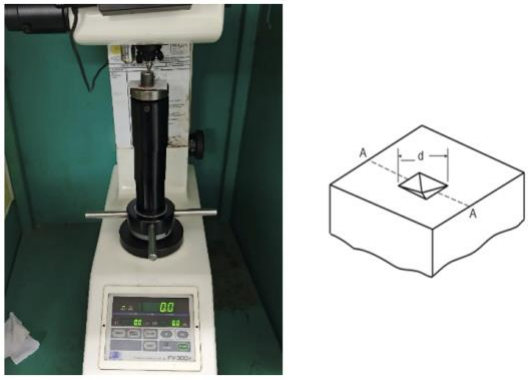


Figure 3. Vickers hardness test apparatus

The open circuit potential (OCP) and linear sweep voltammetry (LSV) measurements were performed using an Ossila potentiostat in a 3.5% NaCl solution under room temperature conditions. Prior to testing, the specimen surfaces were mechanically polished up to #5000 grit to obtain a smooth and uniform finish. The electrochemical cell configuration consisted of plain carbon steel as the working electrode (with an exposed surface area of 3.14 cm^2), platinum as the counter electrode, and Ag/AgCl as the reference electrode. The OCP test was conducted for 1200 seconds, followed by LSV measurements (Chai *et al.*, 2024; Faisal *et al.*, 2024).

The electrochemical measurement employed the linear sweep voltammetry (LSV) method, conducted at a scan rate of 5 mV/s within the potential range of −1.2 to −0.8 V vs. Ag/AgCl. The Tafel extrapolation was performed from the LSV curve to determine the corrosion potential and corrosion current. The Tafel extrapolation technique was employed to analyse the LSV data, and the corrosion

rate was determined based on the methodology adopted from previous studies (Maitimu *et al.*, 2024). Corrosion rate was calculated using the following expression:

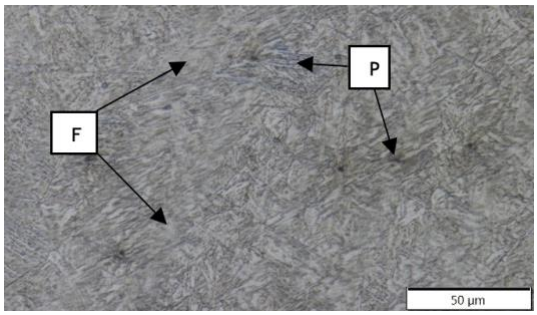
$$CR = \frac{W.K}{D.A.T} \quad (1)$$

where CR is corrosion rate (mm/y); W is mass loss (g); K is constant factor; A is exposure area (cm^2); T is time (h); and D is density (g/cm^3).

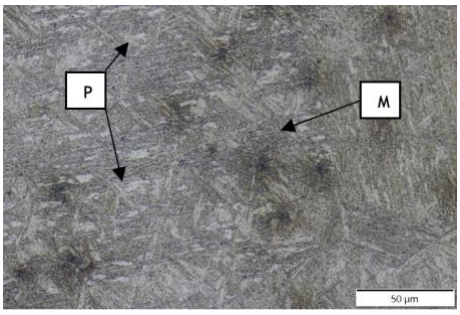
3. RESULTS AND DISCUSSION

3.1. Motor temperature rise under different generator loads

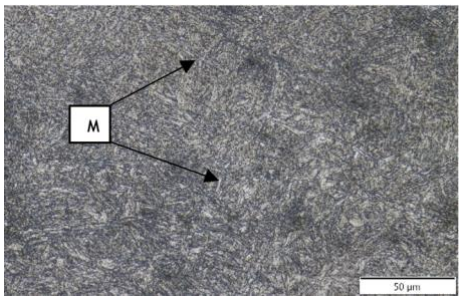
Microstructural observations were carried out using an Olympus BX51M optical microscope to analyze the effect of coolant solution variation on the quenching results. Figure 4 shown the optical micrographs reveal the presence of ferrite (F), pearlite (P), and martensite (M) phases in the hardfaced low-carbon steel after quenching. Specimens quenched in higher NaCl concentrations exhibit a more dominant martensitic structure with finer lath morphology. This behavior is attributed to the increased cooling severity of higher NaCl concentrations and is consistent with the higher hardness values obtained in these specimens.



(a). NaCl 3,5% showing Ferrite (F), Pearlite (P) phase



(b). NaCl 7% showing Pearlite (P), Martensite (M) phase



(c). NaCl 10,5% showing Martensite (M) phase

Figure 4. Microstructure of various NaCl concentrations

In the specimen quenched with a 10.5% NaCl solution, Figure 4c shown the martensitic phase appeared more dominant and uniformly distributed compared to those quenched in 3.5% and 7% NaCl solutions. This condition indicates that the 10.5% NaCl concentration provides the most efficient cooling rate, as it enhances heat diffusion from the metal surface, thereby promoting a more complete austenite-to-martensite transformation (Mersilia, Karo and Supriyatna, 2016).

Conversely, the specimen quenched in the 3.5% NaCl solution as shown on Figure 4a, the exhibited a microstructure containing a mixture of ferrite and pearlite phases, indicating a relatively slower cooling rate that hindered the complete formation of martensite (Syamsuir *et al.*, 2025). Meanwhile, Figure 4b shown the 7% NaCl solution, although the cooling occurred rapidly, non-uniform cooling likely occurred due to the formation of a vapor film (film boiling), resulting in fine martensite accompanied by bainite in several regions.

Overall, the results indicate that the 10.5% NaCl concentration provides the most optimal cooling characteristics, producing a dominant martensitic structure that contributes to a significant increase in material hardness compared to other concentration variations.

3.2. Hardness Test Results

The hardness test results using the Vickers method are presented in Table 2. The test was conducted five times on the surface of each sample. The average hardness values were then plotted and presented in Figure 5.

Table 2. Vickers Hardness test results

Sample (NaCl)	Hardness Data (HV)					Average Hardness ± SD (HV)
	1	2	3	4	5	
3.5%	540.2	551.6	548.3	553.1	551	548.8
7%	560.5	567.8	564	565.1	562.3	563.9
10.5%	578.9	585.4	580.7	583.2	582	582.1

The average hardness increased from 548.8 HV at 3.5% NaCl to 563.9 HV at 7% NaCl, reaching a maximum of 582.1 HV at 10.5% NaCl. Standard deviation calculated from five repeated measurements and corresponding error bars were included to represent data dispersion and improve the reliability and clarity of the hardness results.

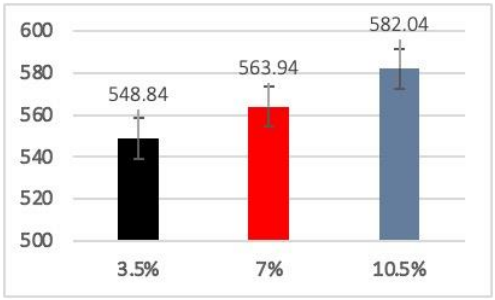


Figure 5. Average VHN of various NaCl concentrations

This increasing trend in hardness is closely related to the cooling rate that occurs during the quenching process. The higher the NaCl concentration, the greater the ability of the solution to accelerate heat dissipation from the metal surface, resulting in a faster and more complete transformation of austenite into martensite (Mersilia, Karo and Supriyatna, 2016).

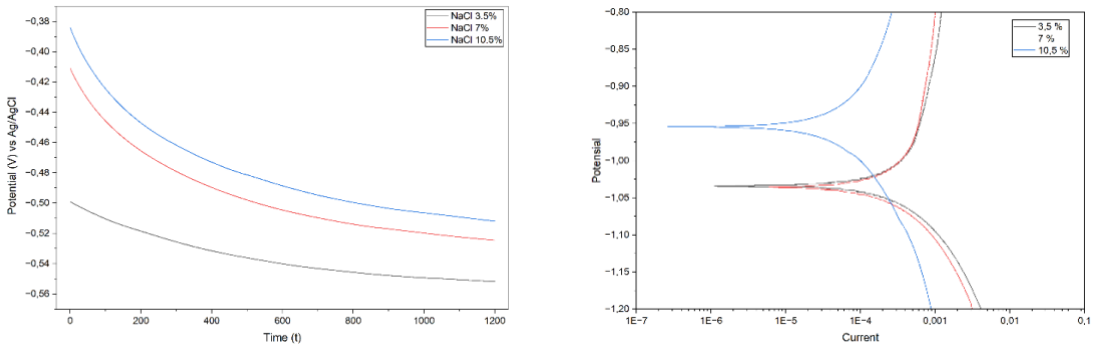
The dominant formation of martensite in the specimen quenched with a 10.5% NaCl solution is consistent with the microstructural observations, where the martensitic phase appears denser and more uniformly distributed compared to specimens with lower concentrations.

Conversely, the specimen quenched in a 3.5% NaCl solution still exhibited a mixed structure of ferrite and pearlite, indicating a relatively slower cooling rate (Sopiyan, Basori and Susetyo, 2020). As a result, not all austenite transformed into martensite, leading to a lower hardness value.

Therefore, the correlation between microstructural and hardness test results clearly demonstrates that increasing the NaCl concentration plays a significant role in accelerating martensite formation, which directly contributes to the improvement of material hardness after the quenching process (Putratama, Suprihanto and Umardani, 2021).

3.3. Open Circuit Potential (OCP) vs Linear Sweep Voltammetry (LSV) Result

In this study, The corrosion rate was determined based on electrochemical parameters obtained from Open Circuit Potential (OCP) and linear sweep voltammetry (LSV) measurements. The corrosion current density (Icorr) derived from Tafel extrapolation was used for corrosion rate calculation, rather than conventional weight loss based methods.



(a). OCP (b). LSV

Figure 6. Test results

The results of the OCP measurements are shown in Figure 6a. The three different curves are presented on Figure 6a, each corresponding to a different concentration of sodium chloride (NaCl) solution: 3.5%, 7%, and 10.5%. The black line represents the OCP in a 3.5% NaCl solution, the red line in a 7% NaCl solution, and the blue line in a 10.5% NaCl solution. The chosen concentrations are meant to mimic a variety of harsh environments, and higher levels of NaCl usually mean more severe corrosive conditions. The open circuit potential (OCP) becomes more negative over time for all three concentrations of NaCl. This means that the metal surface is changing in ways that make it more likely to corrode. This is a sign that the passive layer is breaking down or that corrosion products are forming on the surface.

The first and last OCP readings show less negativity when the NaCl concentration is high. The blue curve (10.5% NaCl) starts at the highest point and doesn't drop as much as the red (7% NaCl) and black (3.5% NaCl) curves. This indicates that the corrosion potential is less negative (i.e., less prone to corrosion) at higher salt concentrations, which may seem counterintuitive at first. This phenomenon may be ascribed to the potential formation of a protective layer of corrosion products at elevated salt concentrations, or modifications in the electrochemical double layer at the metal-solution interface.

A bigger negative OCP usually means that the metal is more likely to have anodic (corrosive) reactions. The black line (3.5% NaCl) shows the most corrosion activity, while the blue line (10.5% NaCl) shows the least negative potential. This could mean that the corrosion rate is lower or that the passive coating is stable. Based on Figure 6a, it can be observed that the curve gradually shifts toward a more negative direction over time. This indicates that the oxide layer formed on the surface subsequently detached into the NaCl solution.

Figure 6b shows the LSV data, which shows that the corrosion potential and the corrosion current are linearly related. When the current is low (between 1E-7 and 1E-4 A), all three curves are relatively flat. This means that the electrode reactions are controlled by kinetics and the current response is not very strong. This means that the electrochemical system is relatively stable at low currents, with little electrochemical activity regardless of concentration. When the current goes above 1E-4 A, the curves start to look very different, especially at the higher concentration of 10.5%. The blue curve (10.5%) shows a bigger change in potential as the current goes up than the 3.5% and 7% curves do. This behavior shows that concentration has a big effect on how the system reacts electrochemically. As the concentration rises, the current response for a given potential also rises. This is typical of systems with more electroactive species, which speeds up electrochemical processes.

The substantial increase in current at specific potentials for the 10.5% concentration signifies heightened electrochemical activity, likely due to improved ion availability or conductivity within the system. On the other hand, the lower concentrations (3.5% and 7%) show fewer major changes, which could mean that the reaction is slower or that the ions move less easily. As the corrosion potential becomes more negative, the corresponding corrosion current increases, indicating a higher corrosion rate. This behavior suggests that greater electrochemical activity accelerates material degradation.

Table 3. Electrochemical corrosion parameters

NaCl Concentration (wt%)	Potential vs Ag/AgCl (V)	Corrosion Current Density (A/cm^2)
3.5	−1.03365	2.86×10^{-4}
7.0	−1.03576	2.19×10^{-4}
10.5	−0.95380	3.41×10^{-5}

Table 3 summarizes the electrochemical corrosion parameters obtained from open circuit potential (OCP) and linear sweep voltammetry (LSV) measurements at an immersion time of 1200 s in NaCl solutions with different concentrations. The corrosion potential (Ecorr) values are reported relative to the Ag/AgCl reference electrode, while the corrosion current density (Icorr) was determined from Tafel extrapolation of the polarization curves.

As shown in Table 3, the specimen quenched in 10.5 wt% NaCl solution exhibits the lowest corrosion current density (3.41×10^{-5} A/cm^2), indicating the highest corrosion resistance among all tested conditions. In contrast, specimens quenched in 3.5 wt% and 7 wt% NaCl solutions show higher Icorr values, suggesting more active corrosion behavior.

The shift of Ecorr toward a less negative value for the 10.5 wt% NaCl condition further indicates a relatively more stable electrochemical state, which is attributed to the formation of a harder martensitic structure after quenching. These results demonstrate that increasing NaCl concentration

in the quenching medium significantly influences the corrosion behavior of hardfaced low-carbon steel.

4. CONCLUSION

The experimental results demonstrate that variations in NaCl concentration within the quenching medium significantly affect the microstructure, hardness, and corrosion behavior of low-carbon steel after the hardfacing process. Increasing the NaCl concentration enhances the cooling rate, leading to a more dominant and uniform martensitic structure formation.

The specimen quenched in 10.5% NaCl exhibited the highest average hardness of 582.1 HV, compared to 563.9 HV for 7% and 548.8 HV for 3.5%. These results confirm that a higher salt concentration promotes faster heat dissipation, improving the transformation of austenite to martensite and resulting in superior hardness.

Electrochemical analyses (OCP and LSV) indicated that the 3.5% NaCl solution produced the most negative corrosion potential and highest corrosion current density, signifying the highest corrosion rate. Conversely, the 10.5% NaCl solution showed a more positive corrosion potential and the lowest corrosion current, indicating improved corrosion resistance.

Overall, the 10.5% NaCl quenching medium provided the most optimal combination of mechanical strength and corrosion resistance. This concentration is therefore recommended for post-hardfacing quenching of low-carbon steel in applications requiring enhanced surface hardness and durability against corrosion.

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