

# Tailoring Heat Treatment Strategies to Enhance Corrosion Resistance and Mechanical Performance of Low-Carbon Steel in Marine Environment

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## Abstract

This study examines the impact of various heat-treatment processes on the corrosion resistance and mechanical properties of low-carbon steel, specifically for maritime applications. The carbon steel samples were evaluated at 750°C and subsequently cooled using two methods: normalizing and quenching. Alterations in the microstructure, hardness, and corrosion resistance were examined using contemporary techniques such as X-ray diffractometry (XRD), optical microscopy, wear testing, and electrochemical analysis in simulated seawater. The primary findings indicate that quenching enhances the hardness (from 170 to 404 HV) and corrosion resistance of steel by producing martensite, with a corrosion rate of  $8.44 \times 10^{-5}$  mm/year; however, this process also increases the brittleness of the steel. The process of normalizing results in a microstructure characterized by ductility, comprising both ferrite and pearlite phases. This structure exhibited a moderate level of resistance to corrosion, with a corrosion rate of 0.001018 mm/year. Conversely, the integration of normalizing with quenching results in a well-balanced microstructure, enhancing the material's toughness and corrosion resistance, with a lowest corrosion rate of  $6.12 \times 10^{-5}$  mm/year. Testing under saline conditions revealed that the quenched samples exhibited superior performance, highlighting the significance of cooling rates in enhancing material properties. This study demonstrates the importance of heat treatment in reducing the damage caused by saltwater corrosion of carbon steel. It also provides useful information on how to ensure that marine infrastructure is more durable and functions better.

**Keywords:** *heat treatment, low-carbon steel, marine environment, microstructural evolution, mechanical properties*

## 1. Introduction

Marine infrastructure is necessary for the growth of contemporary civilization because it supports commercial activities including shipping, energy production, and coastal security [1]. Since the Roman era, when hydraulic concrete was first used in naval construction, substantial improvements have been made in materials and technological techniques [2]. Nevertheless, the degradation of materials due to corrosion in marine

environments remains a persistent challenge [3]. This problem is particularly detrimental to facilities such as bridges, pipelines, offshore platforms, and seawalls, which continually face harsh conditions such as high salinity, fluctuating temperatures, and oxygen-rich environments [4].

Carbon steel is a key component in marine construction because it is strong, flexible, and cost-effective [5], [6], [7]. It can be used for fabricating

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important parts for pipelines and offshore platforms, and for strengthening structures. However, carbon steel is especially prone to corrosion in marine applications, which makes construction less safe and durable [8], [9], [10], [11]. Corrosion deteriorates materials, increases maintenance expenses, and in the most severe circumstances, structures fail completely [12]. This problem needs to be solved to ensure that marine infrastructure is durable, especially because the world is becoming increasingly dependent on marine industries. Many people believe that materials used in marine applications are separate groups of materials made just for this environment. Stainless steel and sophisticated alloys are used to resist corrosion, but carbon steel is still vital for large-scale marine projects because of its cost-effectiveness and mechanical properties. Improvements in engineering design have made it possible to effectively employ carbon steel in marine environments. Consequently, specific strategies must be used to prevent corrosion [13], [14].

It has been shown that heat treatment improves the performance of carbon steel in marine environments. Heat treatment involves careful control of the heating and cooling cycles of a material to change its microstructure and improve its chemical and mechanical properties. Annealing, quenching, normalizing, and tempering are common methods to make carbon steel stronger, more flexible, and more resistant to wear and corrosion. Changing the distribution and composition of phases, such as ferrite, pearlite, and martensite, inside the steel microstructure makes these improvements possible [15].

Depending on how quickly the steel is heated and cooled, heat treatment can provide certain qualities [15]. Quenching provides the material with a martensitic microstructure, which makes it harder and more brittle. However, normalizing makes the microstructure more balanced, which makes it stronger and tougher. Improving these processes for marine infrastructure can strengthen carbon steel, making it less likely to corrode and last longer under harsh conditions [15].

The changes in the microstructure of a material caused by heat treatment are closely related to how well it works in corrosive environments [16]. Studies have shown that the distribution of phases, including ferrite and cementite, is very important for the resistance of a material to corrosion [15]. Corrosion often occurs in separate galvanic cells in the microstructure, where certain phases

act as anodic sites, causing the material to break. Changing the parameters of heat treatment can improve the microstructure and make carbon steel less likely to corrode in certain areas [17], [18].

Heat treatment might help with corrosion problems, but there are still significant gaps in the knowledge of how it works on carbon steel in marine environments [16]. Most of the research to date has focused on improving short-term performance or examining specific heat treatment methods. This shows that questions about how long heat-treated steel can last in dynamic and very corrosive marine conditions remain unanswered. Further research is needed because the changes in microstructure caused by heat treatment interact with the unique features of marine settings such as high salinity and microbial activity [19].

It is clear that this study is necessary because material failure in marine infrastructure can have serious effects on economy and safety. Corrosion weakens the structure of important infrastructures and poses serious threats to both the environment and public safety. Corrosion is a major threat to pipes because it can cause leaks of dangerous substances, pollute the environment, and cost a lot of money to fix [20]. Using customized heat treatment methods to make carbon steel more resistant to corrosion may lower these hazards, while also making marine operations more environmentally friendly and cost-effective [19], [21].

A number of factors affect how well heat treatment improves the properties of carbon steel, such as temperature, holding time, and cooling medium employed [22]. For instance, quenching the metal quickly makes it harder, but this process can also cause internal stresses or strains, which means that tempering is needed to make it flexible. Similarly, slowly cooling the metal during the normalizing or annealing procedures can make the grains finer and tougher, but it can also soften the metal. To enhance the heat treatment processes and achieve the desired outcomes, it is essential to understand the interplay between these components [15].

Various factors affect the corrosion resistance of materials in marine environments, such as salinity, temperature, oxygen concentration, and microbial activity [23]. Higher salinity accelerates electrochemical reactions that result in corrosion, whereas increased temperatures hasten the dissolution of metals [24]. The activity of microbes, especially sulfate-reducing bacteria, can trigger

localized corrosion through the generation of corrosive byproducts, such as hydrogen sulfide [25]. The interaction of these environmental factors with the microstructure of carbon steel underscores the importance of tailoring material properties to specific conditions [15].

The objective of this study is to address the existing gaps in the understanding of how heat treatment can enhance the corrosion resistance and mechanical properties of carbon steel under marine conditions. In this study, the impact of various heat treatment processes on the microstructure and chemical characteristics of carbon steel was investigated by replicating coastal conditions, such as salt exposure, to provide valuable insights into the performance and durability of heat-treated carbon steel in actual marine environments.

## 2. Materials and Methods

This section details the comprehensive experimental approach employed to evaluate the impact of various heat-treatment techniques on the corrosion resistance and mechanical properties of carbon steel. This approach encompasses sophisticated techniques for material characterization, assessing corrosion, and examining the microstructure of specimens to comprehensively analyze their performance in marine-like conditions.

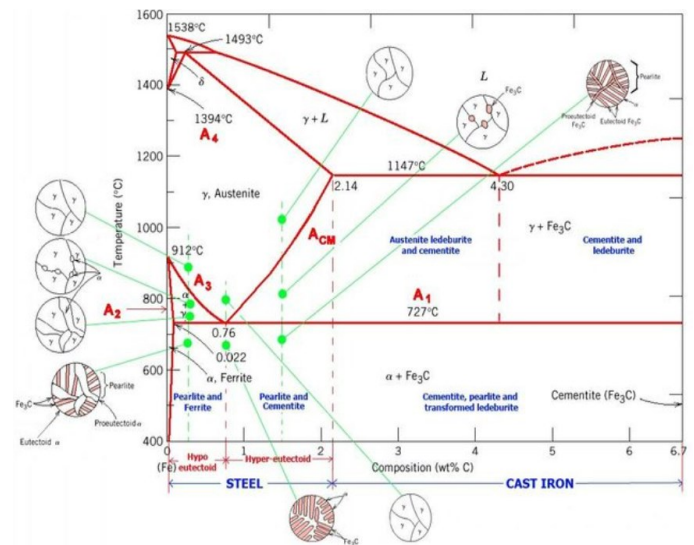
This study mostly utilized low-carbon steel, owing to its extensive industrial applications and economic efficiency. The carbon steel utilized comprised 0.5–1.5% carbon, with the remainder being iron and trace quantities of other elements, including manganese, silicon, and aluminium (see Table 1). The samples were prepared as 5 mm-thick plates to provide consistency throughout all trials.

**Table 1.** The elemental composition of the carbon steel.

Element	C	Al	Si	Mn	Fe
Weight%	0.45	0.17	0.12	1.32	Balance

The heat treatment was conducted using an electric muffle furnace to achieve the desired microstructural and mechanical properties of carbon steel. Four different treatments were applied: (1) *normalization*, in which samples were heated to 750 °C [26], [27], [28] and cooled in ambient air to refine the grain structure and enhance the toughness and ductility; (2) *quenching*, involving heating

to 750 °C followed by rapid cooling in water to form a martensitic structure and increase the hardness; (3) *normalization followed by quenching*, where normalized specimens were reheated to 1000 °C [26], [27], [28] and quenched to combine the toughness of normalizing with the hardness from quenching; and (4) *repeated (cyclic) quenching*, where samples underwent a second quenching cycle at 1000 °C to further increase the hardness and structural uniformity. Figure 1 shows the transformation process of the iron–carbon phase diagram.



**Figure 1.** Iron-carbon face diagram transformation process.

The specimens were precisely cut using a wire-cutting machine and edge-finished to eliminate defects. After treatment, the samples were ground and polished using Struers equipment with abrasive grits ranging from 10 to 30 μm, followed by monocrystalline diamond suspensions (1 and 9 μm) to achieve a mirror-like, scratch-free surface. Metallographic etching was performed using a 2% nital solution to reveal the microstructural features. Microstructural characterization was carried out using optical microscopy (Nikon OPM, 5×–100×) and X-ray diffraction (PANalytical Empyrean diffractometer) to identify phases such as ferrite, pearlite, and martensite and to study the crystallographic changes caused by thermal treatment. The corrosion behavior was evaluated in artificial seawater using an AUTOLAB potentiostat via polarization resistance and corrosion current density measurements to simulate marine conditions. A 300 g load and a 15-second dwell time were employed to assess the surface hardness using a fully automated FM-ARS 900 Vickers hardness tester. The

investigation comprised of untreated control samples and four groups subjected to heat treatment. All subjects were evaluated under identical conditions to ensure comparability of the outcomes. This comprehensive method enabled the correlation of heat-treatment parameters with alterations in the microstructure, mechanical properties, and corrosion resistance of carbon steel utilized in maritime applications.

### 3. Results and Discussion

Various heat-treatment factors, such as temperature and cooling rate, were investigated for their effects on the grain structure and phase distribution, as well as how these changes relate to wear and corrosion resistance. By comparing these findings to untreated specimens, we aimed to identify the most effective strategies for increasing the longevity of carbon steel used in marine infrastructure. The interaction of environmental elements and treated surfaces was investigated to provide a thorough understanding of the corrosion behavior in marine environments. This study demonstrates how enhanced heat-treatment processes can considerably increase the durability and reliability of carbon steel in demanding environments.

#### 3.1. Microstructural analysis of the heat-treated steel

In untreated carbon steel, which is characterized by a carbon content of less than 0.5%, the microstructure is composed of a ferrite matrix with pearlite colonies distributed throughout (see Figure 2). The ferrite regions dominate, offering ductility, whereas the pearlite colonies enhance strength and hardness [29]. The grain boundaries are clearly defined, and the overall microstructure remains relatively coarse owing to the lack of post solidification heat treatments. The integration of soft ferrite and hard pearlite phases yields a well-balanced array of mechanical properties. Ferrite contributes to ductility and toughness, whereas pearlite enhances strength and wear resistance [30], [31].

The microstructures of carbon steel, when subjected to various heat treatments, display distinct characteristics contingent on the cooling rate and thermal history, as shown in Figure 2. Figures 3 illustrates the SEM

micrographs corresponding to four different heat-treatment conditions: A (normalized), Q (quenched in water), AQ (normalized followed by quenching in water), and QQ (cyclic quenched in water). The normalized specimen (Sample A) exhibited a typical microstructure consisting of ferrite and pearlite. The gradual cooling process promotes the transformation of austenite into coarse pearlite and ferrite. Ferrite is characterized by light regions with polygonal grains, whereas pearlite is distinguished by dark lamellar colonies. This relatively coarse-grained structure enhances ductility and provides moderate strength, making it well suited for applications that demand formability.

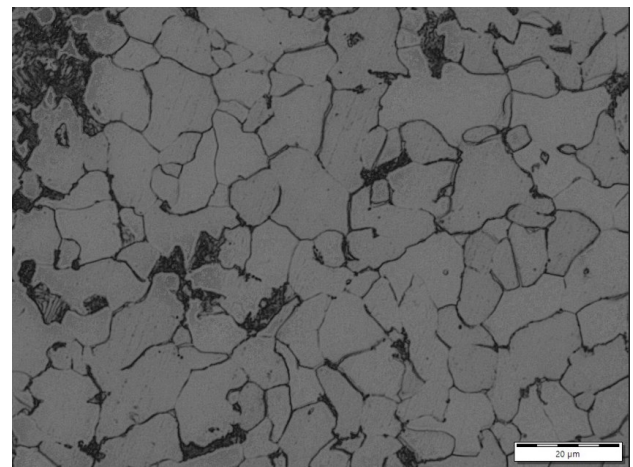


Figure 2. OPM microstructure of as-received carbon steel.

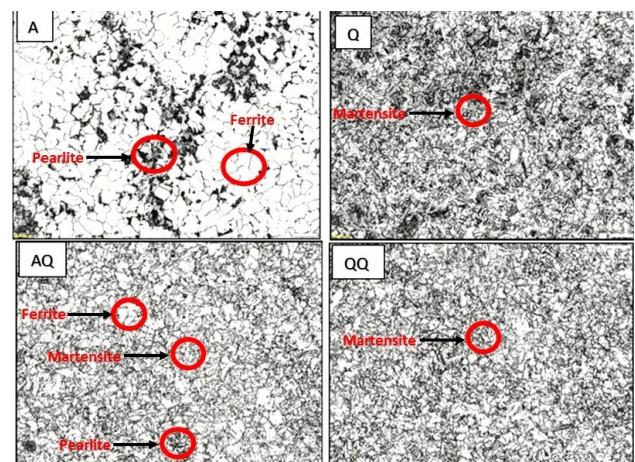


Figure 3. The optical microscope image of the heat-treated samples.

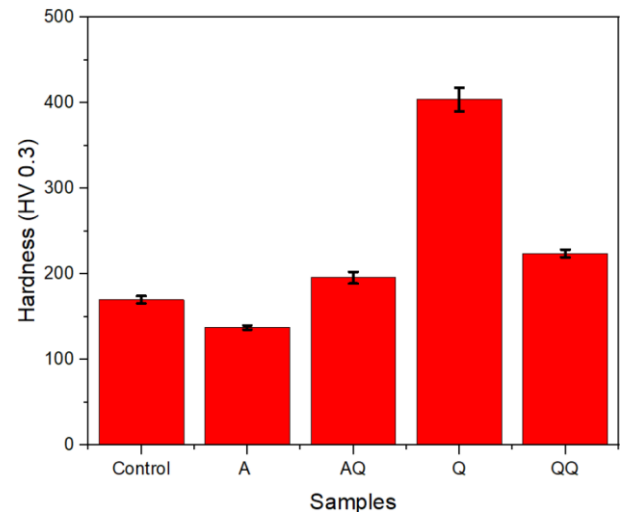
Water quenching (sample Q) led to the development of a predominantly martensitic microstructure, distinguished by its fine needle-like (acicular) features (Figure 3). The rapid cooling process inhibits diffusion-controlled transformations such as pearlite formation, resulting in the

formation of hard, brittle martensite. This structure significantly enhances the hardness and strength, while markedly reducing ductility. The micrograph reveals a dense and refined arrangement, indicating successful transformation from austenite to martensite. For sample AQ, the treatment resulted in a composite microstructure characterized by elements of both the ferrite-pearlite system and martensite. The initial air cooling facilitated partial transformation into ferrite and pearlite, which were subsequently quenched by converting the remaining austenite into martensite. Consequently, the microstructure was heterogeneous, comprising regions of retained ferrite/pearlite and newly formed martensite. This condition is anticipated to exhibit a balanced combination of toughness and hardness contingent upon the proportion of martensite formed during the second stage.

Sample QQ underwent two repeated quenching cycles (cyclic quenching), which facilitated the formation of highly refined martensite. In comparison to the single-quenched (Q) sample, this cyclic quenching process likely diminishes the retained austenite and enhances the structural uniformity, as shown in Figure 3. The martensite is observed to be denser and more uniformly distributed. This microstructure results in a significantly high hardness and strength, accompanied by a further reduction in ductility. Cyclic quenching may also contribute to increased internal stresses unless subsequently tempered [32].

### 3.2. Microhardness properties of the heat-treated steel

The microhardness results for the control and heat-treated carbon steel samples are summarized and graphically illustrated in Figure 4. The control sample, which did not undergo any heat treatment, exhibited a microhardness of 170 HV<sub>0.3</sub>, serving as a baseline for comparison. Among the heat-treated specimens, the quenched (Q) sample recorded the highest hardness value of 404 HV<sub>0.3</sub>, more than doubling the hardness of the control. This significant increase was attributed to the formation of a martensitic structure during rapid water quenching from the austenitizing temperature, which is well known for its high dislocation density and lattice distortion, resulting in enhanced hardness.



**Figure 4.** Graphical depiction of the microhardness of heat-treated samples compared to the control.

Conversely, the normalized (air-cooled) (A) specimen exhibited the lowest hardness at 138 HV<sub>0.3</sub>, reflecting the development of a predominantly ferrite-pearlite microstructure. This phase composition, which is associated with relatively lower hardness, prioritizes ductility and toughness over strength. The AQ sample, which underwent normalizing followed by water quenching, showed a moderate increase in hardness (196 HV<sub>0.3</sub>), indicating partial transformation to martensite within a matrix of ferrite and pearlite. This intermediate hardness suggests a balance between toughness and strength, which may be beneficial in applications in which a compromise between ductility and hardness is desired.

The cyclic-quenched (QQ) sample demonstrated a further increase in hardness to 224 HV<sub>0.3</sub>, higher than the AQ sample but lower than the single-quenched Q sample. The slight increase in AQ may have resulted from the refinement of martensitic laths or increased homogeneity in martensitic transformation due to repeated thermal cycling. However, the reduction compared to Q could indicate that excessive quenching cycles may lead to retained austenite or tempering-like effects from reheating, slightly reducing the overall hardness [32].

Moreover, the X-ray diffraction (XRD) patterns of the heat-treated carbon steel samples, as shown in Figure 5, reveal the phase evolution associated with different thermal histories, highlighting the presence of ferrite and martensite in varying proportions.

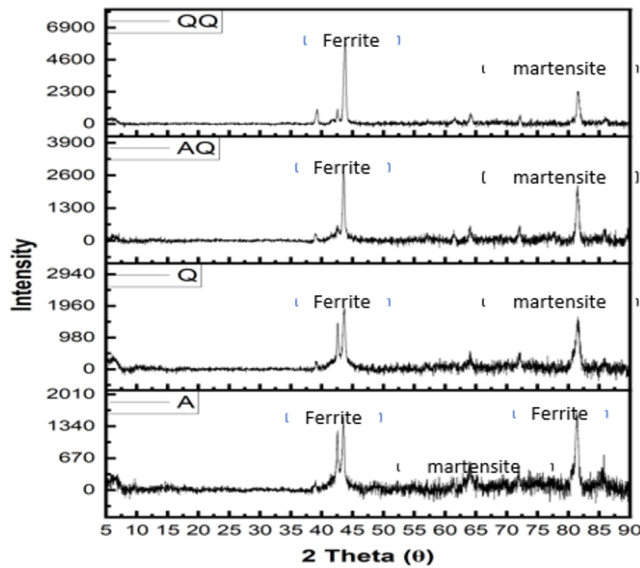


Figure 5. XRD graphs of the heat-treated samples.

The normalized sample (A) displays dominant ferrite peaks with weak martensitic signals, indicating limited transformation due to slow cooling, which favors a ferrite-pearlite microstructure. In contrast, the water-quenched sample (Q) exhibited sharp and intense martensitic peaks with reduced ferrite intensity, confirming a predominantly martensitic structure resulting from rapid cooling. The sample subjected to normalizing followed by quenching (AQ) showed a mixture of ferrite and martensite phases, suggesting a partial transformation during the second thermal cycle and the development of a dual-phase structure. The cyclic-quenched sample (QQ) presents enhanced martensitic peaks, similar to those in the Q sample, but slightly broadened, indicating a more refined and homogeneously distributed martensitic matrix with residual ferrite. These observations demonstrate a clear trend of increasing martensite formation from A to Q, correlating strongly with the hardness values observed under each condition. The results confirm that the extent of martensitic transformation, and hence the mechanical performance, is highly sensitive to the heat treatment route, with repeated or cyclic quenching enhancing the formation of martensite and improving hardness, albeit with potential implications for toughness and internal stresses [33].

### 3.3. Electrochemical properties of the heat-treated steel

The corrosion behavior of the heat-treated carbon steel samples in a simulated salty environment is illustrated in

Table 3 and Figure 6, highlighting the significant variations in electrochemical performance as a function of thermal processing.

Table 3. Corrosion test data of the heat-treated samples.

Samples	ECORR	ICORR	Corrosion Rate	Polarization Resistance
A	-0.82584	8.76E-08	0.001018	6235100
AQ	-0.32299	5.26E-09	6.12E-05	10501000
Q	-0.49239	7.26E-09	8.44E-05	8294100
QQ	-0.71912	3.16E-07	0.003667	3267000

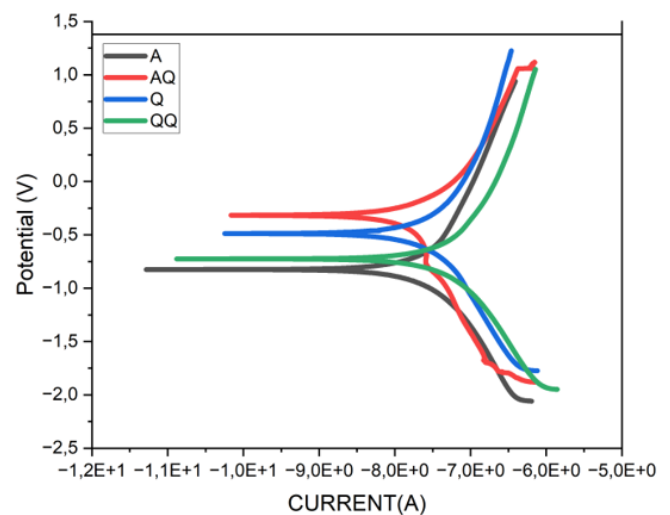


Figure 6. The linear polarization curve of the heat-treated samples in the salinity environment.

The normalized sample (A) exhibited the most negative corrosion potential ( $E_{CORR} = -0.82584$  V) and a moderate corrosion current density ( $I_{CORR} = 8.76 \times 10^{-8}$  A), indicating a higher tendency for electrochemical degradation compared to other samples. However, its corrosion rate remained relatively low (0.001018 mm/year), which may be attributed to a stable passive film, albeit with limited polarization resistance ( $6.23 \times 10^6 \Omega \cdot \text{cm}^2$ ). The AQ-treated sample, subjected to normalizing followed by quenching, demonstrated the highest corrosion resistance, evidenced by the most positive  $E_{CORR}$  (-0.32299 V), the lowest  $I_{CORR}$  ( $5.26 \times 10^{-9}$  A), and the lowest corrosion rate ( $6.12 \times 10^{-5}$  mm/year), accompanied by the highest polarization resistance ( $1.05 \times 10^7 \Omega \cdot \text{cm}^2$ ). This indicates that AQ treatment may lead

to a refined microstructure with enhanced passivity and electrochemical stability [33].

Conversely, the Q-treated sample (quenched in water) showed intermediate corrosion resistance ( $ECORR = -0.49239$  V), with an  $ICORR$  of  $7.26 \times 10^{-9}$  A and a corrosion rate of  $8.44 \times 10^{-5}$  mm/year, supported by a relatively high polarization resistance ( $8.29 \times 10^6 \Omega \cdot \text{cm}^2$ ). The performance suggests the formation of martensitic phases that, while contributing to the mechanical hardness, might compromise corrosion protection to some extent. The sample subjected to cyclic quenching (QQ) presented the poorest corrosion resistance, characterized by a relatively negative  $ECORR$  ( $-0.71912$  V), a significantly higher  $ICORR$  ( $3.16 \times 10^{-7}$  A), and the highest corrosion rate ( $0.003667$  mm/year), coupled with the lowest polarization resistance ( $3.27 \times 10^6 \Omega \cdot \text{cm}^2$ ). These findings suggest that repeated quenching may introduce microstructural stress and heterogeneity, increasing the susceptibility to corrosion [33].

The polarization curves in Figure 6 corroborate these electrochemical data, where the AQ sample (red curve) shows the noblest potential and lowest current density, indicative of superior passivation, whereas the QQ sample (green curve) exhibits a steeper current rise and more negative potential, consistent with accelerated anodic activity. Collectively, these results confirm that heat treatment routes exert a profound influence on corrosion resistance, with AQ treatment offering an optimal balance between phase transformation and electrochemical stability in chloride-rich environments.

#### 4. Conclusion

This study examined the effects of four distinct heat treatment processes—normalizing (A), quenching in water (Q), normalizing followed by quenching (AQ), and cyclic quenching (QQ)—on the microstructure, hardness, and corrosion resistance of low-carbon steels for potential marine applications. Microstructural analysis revealed that normalizing produced a coarse ferrite–pearlite matrix with good ductility but low hardness, while quenching led to a predominantly martensitic structure, significantly increasing hardness ( $404 \text{ HV}_{0.3}$ ) but compromising corrosion resistance. AQ treatment resulted in a dual-phase microstructure comprising ferrite, pearlite, and

martensite, which provided a desirable balance between strength and toughness. Notably, the AQ sample also exhibited the highest corrosion resistance, with the most positive corrosion potential, the lowest current density, and the highest polarization resistance, suggesting enhanced passivity. The QQ sample, although achieving better hardness than AQ ( $224 \text{ HV}_{0.3}$ ), demonstrated the poorest corrosion resistance, likely due to structural inhomogeneity and residual stresses introduced by repeated quenching. These findings underscore the critical role of heat-treatment design in optimizing the performance of carbon steel in marine environments, with AQ emerging as the most effective treatment for achieving both mechanical durability and corrosion resistance.

Future research should explore tempering strategies for post-quenching to relieve internal stresses and further improve the corrosion resistance. Additionally, long-term exposure studies under dynamic marine conditions and the use of alternative quenching media (e.g., oil, polymer, brine) may provide deeper insights into the practical applications and limitations of these heat treatment protocols in real-world settings.

#### Competing Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

#### Data Availability Statement

All data generated or analyzed during this study are included in this article.

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