International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 11, pp 275-279, November-2025

https://doi.org/10.47001/IRJIET/2025.911035

The Effect of Heat Treatment on the Corrosion Rate of Medium Carbon Steel in Seawater from the North Coast of Java

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***Abstract* - This study investigates the effect of various heat treatment processes on the corrosion rate of medium carbon steel AISI 1045 when exposed to a seawater environment. The research aims to understand how different microstructural changes caused by heat treatment influence corrosion resistance. Five types of specimens were prepared: non-heat-treated, annealed, normalized, quenched, and tempered. The corrosion test was conducted using a CorrTest CS300 Potentiostat with seawater as the corrosive medium, and the test duration was 15 minutes for each specimen. The results show that the heat treatment process significantly affects the corrosion behavior of AISI 1045 steel. The annealed specimen exhibited the lowest corrosion rate (0.013 mmpy), while the untreated specimen had the highest (0.069 mmpy). The improved resistance of the annealed sample is attributed to its homogeneous ferrite-pearlite structure and reduced internal stress. In contrast, the quenched specimen showed poor corrosion resistance due to martensitic formation and residual stress. Overall, annealing was found to provide the most effective improvement in corrosion resistance for AISI 1045 steel in seawater environments.**

Keywords: AISI 1045 steel, heat treatment, corrosion rate, seawater.

I. INTRODUCTION

Medium carbon steels are widely used in mechanical and structural components because of their good combination of strength, toughness, and machinability [1]. These steels are often used in construction, shafts, gears, connecting rods, and machinery parts that experience repeated stresses and wear [2]. Despite these advantages, medium carbon steels exhibit relatively poor corrosion resistance, particularly in aggressive environments such as seawater, where chloride ions accelerate corrosion processes [3,4]. Corrosion in marine environments not only weakens the structural integrity of materials but also increases maintenance costs and reduces the service life of industrial components [5]. Therefore, enhancing corrosion resistance without compromising mechanical properties is a crucial objective in materials engineering.

Corrosion is an electrochemical process involving the deterioration of metal surfaces due to reactions with their environment. In seawater, the high concentration of chloride ions promotes anodic dissolution and localized corrosion such as pitting and crevice attack [6]. The rate and mechanism of corrosion depend on factors including material composition, microstructure, temperature, and the presence of stress or residual strain. For carbon steels, the microstructure — which is determined by heat treatment history — plays a dominant role in controlling corrosion behavior [7]. The balance between ferrite and pearlite phases, the distribution of cementite (Fe_3C), and the presence of martensite or bainite influence both mechanical and electrochemical performance.

The northern coast of Java is currently being developed as an industrial zone. Steel is widely used in the construction of infrastructure in these areas. As is known, during the construction process, steel is welded to assemble structural components. This welding process changes the steel's microstructure. These changes are caused by the heat generated by the welding process. Simulation of microstructural changes due to welding can be performed on a laboratory scale using heat treatment.

Heat treatment is one of the most effective methods to modify the microstructure of steel to achieve desirable mechanical and physical properties. It involves controlled heating and cooling to alter the distribution of phases within the iron-carbon system [8]. Typical heat treatments for medium carbon steels include annealing, normalizing, quenching, and tempering. Each process produces distinct microstructures that affect corrosion behavior differently. Annealing involves heating the steel to a specific temperature and cooling it slowly, producing a soft structure with coarse pearlite and ferrite, which reduces internal stresses. Normalizing also results in ferrite and pearlite but with finer and more uniform grains, enhancing mechanical strength. Quenching, on the other hand, produces a hard but brittle martensitic structure due to rapid cooling, often increasing internal stress and susceptibility to corrosion. Tempering is applied after quenching to reduce brittleness and relieve internal stresses, generating a combination of ferrite, bainite, and tempered martensite [9].

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Previous research has shown that microstructural differences caused by heat treatment strongly influence the corrosion rate of steels [10]. For example, annealed steels often show improved corrosion resistance because of the reduction of internal stress and the formation of uniform ferrite-pearlite structures. In contrast, quenched steels exhibit higher corrosion rates due to non-homogeneous martensitic phases and higher dislocation densities that act as active corrosion sites [11]. Tempered steels usually demonstrate intermediate behavior, balancing mechanical strength with moderate corrosion resistance. Normalized steels, with fine pearlite structures, show enhanced mechanical strength but may still exhibit moderate corrosion rates depending on the environment [12].

In marine engineering and coastal infrastructure, components made from medium carbon steels are frequently exposed to saline environments, where durability against corrosion is critical. Using seawater as the testing medium represents real-world conditions where such materials are often applied. The corrosion mechanism in seawater is influenced by the presence of dissolved oxygen, temperature, pH, and ion concentration. Among these, chloride ions are the most detrimental because they can penetrate protective oxide layers and promote anodic reactions at localized spots, leading to pitting corrosion [5]. Therefore, evaluating the influence of heat treatment on the corrosion performance of AISI 1045 steel in seawater is of practical importance.

This study aims to provide a comparative understanding of how various heat treatments affect the corrosion rate and microstructural characteristics of AISI 1045 medium carbon steel. The investigation focuses on five conditions: non-heat-treated (as-received), annealed, normalized, quenched, and tempered specimens. The corrosion behavior was analyzed using an electrochemical approach with a CorrTest CS300 Potentiostat in natural seawater, with each test lasting 15 minutes under identical conditions. The microstructures of the samples were also observed using metallographic analysis to identify the dominant phases that influence corrosion performance.

The significance of this study lies in providing insights into the optimization of heat treatment processes for steels intended for marine applications. Understanding the relationship between heat treatment, microstructure, and corrosion behavior can guide material selection and design for improved durability and reduced maintenance in corrosive environments. Furthermore, the results contribute to the broader field of corrosion engineering by highlighting the interplay between metallurgical treatments and electrochemical properties, which is essential for developing more corrosion-resistant steels.

II. MATERIALS AND METHODS

The material used in this study was medium carbon steel AISI 1045, which is widely employed in industrial components such as shafts, gears, and machine parts requiring moderate hardness and strength. The steel composition, as obtained from the manufacturer's specification, contains approximately 0.43–0.50% C, 0.60–0.90% Mn, 0.04% P (max), and 0.05% S (max), with the balance being iron (Fe). This chemical composition provides a balance between ductility, toughness, and machinability but also makes the steel moderately susceptible to corrosion in chloride environments such as seawater.

A total of five types of specimens were prepared for corrosion testing, each representing a different heat treatment condition annealed, normalized, quenched and tempered. Non heat treated or as received specimens was used as a comparison. All specimens were cut into uniform rectangular shapes with dimensions of 30 mm × 20 mm × 5 mm to ensure consistency during testing. Prior to heat treatment, each specimen was cleaned and polished using emery papers of different grit sizes (100, 400, 800, and 1200) to remove oxides and surface irregularities. After polishing, specimens were rinsed with ethanol and dried using warm air to avoid contamination.

The heat treatment process was conducted using a Hofmann Industrieofenbau Linz-Austria electric furnace with precise temperature control. Each treatment followed a specific heating temperature, soaking time, and cooling medium as shown in Table 1. During annealing, the specimens were slowly cooled inside the furnace to allow for recrystallization and stress relief, resulting in a coarse pearlite-ferrite microstructure. In contrast, the normalized specimens were air-cooled, producing a finer and more uniform pearlite structure. Quenching was performed by immersing the hot specimens in water. These processes produced a hard martensitic structure and also introduced high internal stresses. Finally, tempering was carried out on the quenched specimens by reheating them to 450°C, followed by air cooling to reduce brittleness and partially restore ductility.

Table 1: Summary of heat treatment parameters

Type of Treatment	Heating Temperature (°C)	Soaking Time (min)	Cooling Medium
Annealing	850	60	Furnace cooling
Normalizing	850	30	Air cooling
Quenching	850	30	Water

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Type of Treatment	Heating Temperature (°C)	Soaking Time (min)	Cooling Medium
Tempering	450	30	Air cooling
Non-heat-treated	—	—	—

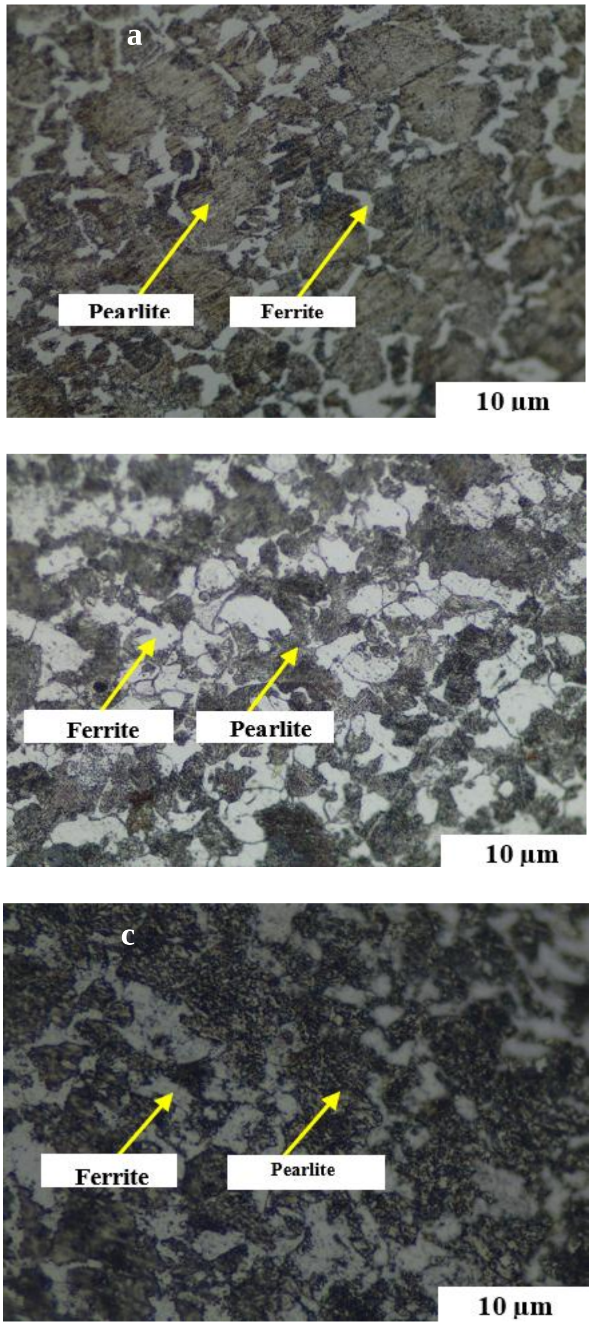
Microstructural and macrostructural examinations were conducted to analyze the effect of heat treatment on the phase transformation of AISI 1045 steel. After heat treatment, each specimen was ground and polished using a standard metallographic procedure. The polished surfaces were etched using 2% Nital solution (98% ethanol + 2% nitric acid) for approximately 5–10 seconds to reveal the grain boundaries and phase constituents. The microstructures were observed using an Olympus GX51 optical metallurgical microscope, while macrostructural images were captured using a digital camera under controlled lighting. The observed microstructures were analyzed to identify the presence of ferrite, pearlite, bainite, or martensite phases, which are known to influence corrosion resistance.

The corrosion behavior of each heat-treated specimen was evaluated using an electrochemical method with a CorrTest CS300 Potentiostat. The tests were performed in natural seawater obtained from the northern coast of Java, Indonesia. The seawater used as a corrosion medium was taken from the Tanjung Emas port area in Semarang. This port area is part of an industrial area on the north coast of Java. The seawater was collected form several locations approximately 100 meters from the shoreline. The seawater was filtered and used as the electrolyte solution without chemical modification to maintain natural salinity. The experimental setup used saturated calomel electrode (SCE) as reference electrode and platinum wire as counter electrode. Before each test, the specimen surface was polished with 1200-grit emery paper, cleaned with ethanol, and dried. The specimen was then immersed in the seawater electrolyte, and polarization was carried out for 15 minutes at room temperature (27 ± 2°C). The corrosion potential (Ecorr) and corrosion current density (Icorr) were obtained from the Tafel extrapolation curves using the CorrTest software.

The corrosion rates obtained from the potentiostat measurements were compared among all heat treatment conditions. The resulting data were tabulated and analyzed statistically to determine the correlation between microstructural characteristics and corrosion resistance. The micrographs were used to support the interpretation of the electrochemical results. The relationship between microstructure and corrosion rate was further discussed based on the distribution of ferrite and pearlite phases, the presence of martensite, and the homogeneity of grain boundaries. These structural characteristics were linked to the electrochemical activity and potential formation of micro-galvanic cells within the steel. Finally, the comparative performance of each heat treatment condition was ranked according to the observed corrosion resistance in seawater.

III. RESULTS AND DISCUSSION

The microstructural analysis of AISI 1045 specimens revealed significant differences among the heat treatment conditions. Figure 1shows the observed microstructures of the all specimens. The micrographs were analyzed to identify ferrite, pearlite, bainite, and martensite phases that determine corrosion behavior.



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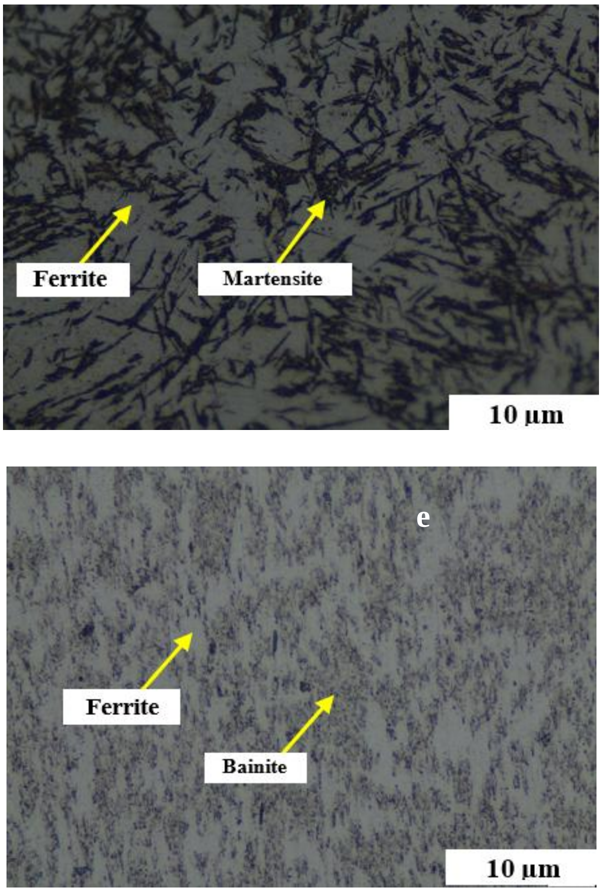

Figure 1: The microstructure of heat treated and non-heat-treated specimen. a) Non-heat treated, b) annealed, c) normalized, d) quenched, & e) tempered at 450^{0}C

The results of the corrosion test are shown in Table 2. The results indicate a clear correlation between heat treatment and corrosion behavior. The annealed specimen recorded the lowest corrosion rate (0.013 mmpy), while the non-heat-treated and quenched specimens showed the highest corrosion rates (0.069 and 0.057 mmpy, respectively).

Table 2: Corrosion rate test result

Specimen Type	Ecorr (mV)	Icorr (µA/cm²)	Corrosion Rate (mmpy)	Corrosion Resistance Category
Non-heat-treated	-662.1	1.532	0.069	Poor
Annealed	-583.4	0.287	0.013	Outstanding
Normalized	-602.5	0.414	0.019	Excellent
Quenched	-654.9	1.276	0.057	Moderate
Tempered	-612.8	0.596	0.027	Good

The non-heat-treated specimen showed a dual-phase structure consisting of ferrite and pearlite, where pearlite was more dominant. The ferrite appeared as light regions, while pearlite (a lamellar mixture of ferrite and cementite) appeared as dark colonies. This microstructure provided moderate strength but was prone to corrosion due to the formation of micro-galvanic cells between ferrite (anodic) and cementite (cathodic).

The microstructure of annealed specimens shows the same phase as non-heat treated. However, the structure pearlite and ferrite transformed into coarse pearlite and ferrite. Its indicating grain growth and also stress relief occur. The slower cooling rate during annealing allowed for a uniform distribution of carbon atoms, reducing dislocation density and internal stresses. As a result, the annealed specimen exhibited higher corrosion resistance due to reduced energy sites for anodic dissolution and a more homogeneous matrix.

The microstructure of normalized specimens consisted of finer ferrite and pearlite compared to the annealed one. Air cooling after normalizing refined the grain size and produced a uniform distribution of pearlite colonies. Although this structure improved mechanical strength. The finer pearlite lamellae increased the interface area between ferrite and cementite. Its produce localized electrochemical activity and slightly reduced corrosion resistance relative to the annealed sample.

The microstructure of quenched specimen shows the needle-like and acicular patterns. This morphology exhibited a martensitic microstructure. Martensite is known for its high hardness but also high internal stress. It's could accelerate corrosion initiation. Martensite phase formed due the rapid cooling which trapped carbon atoms in a supersaturated solid solution. It's resulting in a distorted lattice structure that facilitates anodic reaction sites. Consequently, the quenched specimen showed the poorest corrosion resistance among all samples.

In the tempered specimen showed a tempered martensitic or bainitic structure. It's consisting of ferrite and fine carbides. Tempering at 450°C reduced internal stress and increased ductility. It's lead to improved corrosion resistance compared to the quenched sample. However, the presence of retained carbides and incomplete stress relief still caused higher corrosion rates than in the annealed condition.

IV. CONCLUSION

The heat treatment not only changes microstructure and mechanical properties but also strongly influences corrosion behavior by altering phase distribution and internal energy states.the corrosion rate varied significantly among the treatments. The lowest corrosion rate was obtained in the annealed specimen (0.013 mmpy), while the highest occurred in the non-heat-treated (0.069 mmpy) and quenched specimens (0.057 mmpy). The annealed specimen

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demonstrated *outstanding* corrosion resistance, while the quenched one exhibited *poor* resistance due to the presence of residual stresses and martensitic phases.

Corrosion resistance improved with increasing phase uniformity and decreasing internal stress. The presence of martensite and high dislocation density increased anodic activity and accelerated corrosion, whereas ferrite-pearlite structures provided better stability in chloride-rich environments. The reduction in micro-galvanic activity between ferrite and cementite phases in the annealed steel played a crucial role in lowering the corrosion rate.

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Citation of this Article:

Susilo Adi Widyanto, Agus Suprihanto, & M Ainus Solikhin. (2025). The Effect of Heat Treatment on the Corrosion Rate of Medium Carbon Steel in Seawater from the North Coast of Java. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(11), 275-279. Article DOI https://doi.org/10.47001/IRJIET/2025.911035

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