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Enhancement of the Corrosion Resistance of Mild Steel in Marine Applications

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ABSTRACT

This study aims to improve mild steel's corrosion resistance in marine applications. Mild steel has low corrosion resistance, especially in salty conditions, so enhancing this property is required. This study aims to increase the corrosion resistance of mild steel by heat treatment processes. The specimens were heated to the temperature of 800°C, then the specimens were separated into two groups, specimens of both of the groups cooled inside a furnace (annealing), cooled in air to room temperature (normalizing), and cooled in water (quenching), then the first group of specimens was immersed in salinity of (33.9) ppt for 45 days, and the other group of specimens was immersed in salinity of (37.8) ppt for 45 days. The corrosion resistance is determined experimentally by the weight loss method, with the consideration of the effect of each parameter, such as salinity and cooling rate. The results obtained showed that corrosion resistance in the quenching process is higher than in other cooling processes in both salinities, followed by annealing and normalizing processes. In which the weight loss of the quenched specimen was (0.0057) g in a salinity of (33.9) ppt, while it was (0.0072) g in (37.8) ppt.

Keywords: Salinity, Weight loss, Corrosion resistance, Heat treatment

1. INTRODUCTION

Seawater is one of the most complex and transgressive media in the world because it includes particles, atmospheric gases, and organic and inorganic materials. Marine corrosion is influenced by a variety of interrelated parameters that include mechanical, biological, and chemical factors. The effect of these parameters on the atmospheric corrosion of carbon steel is a significant subject that has been extensively studied by several researchers throughout the years **(Alcántara et al., 2017; Eruguz et al., 2017; Wang et al., 2021).** The secret of optimizing the design of metal structures used in marine environments is to comprehend the influence of each of these parameters and factors and develop an anti-corrosion technique to enhance material efficiency **(Dhawan et al., 2020).** Corrosion is a natural phenomenon that is a degradation characteristic of metallic materials due to environmental

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interactions, such as acid, water, moisture, salt, and oil; these media lead to the occurrence of corrosion in a metal **(Anaee et al., 2021).** The percentage of carbon in steel gives different mechanical properties to the steel, such as strength, hardness, ductility, and corrosion resistance. Mild steel is low alloy with (<0.25% C) and is widely used in engineering applications, including marine applications, due to its low cost and tendency to be treated and formed **(Chigondo and Chigondo, 2016; Dwivedi et al., 2017)**. Furthermore, seawater is one of the most powerful, complex, and aggressive mediums in the world. Marine corrosion is influenced by a variety of interrelated factors, which include mechanical, biological, and chemical elements **(Refait et al., 2020)**. The secret of optimization is comprehending the effect of each of these factors to design devices and structures that can be used in marine environments and developing treated or new materials can significantly improve corrosion resistance **(Thompson, 2023)**.
(**Loto et al., 2018)** studied the effect of heat treatment process (normalizing and quenching) on corrosion resistance for 301 austenitic stainless steel in NaCl acid, and the results were analyzed by optical microscopy. The dimensions of the samples were 0.8 cm^2 and 0.91cm^2; the samples were heated inside the furnace to 1000°C and kept for 30 min. The annealed sample was cooled in air, while the quenched one was cooled in water. The results indicated that the quenched sample has more corrosion resistance than the annealed sample with respect to the concentration of NaCl. Additionally, **(Hwang and Park, 2009)** studied the influence of heat treatment processes on the corrosion resistance of duplex stainless steel. The specimens were heated to around 1050 to 1200℃, and the holding time was 30 min. Findings indicated that corrosion resistance values for austenite and ferrite phases after the treated process have better corrosion or pitting resistance at 1090℃.
Furthermore, **(Li et al., 2020)** investigated the influence of heat treatment processes on the corrosion resistance of bimetal plate (carbon steel and stainless steel) because this type of plate has a popular application in the engineering field. However, the influence of element diffusion needs to be taken into consideration when studying the evolution of corrosion resistance in carbon steel/stainless bimetal plates. Many previous studies have shown that a diffusion area exists with a certain thickness between the stainless steel and carbon steel, which allows them to bond effectively. Meanwhile, the results obtained from the experiment on the sample annealed at 700 °C showed that the higher percentage of carbon in carbon steel compared to stainless steel leads to a diffusion process between them. This process increases the carbon content in stainless steel, resulting in the lower surface of the bimetal plate's stainless steel having less corrosion resistance than that of stainless steel subjected to the same annealing conditions. Martensitic stainless steel is another type of steel in which its mechanical properties, including corrosion resistance, can be improved, which leads the author **(Isfahany et al., 2011)** to be inveterate in this field.
The experiment starts with heating the specimen in an induction furnace to a temperature between 900 to 1000 ℃, then annealing it to 700 ℃, after that cooled in air. All specimens were automatized for 30, 60, and 120 minutes at 980, 1015, and 1050°C. For one hour, then all samples were tempered at 200°C. A tempering treatment was carried out in the 200–700°C range to identify the second hardening temperature range. The results obtained show enhancements in corrosion resistance and other mechanical properties due to the heating tempering process. Metals that are printed by 3D printing technology can improve their corrosion property **(Kong et al., 2019)**.
After heat treatment, the samples at 1050℃ showed angle boundaries, and sub-grains changed, and some degree of corrosion resistance was found **(Gaggiotti et al., 2022),**while

strength dropped as a result of the decrease in dislocation density. The effect of heat treatment on corrosion properties has been studied on many materials **(Seidu and Kutelu, 2013).** They investigated this effect on low-carbon steel because this type of steel is used approximately 98% in construction.
The specimen used in this experiment had dimensions of 10×10×10 mm, was cut and polished with emery paper, and was then divided into four groups (A, B, C, and D). The samples were annealed to 920°C and held for 30 min, then cooled to ambient temperature inside the furnace, while other groups of samples were cooled in water to ambient temperature at the same heating temperature. All the samples were exposed for 21 days to HCl and NaCl as corrosive media. The weight loss technique was used to measure the difference in weight before and after immersion. The results indicate that the corrosion rate of the heat treatment process largely depends on the corrosive environment concentration. High-manganese austenitic steels are another type of steel that can develop its corrosion resistance with heat treatment processes. This type of steel is found in the agriculture and mining sectors due to its high impact and wear resistance**.**
The samples were initially cleaned using various grades of emery paper, followed by cleaning with tap water, then distilled water, and finally acetone. Thereafter, they were submerged in HCl and HNO_3 solutions for a specific period of time and then removed from the solution. The specimens were weighed on an analytical balance, and weight differences at each period were recorded. The formula W.L = (Wb – Wa) / S was used to determine the weight loss, where S is the specimen's total surface area in cm^2 ($2*\pi*r*h+2*\pi*r^2$), and Wb and Wa are the weights before and after immersion in salted water in milligrams. The results obtained from this study show that the acidic fluids greatly corroded the metals, and the corrosion rate is basically dependent on the concentration of the acid. **(Gürol and Kocaman, 2025)** investigated the corrosion resistance, which can be affected by heat treatment processes in this type of steel. The results demonstrated that annealing significantly enhanced the homogeneity of the microstructure and reduced the quantity of carbides. Additionally, the weight loss method is used by **(Ali and Fulazzaky, 2020; Usman et al., 2016)** to determine the percentage of corrosion rate or weight loss due to corrosion in a different acid.
In addition, **(Malaret, 2022; Zou et al., 2011)** studied the quantification of corrosion rate by weight loss technique based on direct contact surface area while considering some errors that happen if the area of contact is not calculated accurately. Finally, **(Tang et al., 2010)** used the weight loss method to determine the corrosion rate of the carbon steel under 90°C in H_2S concentration.

2. EXPERIMENTAL WORK

Experimental data are essential for obtaining precise and reliable results. A glass container that was separated into different chambers was designed for this purpose, and salted water with different salinities was prepared.

2.1 Materials and Sample Preparation

The specimens that were used in this experiment were mild steel. The specimens were round in shape with a length of 7-8 cm and a diameter of 10-11 mm, as shown in **Fig. 1.**

Figure 1. Glass Container and the samples

2.2 Heating Temperature

The design of the experimental work procedure was carried out according to its carbon content and then heated to above the critical temperature (723°C in the iron-carbon diagram) to ensure that the phase transportation occurs **(Pfennig, 2022; Egwuonwu et al., 2023)**. Holding time is another factor that is considered during the heating process, which depends on the geometry of the specimen to make sure the whole specimen, inside and outside, gets the same heating temperature.

2.3 Cooling Schemes

Cooling temperature consists of three different processes: (1) rapidly cooling in water, which is called quenching, (2) slow cooling in a furnace to room temperature, which is called annealing, and (3) moderate cooling in air to room temperature, which is called normalizing **(Chandra et al., 2021).** This is based on a time-temperature transformation diagram of carbon steel. The alteration in microstructure of the heat treatment process led to improved corrosion resistance of the specimen **(Caballero et al., 2005)**.

2.4 Immersion in Salted Water

The samples were divided into two groups, then immersed in a glass container within a different specific gravity of salted water for a period of time (45 days) at a constant temperature of (25°C). Group 1 immersed in 1.024 specific gravity, which equals salinity 33.9 ppt, while group 2 specimens were immersed in 1.027 specific gravity, which equals salinity 37.8 ppt. Salinity refers to the concentration of minerals and dissolved salts in water, quantified in parts per thousand (ppt) **(Hopmans et al., 2021).** On the other hand, specific gravity is a unitless quantity defined as the ratio of the density of a liquid divided by the density of water or standard substance **(Yesiller et al., 2014)**. A refractometer is used to measure the salinity and specific gravity of the water, as shown in **Fig. 2** (**Grosso, 2010**). A basic principle of working is based on light refraction theory.
Note that the Calibration process of the refractometer must be considered according to the manufacturer's instructions to ensure that the reading line is on the zero line with pure water (**Ugwu et al., 2018**).

Figure 2. Refractometer Image

2.5 Removing Samples from The Media

Samples were removed from the media (salted water) after 45 days, then the corrosive surface layer was cleaned by a grinding process and chemical method to get a smooth surface. After grinding, the samples were dried by hot air and a piece of cloth, as shown in **Fig. 3.**

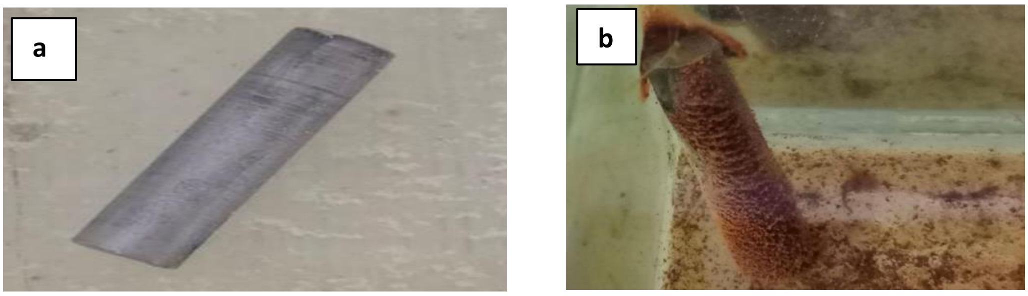

Figure 3. (a)specimen before corrosion, (b)specimen after corrosion

2.6 Calculating Weight Loss

W.L = (Wb – Wa) /S formula was used to measure the weight loss, and the quenching process is taken as an optimal case, as shown in **Table 1.**

Table 1. Weight loss for the quenching process for different salinities

Salinity (ppm)	Wb (g)	Wa (g)	S (cm^2)	W.L (g/cm^2)
33.9	26.75	26.66	15.707	0.00572
37.8	27.21	27.11	13.88	0.00720

Note:

1- The same formula was used for other cooling processes, but only the final result of (W.L) is shown in a curve.

2- Two samples were used for each case, and the average was taken as (n) for a more accurate result.

2.7 Microstructure Examination

To show the microstructure change during the heat treatment process, optical microscopy was used with (X400 magnification power). The process started with the sample preparation, then the samples were ground by a sequence of emery paper, called the grinding process. After the grinding process polishing process was performed, which was performed by a solution (Al_2O_3) (5 Micron). A special rotary device was used for both processes at different speeds. Finally, the specimens sank in the etching solution (HNO_3) with a concentration of (2% HNO_3 and 98 % Ethanol) for 10 seconds and washed with tap water.

3. RESULTS AND DISCUSSION

The influence of parameters (Salinity, heating, and cooling temperatures) on the enhancement of corrosion resistance of mild steel was studied by the experimental method. To determine percentage weight loss, a weight loss formula was used to calculate the losses in weight, before and after the experiment **(Usman et al., 2016)**. The effects of these parameters are shown graphically.

3.1 Effect of Heat Treatment Processes on (1.024) or (33.9 ppt) Salinity

In order to get a desired effect, specimens were heated to austenite temperature (above 700 °C). This is causing a phase transformation phenomenon in steel and thus leads to microstructure modification to improve corrosion resistance in steel. In this study, specimens were heated to (800 °C), followed by different cooling processes. **Fig. 4** shows the influence of different heat treatments on (1.024) salinity. It can be seen that the quenching process gives the best result, which is the minimum weight loss (0.00572 g). This effect is back to the (TTT) diagram of steel in which different microstructures are produced through cooling processes **(Handoko et al., 2018; Nishimoto et al., 2023)**.

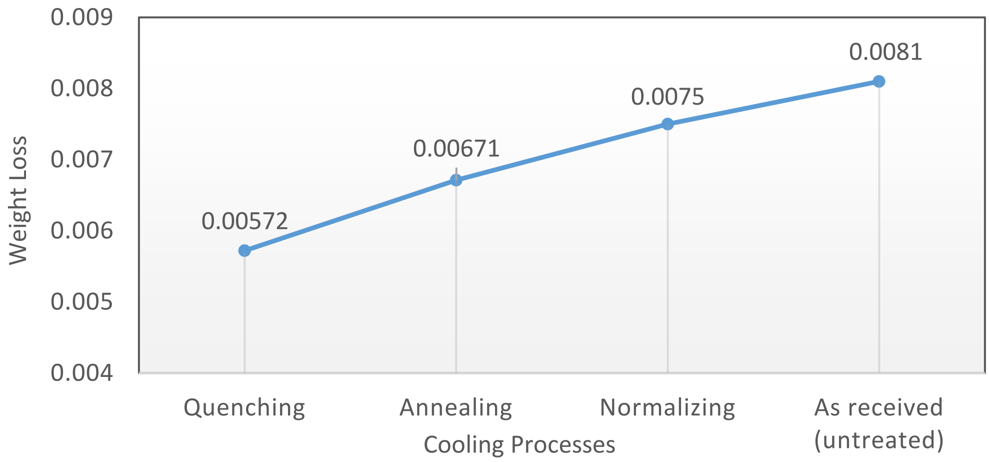

Figure 4. Effect of heat treatment process in (1.024) specific gravity or (33.9) ppt on weight loss

In the quenching process with fast cooling (martensite) is formed as shown in **Fig.5.** The formation of martensite starts when unstable austenite transforms to martensite when the formation process is completed. Additionally, grain size has a great effect on corrosion resistance. Refined microstructure martensitic phase formed by rapid cooling has a fine, uniform microstructure that can reduce the number of local galvanic cells; refined or small grain size is often responsible for corrosion initiation **(Alharbi et al., 2024).**

Annealing process, which is heated above austenite temperature, followed by cooling in a furnace, has lower corrosion resistance or higher weight loss by (0.00671 g). This is because the annealing process may increase the steel's sensitivity to oxidation and corrosion. The annealing process produces a larger grain size, changing from austenite to the pearlite phase. Pearlite consists of ferrite and cementite forming layers or bands, because of this process has a low cooling rate, allowing the growth of grains, which produce coarse or large grain size. This type of microstructure has high ductility but low corrosion resistance **(Adham et al., 2018; Chandra et al., 2021)**.

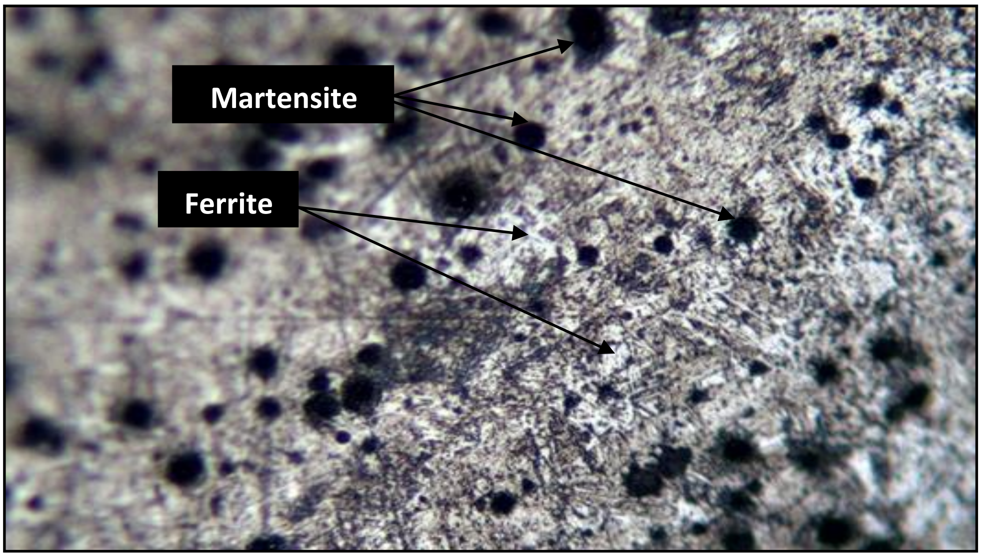

Figure 5. Microstructure under optical microscopy (Martensite)

Finally, the normalizing process has a minimum effect on corrosion resistance close to that of untreated samples with (0.0075 g). Normalizing process with binate microstructure has a faster cooling rate than the annealing process, which leads to refining the grain structure, which improves the mechanical properties, such as strength, but has less effect on the corrosion resistance of carbon steel.

3.2 Effect of Heat Treatment Processes on (1.027) or (37.8 ppt) Salinity

The results in **Fig.6.** show that with increasing the salinity from (33.9 to 37.8) ppt, the metal becomes more sensitive to corrosion resistance in (quenching, annealing, and normalizing) processes. That means weight loss in the quenching process increased from (0.00572 g to 0.0072 g), in the annealing process jumped from (0.00671g to 0.077 g) and in the normalizing process jumped from (0.0075g to 0.008 g).

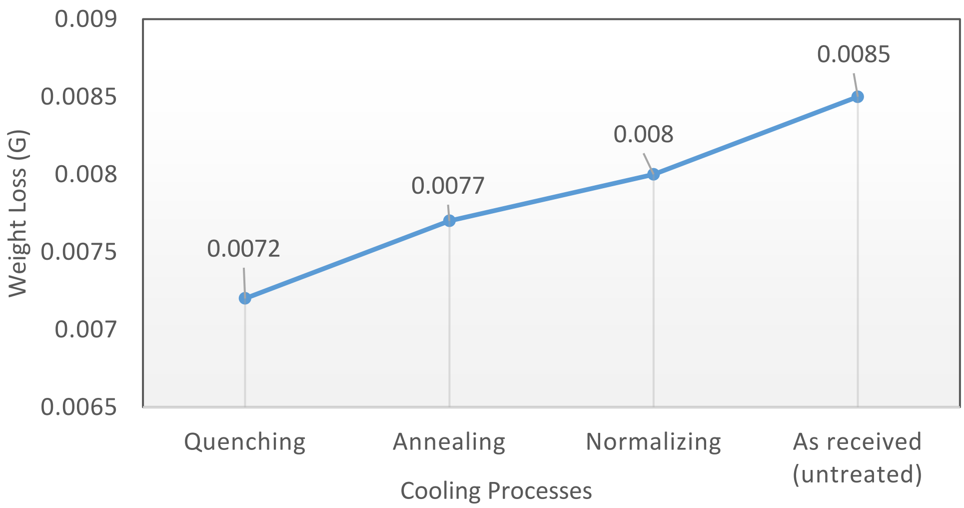

Figure 6. Effect of heat treatment process in (1.027) specific gravity or (37.8) ppt on weight loss

3.3 Effect of Salinity on Corrosion Resistance

The results obtained from the experiments are presented in **Fig. 7.** illustrates that the concentration of salt in water has a great influence on the corrosion phenomenon with respect to the cooling schemes, which is back to when the salt dissolved in water forms ions (chloride and sodium ions). Corrosion may result from these ions' interactions with the steel and its protective oxide coating. This may be due to the ions' attack on the oxide layer on mild steel, which protects the steel from degradation and rust.
Additionally, Saltwater contains a higher concentration of dissolved ions, especially with a higher level of salt concentration, which enhances its electrical conductivity. Higher electrical conductivity in carbon steel facilitates more effective electron transfer during corrosion, hence increasing the corrosion rate, so increasing corrosion resistance for carbon steel is necessary to overcome this phenomenon **(Fan et al., 2024).**

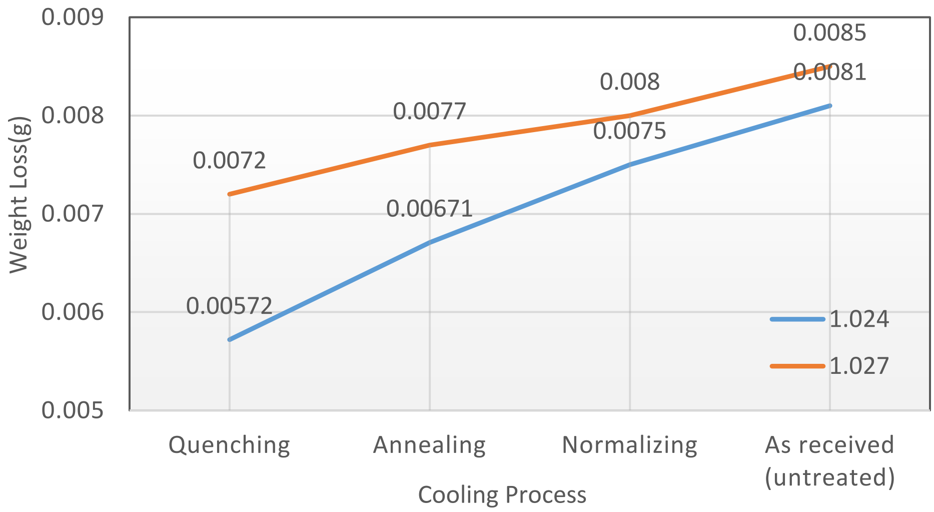

Figure 7. Effect of heat treatment process and weight loss in two different salinities

4. CONCLUSIONS

This experiment investigates the effect of parameters (cooling schemes, salinity) on the corrosion resistance of mild steel. Based on the findings, the conclusion may be summed up as follows:

1- The quenching process has a greater effect among other cooling processes in both salinities (with less weight loss).
2- The annealing process has lower corrosion resistance than the quenching process, followed by the normalizing process.
3- The corrosion resistance of mild steel is enhanced by the cooling rate during the heat treatment procedure.
4- In general, as salinity increases, weight loss increases, and corrosion resistance decreases.

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Credits Authorship Contribution Statements

Ihsan Jabar Khamas: writing original draft, experimental work, and results. Hawre Fatah Amin: writing introduction and abstract.

Declaration of Competing Interests

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

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تحسين مقاومة التآكل للصلب المعتدل في التطبيقات البحرية

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الخلاصة

تهدف هذه التجربة إلى تحسين مقاومة الفولاذ الطري للتآكل في التطبيقات البحرية. يتمتع الفولاذ الطري بمقاومة منخفضة للتآكل خاصة في الظروف المالحة، لذا فإن تعزيز هذه الخاصية مطلوبة. تهدف دراسة التجربة هذه إلى زيادة مقاومة الفولاذ الطري للتآكل من خلال عمليات المعالجة الحرارية. تم تسخين العينات إلى درجة حرارة (٨٠٠) درجة مئوية، ثم تم فصل العينات إلى مجموعتين، تم تبريد كلتا المجموعتين داخل الفرن (التلدين)، وتبريدها في الهواء إلى درجة حرارة الغرفة (التطبيع)، وتبريدها في الماء (التقسية)، ثم تم غمر المجموعة الأولى من العينات في ملوحة (٣٣.٩) جزء في الألف لمدة ٤٥ يومًا، ومجموعة أخرى من العينات مغمورة في ملوحة (٣٧.٨) جزء في الألف لمدة ٤٥ يومًا. تم تحديد مقاومة التآكل تجريبياً بطريقة فقدان الوزن، مع مراعاة تأثير كل من الملوحة ومعدل التبريد. أظهرت النتائج التي تم الحصول عليها أن مقاومة التآكل في عملية التبريد(التقسية) لها مقاومة أعلى مقارنة بعمليات التبريد الأخرى في كل من الملوحتين، تليها عمليات التلدين والتطبيع. حيث بلغ فقدان الوزن للعينة المقساة (٠.٠٠٥٧) جرام في ملوحة (٣٣.٩) جزء بالألف بينما بلغ (٠،٠٠٧٢) جرام في (٣٧.٨) جزء بالألف.

الكلمات المفتاحية: الملوحة، فقدان الوزن، مقاومة التآكل، المعالجة الحرارية