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Effect of Heat Treatment on Corrosion Rate of Low-Carbon Steel Plates Welded by SMAW

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Abstract

Corrosion is one of the main problems materials face, leading to degradation and loss of mechanical properties. Welding also deforms the heat-affected zone (HAZ), altering metal properties, requiring improved connections through heat treatment. Two Plates from (DIN 17100 St 60-2) measuring 42×20×6 mm with a V-groove shape at a 74-degree angle were welded using shielded metal arc welding (SMAW), exposure to heat treatment process (annealing and tempering) with different holding times of 0.5, 1, 1.5, and 2 hours subsequently, the samples immersed in 5M HCL acidic and brine solution. Vickers microhardness was assessed before and after immersion of the samples in the two solutions; he results were analyzed using SPSS. The results indicate that the heat treatment technique enhances hardness after corrosion. The most effective treatment for the acidic and brine solutions with the least decrease in hardness was 2-hour annealing, followed by oven cooling, resulting in corrosion rates of 1.249 for the acidic solution and 0.598 for the brine solution. Due to the importance of corrosion in the industry, this research aims to improve the corrosion resistance and hardness of welded low-carbon steel.

Keywords: Corrosion Rate, Heat Treatment, Low Carbon Steel, Shielded Metal Arc Welding (SMAW), Vickers Microhardness.

1. Introduction

Corrosion and ways to prevent it are costly engineering problems that grow in relevance as engineering businesses develop. Most engineering materials corrode due to their environment. This interaction influences the material's characteristics, leading to detrimental effects and altering its mechanical and physical properties. Iron or steel is the most commonly corroded metal [1]. Low-carbon steel, often known as mild steel, is a metallic alloy composed primarily of iron and carbon, used in structural applications for petroleum extraction and refining, pipelines, and various industries, including oil and gas storage tanks and transportation pipes, due to its moderate strength, exceptional weldability, and formability. It is also widely used in saline regions, despite its high corrosion rate, due to its availability and good mechanical properties [2]-[4]. Low-carbon steel is the most commonly used steel in welding due to its good mechanical properties [5]-[7]. Welding is a common method of joining metals, and SMAW is the most widely used. Because of Welding changes to the metal base and its microstructure, especially in the heat-affected zone (HAZ), corrosion resistance is reduced. Heat treatment is used to improve this region; mild steel is susceptible to corrosion. [5], [8], corrosion destroys welded steel infrastructure, especially in oil and gas pipelines [9], and weakens metals due to oxidation caused by the surrounding environment, which includes water, acids, bases, salts, oil, and metal polishes [10]. Given that corrosion causes significant damage and financial losses, mechanical characteristics must be improved to reduce corrosion. One way to do so is through heat treatment. Heat treatment enhances the corrosion resistance and mechanical and microstructural characteristics of carbon steel. By manipulating the temperature of metal heating, holding time, and cooling to reduce residual stress from welding [11]-[13]. Given its importance, the corrosion rate of carbon steel is examined. Majeed et al. [14] examined the impact of heat treatments (annealing cooled with an oven, normalizing cooled with air, and hardening cooled with oil and water) on the corrosion of low-carbon steel in sulfuric acid solutions at 850ºC for 1 hr. for 3 days. Using Stat Graphics/Experimental Design, estimated Acid and T corrosion rates for each heat treatment. R-squared shows that fitted models explain 81-93% corrosion rate. The optimal corrosion rate for the samples is normalized. Hamid et al. [15] examined the effects of heat treatment on the corrosion of carbon steel with different carbon contents (0.08, 0.15, 0.2, 0.3, 0.4%) using brine (50 g salt in 100 mL water) and Tafel polarization for 30 min. Increased carbon content lowered corrosion durability in samples without heat treatment, while annealing (850℃ for 17 minutes and with furnace cooling) reduced corrosion resistance and increased surface roughness. Rachmawati and S. Ma'arif [16] examined the corrosion rates of 3% KCL- and 10% NaOH-treated, heat-treated at 300℃, and untreated ST37 mild steel welded joints over 100, 200, 300, and 400 hours. Heat-treated specimens after welding have a lower corrosion rate. Corrosion with 3% KCL, more than 10% NaOH alkaline. Mohamed et al. [17] studied the impact of an annealing heat treatment on the microstructure and corrosion resistance of SMAW- and GMW-welded duplex stainless steel after 25 minutes at 1050 ◦C, followed by water cooling. The samples were immersed in 20% KOH for 10-15 s using electrolytic etching. The decreased ferrite volume percentage in heat-treated welded joints reduced the ultimate tensile strength, but they had greater corrosion resistance and weld-zone hardness than the base alloy. Lipinski [18] examined the weight loss of 5 mm-thick S235JR steel in 2.5% sulfuric acid in distilled water to test its corrosion resistance after normalizing and annealing at 860°C and 1100°C for 8 and 30 minutes, respectively, and chilling in air. Tested steel shows continuous deterioration in both corrosive situations. Suprihanto and Wibowo [19] examined the effect of heat treatment on the corrosion rate of AISI 1020 steel welded using Shielded Metal Arc Welding (SMAW) in seawater. Post-weld heat Treatment (PWHT) is conducted at 400, 500, and 600 °C for 1, 2, and 3 hours, respectively. Tests show that higher temperatures and longer holding times (600℃ with 3 hr.) provide a more homogeneous microstructure, lower hardness, and lower corrosion rates. Reduced corrosion rates due to increased uniformity of the microstructure and the reduction in residual stress.

Welding deforms low-carbon steel joints in the heat-affected zone (HAZ), changing metal corrosion rates and adversely affecting oil pipes, pressure vessel components, and engineering industries that require improved connections. Heat treatment improves welded joint hardness and corrosion resistance, and previous studies focused on constant heat-treatment conditions (temperature and holding time) without examining the effect of varying holding time for the same heat treatment (temperature) on corrosion rate during short soaking periods. This work examined hardness values and corrosion rates (important properties in the petroleum industry) after annealing and tempering with different holding times, and during long soaking periods with periodic checks every week.

2. Experimental Work

2.1. Materials and Practical Procedures

A 6mm-thick plate of low-carbon steel (DIN17100 St 60-2) was cut and prepared using the DURMA SB 3013 press machine and welded using shield metal arc welding (SMAW) with Electrode E-6013 from the middle as a single V-groove with 74°. After the welding process, the samples were shaped for hardness and corrosion tests in accordance with ASME IX standards, then cleaned using a milling machine. Sample dimensions are shown in Fig. 1. Table 1 and 2 describes the Chemical composition of the metal and the used electrodes.

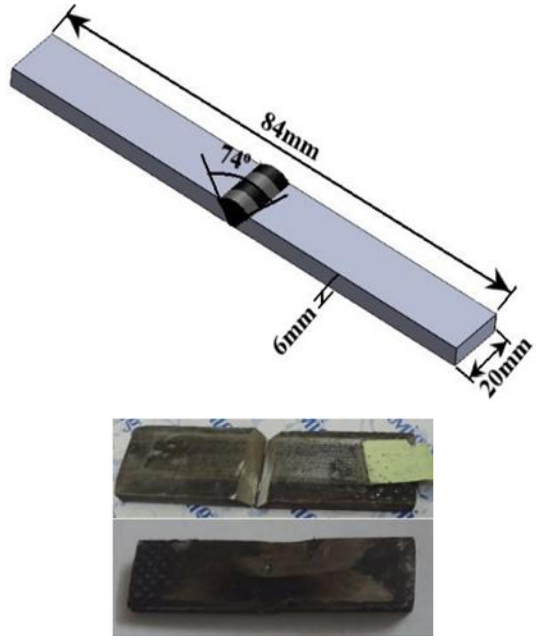

Figure 1. The sample dimensions.

Table 1. Chemical compositions for low-carbon steel (DIN 17100 St 60-2) were done at SIER.

C	Mo	P	S	Mn
0.1%	0.0027%	0.013%	0.0016%	0.53%
Si	**Cr**	**Ni**	**Cu**	**Fe**
0.19%	0.018%	0.024%	0.005%	Bal

Table 2. Chemical composition for Electrode 6013. [20]

C	Mn	Si	P	S	Fe
0.08%	0.45%	0.18%	0.014%	0.012%	Bal

Then, the samples were subjected to a set of different thermal treatments in terms of temperature and heating time after welding by using the electrical furnace (Nabertherm Gmblt 30-3000℃ made in Germany) shown in Fig. 2.

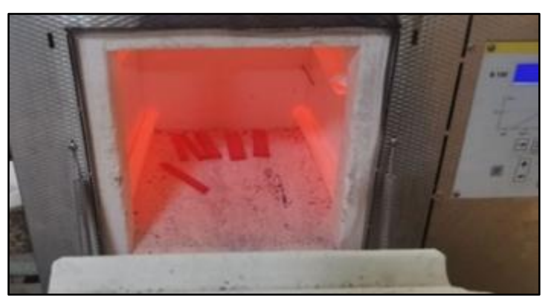

Figure 2. The furnace.

The processes used in this work are an annealing process at temperatures of 900℃ with holding times of 0.5, 1 hour, cooling using air, and 1.5, 2 hours of cooling using the oven, and a tempering process at temperatures 650°C after quenching at a temperature 820 ℃ with holding times 0.5, 1, 1.5, 2 hours and cooling using air. Fig. 3 shows the heat treatment process used in this work.

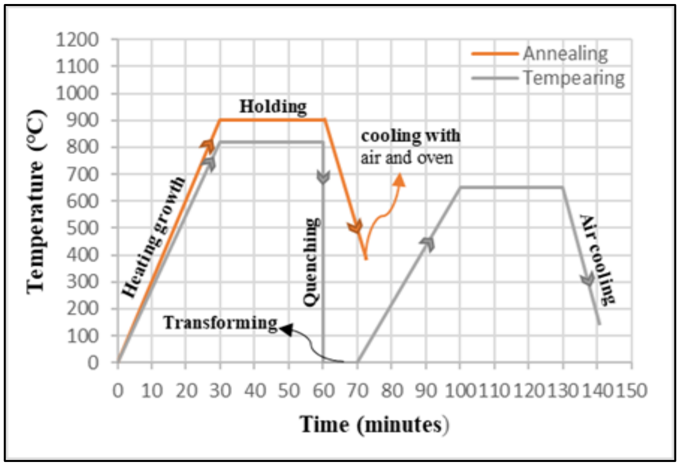

Figure 3. The heat treatment process.

Fig. 3 illustrates the heat-treatment procedure, in which the temperature increases gradually from 0 to the temperature required for each treatment (Annealing and tempering after quenching). The temperature is then maintained for 0.5 hours before being cooled to room temperature with air. The processors mentioned above follow the same procedure, with holding times of 1, 1.5, and 2 hours, respectively.

2.2. Tests

2.2.1. Corrosion rate

Is the rate of decrease in weight over a unit of area and a unit of time called corrosion rate can be measured by the weight loss method, which is summed up by immersing a weighed sample of the metal in the corrosive medium for a known period of time and then weighing it after this period has passed, after removing it from the corrosive medium and washing it well with plain water, distilled water, and alcohol. And either for drying purposes, use a metal drying device. A corrosion test was conducted on low-carbon steel samples in two groups to compare results. Group one samples were heat-treated after welding, and group two samples were only welded (without heat treatment). Then, samples were immersed for 126 days with periodic checks every week (7 days). At room temperature in two solutions: a 5M HCL acidic solution (0.2 L HCL with 2 L distilled water) and a brine solution (3.5 g salt with 1 L distilled water). The solution's percentage is determined, according to (1) [21].

$$C_1 \times V_1 = C_2 \times V_2 \quad (1)$$

Where: C1 Original concentration 38 Mol for an acidic solution, V1 volume of acidic solution, C2 Required concentration 5 Mol for an acidic solution, V2 Required volume 1.5 L for an acidic solution. Fig. 4 describes the tools that are used for a corrosion test.

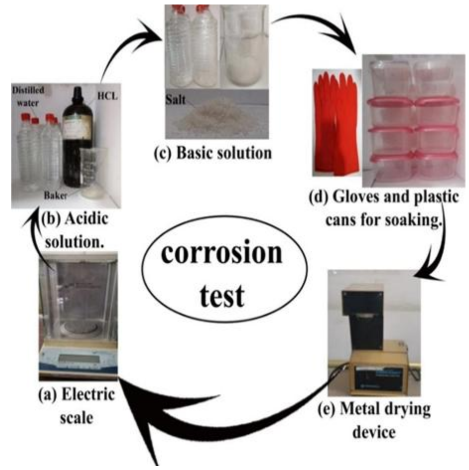

Figure 4. The tools that are used for a corrosion test.

2.2.2. Viker micro-hardness

Micro-hardness tests were performed on specimens before and after the corrosion test for all groups to study the effects of heat treatment and corrosion on welded low-carbon steel using a Vickers micro-hardness tester with a load of 2 N and a dwell time of 10 seconds. The Viker micro-hardness tester used is shown in Fig. 5.

Figure 5. Micro-hardness tester.

2.3. Gravimetric Technique

The gravimetric methodology, commonly referred to as the Weight-loss method, was used to determine the weight-loss and corrosion rates. The specimens were weighed before exposure to the corrosive liquid. Subsequently, the test specimen was cleaned to remove surface contaminants. The cleaning procedure includes using ethanol and distilled water before weighing. The method was scheduled for 126 days, during which the specimen was weighed weekly (every 7 days) [4], [7]. The corrosion rate can be calculated using (2) [7].

$$R_{corr.} = \frac{K \times \Delta W}{\rho \times A \times t} \quad (2)$$

Where: R corr. is the corrosion rate (cm/day), K is 8.76×104 constant for unit conversion, ΔW is the Change in mass (g), ρ is the density of low carbon steel 7.86 (g/cm^3), A is the Area of exposed surface in cm^2, and t is the time in days (126 days).

3. Results

3.1. Corrosion Test

Table 3 displays the overall corrosion rate for an acidic and a brine solution after 126 days, determined using a mass-loss approach. Results show that the total corrosion rate increases after welding in both solutions (acidic and brine), rising from 2.026 to 2.322 and from 1.634 to 1.944, respectively, compared with the base metal. This increase was due to deformation from welding, the addition of another metal (welding filler) different from the original metal, leading to a difference in the electrical potential, as well as residual stresses from the welding operations and subsequent corrosion. However, after heat treatment (annealing and tempering), the corrosion rate decreased in both solutions The most effective treatment for the HCL acidic solution was annealing for 2 hours with a cooling process using an oven because this process removes or reduces residual stresses from welding operations, resulting in a corrosion rate of 1.249 (enhanced by 46.21% compared with just a welded sample). For the brine solution, the best treatment was also annealing for 2 hours, resulting in a corrosion rate of 0.598 (74.246% higher than the welded sample) upon cooling in an oven. Carbon steel corrodes in non-oxidizing acids, producing hydrogen gas, especially in hydrochloric acid, which is more effective at corroding iron than other substances. HCl acid exhibits a higher corrosion rate compared to brine solution because HCl is monoprotic, leading to a greater level of dissociation in water due to the presence of many small-sized areas that act as positive and negative electrodes on the surface of the metal, including impurities, the direction of the grains, local stresses, and changes in the surrounding environment. All these factors accelerate the corrosion process. In sodium chloride solution (brine), hydrogen gas is released very slowly, forming a hydrogen layer that covers the metal surface and slows the reaction. Fig. 6 and Fig. 7 display the corrosion rate over time for acidic and brine solutions, respectively, as calculated using (2).

Table 3. Total corrosion rate.

Pro. And Temperature (T)	Cooling type	Holding time (hr.)	Corrosion rate for acidic (cm/days)	Corrosion rate for brine (cm/days)
Base	-----	-----	2.026	1.634
J. W.	-----	-----	۲,۳22	1.944
A. 900(°C)	Air	0.5	1.641	1.02
		1	1.309	0.934
	Oven	1.5	1.287	0.791
		2	1.249	0.598
T. 650(°C)	Air	0.5	3.305	1.02
		1	2.474	0.961
		1.5	2.157	0.967
		2	1.673	0.965

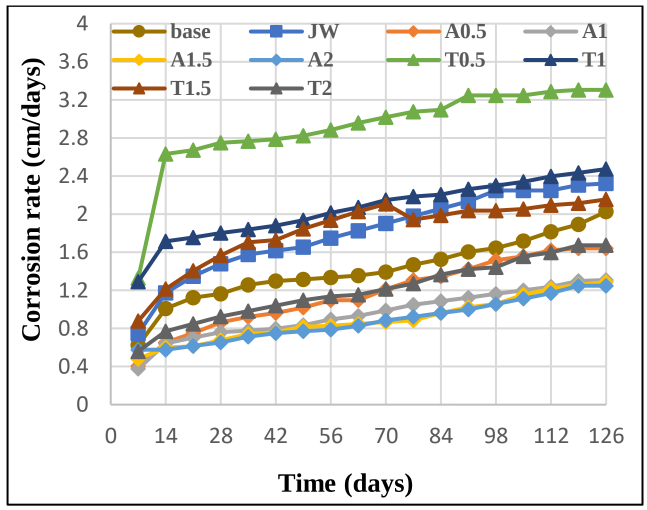

Figure 6. Corrosion rate over time (every 7 days) in an acidic solution

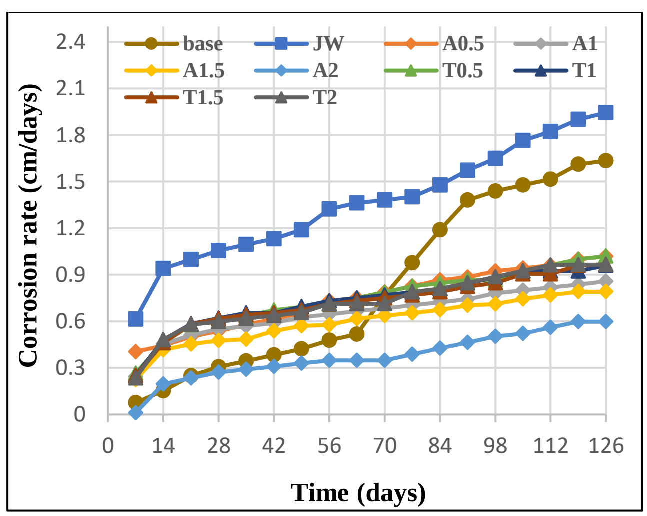

Figure 7. Corrosion rate over time (every 7 days) for a brine solution.

3.2. Hardness Test

Insert tables after they are cited in the text. Table 4 outlines the Vickers hardness values before and after a corrosion test using HCL acidic solution. The hardness values decreased after corrosion due to deformation caused by the corrosion process. The most significant decrease in hardness was observed in the welded samples (not heat-treated samples). After the heat-treatment process, the hardness loss after corrosion decreased, and the lowest loss in hardness occurred during the annealing process with a holding time of 2 hours and cooling in an oven (after the heat-treatment process). Fig. 8 displays the hardness values before and after corrosion in HCl solution.

Table 4. Vickers microhardness results before and after corrosion for an acidic solution.

Pro.	Cooling type	Holding time (hr.)	HV before Corrosion (N/mm^2)	HV After Corrosion (N/mm^2)
J.W.	----	----	230	210.9
A.	Air	0.5	187.5	175.9
900		1	173.8	163.3
℃	Oven	1.5	199	185.9
		2	219.9	210.3
T.	Air	0.5	167.8	156.2
650		1	162.0	151.3
℃		1.5	218.9	200.7
		2	157.2	146.4

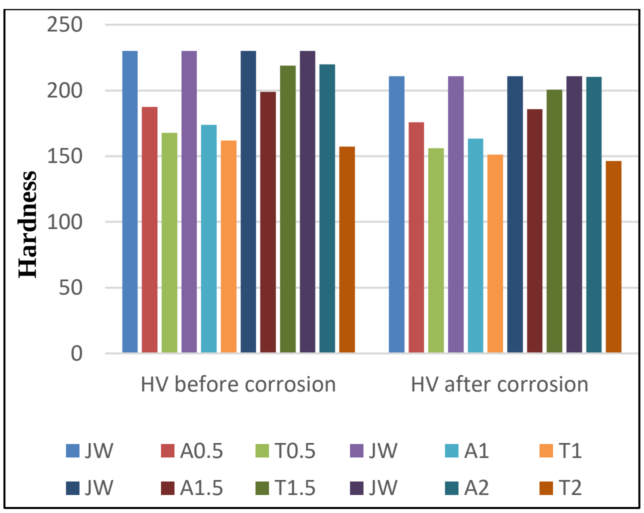

Figure 8. VH before and after corrosion test for an acidic solution.

Table 5 shows the Vickers hardness values before and after a corrosion test with brine solution. Hardness values decreased after corrosion due to deformation induced by the corrosion process. The most significant decrease in hardness was observed in welded samples (not heat-treated samples). After heat treatment, the loss of hardness during corrosion decreased, and the lowest reduction in hardness occurred during annealing with a 2-hour holding time and oven cooling. Fig. 9 shows the hardness values before and after corrosion in the brine solution.

Table 5. Vickers microhardness results before and after corrosion for brine solution.

Pro.	Cooling type	Holding time (hr.)	HV before Corrosion (N/mm^2)	HV after Corrosion (N/mm^2)
J.W.	----	----	230.3	204.4
A.	Air	0.5	188.5	178.5
900		1	173.8	168.8
℃	Oven	1.5	197.1	189.2
		2	213.2	208.3
T.	Air	0.5	169.8	159.8
650		1	176.5	162.7
℃		1.5	218.3	202.3
		2	157.8	146.4

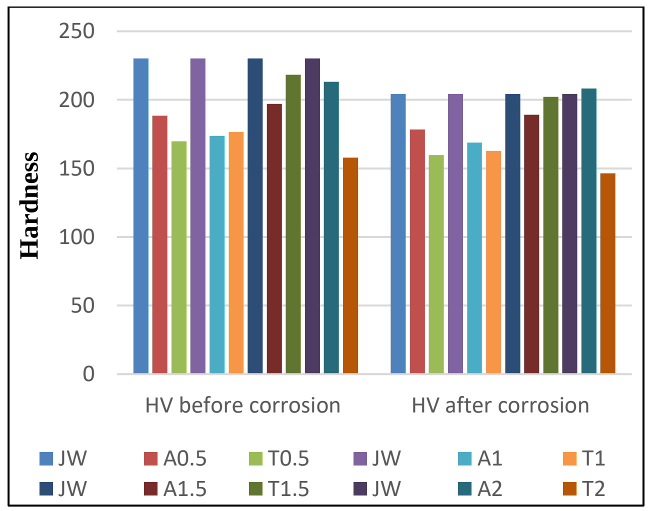

Figure 9. VH before and after corrosion test for brine solution.

3.3 Statistical Analysis

To support the results, the SPSS program was used to analyze the corrosion and hardness data. Table 6 describes the outcome of the ANOVA test, where (Sig) is the significance of the result; it is less than 0.03, indicating the results are significant at the 90% confidence level. From the ANOVA test, the mean corrosion rate during the Annealing process was lower than during the tempering process, as shown in Fig. 10. Therefore, according to the (smaller is better) criterion, the annealing process has the best corrosion resistance at 2 hr.

Table 6. Statistical analysis of corrosion rate for an acidic solution.

Corrosion rate	S. S.	df	M. S.	F	Sig.
Between Groups	2.125	1	2.125	8.439	0.027
Within Groups	1.511	6	0.252		
Total	3.636	7			

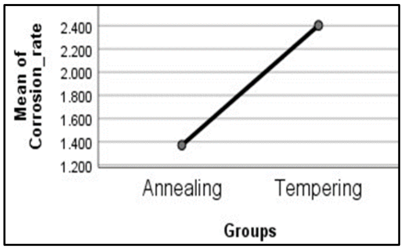

Figure 10. The mean of the corrosion rate for an acidic solution.

Table 7 describes the result of the ANOVA test. Sig., it is greater than 0.03, which means the results are not practical due to the difference between the results being slight (this result is typical due to the corrosion in brine being less than in acidic solutions). According to the condition (smaller is better), the Annealing process had the smallest mean corrosion rate, with the best corrosion value at a holding time of 2 hr., as shown in Fig. 11.

Table 7. Statistical analysis of corrosion rate for brine solution.

Corrosion rate	S. S.	df	M. S.	F	Sig.
Between Groups	0.041	1	0.041	2.332	0.178
Within Groups	0.104	6	0.017		
Total	0.145	7			

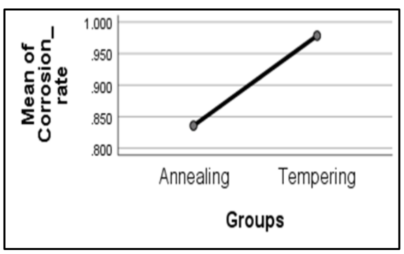

Figure 11. The mean of the corrosion rate for the brine solution.

For the hardness test, Table 8 presents the ANOVA results for hardness after the corrosion test. The (Sig) is greater than 0.03, indicating the results are not effective because the difference between the results is slight (F). According to the (the larger the better) condition, it can be used to choose the best value from the results. The annealing process had a higher mean hardness, with the best value at 2 hr., as shown in Fig. 12.

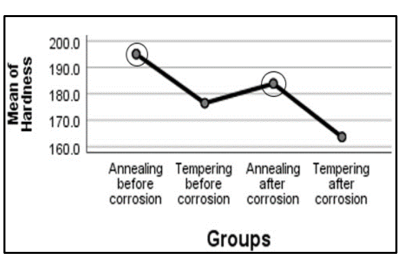

Figure 12. The mean of hardness after corrosion using an acidic solution.

Table 9 describes the result of the ANOVA test for hardness after the corrosion test. The (Sig) is greater than 0.03, indicating the results are not effective because the difference between the results is slight (F). According to the (the larger the better) condition, it can be used to choose the best value from the results. The annealing process had a higher mean hardness, with the best value at 2 hr., as shown in Fig. 13.

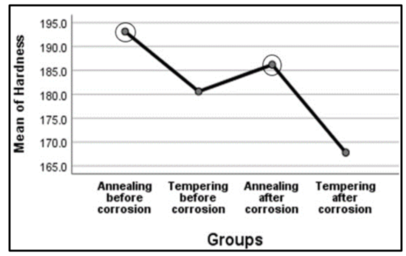

Figure 13. The mean of hardness after corrosion using a brine solution.

Table 8. Statistical analysis of hardness after corrosion in acidic solution.

Hardness	S. S.	df	M. S.	F	Sig.
Between Groups	2083.34	3	694.44	1.25	0.335
Within Groups	6665.47	12	555.45		
Total	8748.82	15			

Table 9. Statistical analysis of hardness after corrosion in brine solution.

Hardness	S. S.	df	M. S.	F	Sig.
Between Groups	1382.187	3	460.73	1.01	0.423
Within Groups	5485.910	12	457.16		
Total	6868.097	15			

4. Conclusions

Corrosion occurs by direct chemical action when the metal enters into a chemical reaction with other elements, such as oxygen and chlorine, to form a non-metallic compound. Therefore, the corrosion media can take many forms, from residual water to strong acids or salt water. The results can be concluded.

1. The welding process increased the corrosion rate and decreased the hardness value for low-carbon steel.
2. HCl acid exhibits a higher corrosion rate compared to the brine solution.
3. The heat treatment process reduces corrosion by 46.21% and 74.246% in acidic and brine environments, respectively, thereby enhancing the hardness of welded low-carbon steel during annealing with a long holding time.
4. The statistical analysis results match the operation results to within 99%.

5. For more study in the future, it is possible to study the same metal and conditions (welding methods, heat treatments, and soaking periods) with a group of different acids, study their effect on the metal and its resistance to corrosion after heat treatments, and use the SPSS (Tukey method) to analyze the differences between solutions at the same condition for each heat treatment.

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Abbreviations

A	Annealing
J. W.	Just welded
N	Normalizing
Pro.	Process
Q	Quenching
SIER	State Company for Inspection and Engineering Rehabilitation
T	Tempering
HV	Vickers hardness

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Haneen Alaa Abdel-hade applied the theory and performed the computations.

Awatif Mustafa Ali proposed the research problem.

Both authors discussed the results and contributed to the final manuscript.

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