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Study the corrosion behavior of low-carbon steel weldments immersed in tap water

Zenaa Moyaser Abid, Qays Hazim Ismael, and Mohammed Shaalan Abed Fathi*

Department of Mechanical Engineering, College of Engineering, University of Mosul, 41002 Mosul, Iraq

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ABSTRACT

Corrosion is one of the main sources of failure for metals and alloys, thus it is a major engineering problem. Engineers must consider the corrosion of metals in different environments when designing engineering parts. Metals tend to corrode in different media; they show different behaviors due to differences in chemical composition and the severity of the corrosive medium. In tap water, the corrosion of mild steel products is an electrochemical phenomenon that includes two reactions: the dissolving of iron (anodic) and the reduction of oxygen (cathodic). This work observes the corrosion behavior of welded low-carbon steel by Friction Welding (FW), Shielded Metal Arc Welding (SMAW) , and MIG welding techniques using immersion tests in tap water at different periods. The results revealed that while the corrosion rate of Base Metal (BM) increases, it reaches a nearly steady state in the friction-welded and SMAW-welded samples. The difference in the corrosion rate of the welded samples can be attributed to changes in the concentrations of Cl^- and $CaCO_3$,as well as the pH values of the corrosive mediums. Pits could be observed in the microstructure of the nugget zone for all weldments.

1. Introduction

The corrosion of mild steel products in tap water is an electrochemical phenomenon that leads to the formation of Fe ions (Fe^{+2}) as a result of the dissolving of iron (anodic reaction) and the formation of hydroxide ions (OH^-) due to the reduction of oxygen (cathodic reaction) [1]. The anodic and cathodic reactions are [2][3]:

$$Fe \rightarrow Fe^{+2} + 2e^- \quad (1)$$

$$O_2 + H_2O + 4e^- \rightarrow 4OH^- \quad (2)$$

The iron ions produced from the anodic reaction react with the hydroxide ions produced from the cathodic reaction to form rust (hydrous iron oxides). Welding joints are produced with different techniques using heat and/or pressure [4]. These joints are subjected to different types of corrosion due to the microstructural changes during the welding and many other factors. According to Yang et al [5], the corrosion occurs around the weld metal and the Heat Affected Zone (HAZ). Some of the corrosion types in weldments are:

1. Galvanic corrosion: due to the improper selection of filler material or microstructural changes along a workpiece which ends in the corrosion of HAZ [6].
2. Intergranular corrosion: grain boundaries become electrochemically different from their adjacent regions inside the grain. This induces a, mostly, microscopical level of galvanic corrosion between the grains and their boundaries [7].

* *Corresponding author.*
E-mail address: mohammedfathi@uomosul.edu.iq (Mohammed Saalan Abed Fathi)

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Nomenclature:

HAZ	Heat-affected Zone	*FCAW*	*Flux-cored arc welding*
PWHT	Post-weld heat treatment	TDS	Total dissolved solids
MIG	Metal inert gas	W	Weight loss (mg)
TIG	Tungsten inert gas	A	*Total area of exposure(in²)*
SMAW	Shielded metal arc welding	T	*Exposure time in hours*
FW	Friction welding	D	*density in gram/cm³*
GMAW	Gas metal arc welding	mpy	*Mills per year*
SEM/EDX	Scanning electron microscopy/X-ray diffract meter		
SAW	Submerged arc welding		

3. Pitting corrosion: non-uniformity in structure or mechanical damage in the coating layer. or the oxide layer[8].

There are several methods for controlling the external and internal corrosion deterioration of metals: cathodic protection, coatings, corrosion inhibitors, and medium corrosivity modification.[9][10]. Corrosion may occur due to the emergence of many serious security risks, which are manifested in the reduced strength of the parts not only due to loss of material but also by breaking bonds in the material. [11] It is not possible with steel structures especially welded ones to completely prevent corrosion phenomenon. There is a risk of formation of galvanic cells due to chemical differences between the base metal and the weld metal. Numerous problems occur during the welding process due to the heat input and other welding parameters. The welding process affects the structure of the workpiece. When a welded structure is subjected to water containing corrosion-aggressive ions such as Cl ions, corrosion occurs quickly and severely [12]**.** Galvanic cells are formed in welded joints which speed up the corrosion process. Corrosion attack also tends to be more intense in places with a concentration of mechanical stress, a broken surface, or in crevices. In aqueous environments, the dissolved chemicals increase the amounts of oxygen which can accelerate the corrosion process. [9,11,13-15]**.** It is difficult to say why welds corrode. However, one or more of the following factors influence the corrosion of welded joints[16].

- Fabrication method
- Welding design
- Welding practice
- Moisture pollution
- Organic or inorganic chemical types
- Surface oxidation and scale
- Welding defects

2. literature survey

A metal corrodes if it undergoes chemical interactions with its environment, which causes it to deteriorate. The rate of corrosion depends on the type of metal used and the environment, particularly the gases that come into contact with the metal [17]. Corrosion rates for steels have been the subject of several studies, and other welding materials have received less attention. Hussein [18] investigated how corrosion would behave in a Tengestin Inert Gas (TIG) - welded low carbon steel (AISI 1020) joint utilizing variable DC and constant voltage. All samples were processed electrochemically in a solution of 3.5% NaCl. Shot peening technique compared to welded connections without shot peening, leading to a reduced incidence of corrosion of the lingering compressive tensions that the shot peening operation produces. **T**he finest outcomes are obtained when the number of welds and welding current is reduced to achieve the desired heat input. the results showed that corrosion resistance improved by using the shot peening technique. Hussin and CheLah [19] studied the effect of welding type (SMAW and GMAW) on the corrosion rate of mild steel compounds immersed in 6 moles of HCL acid. The results were compared by analyzing SEM/EDX microstructures. The corrosion rate decreased with increasing the exposure time for SMAW samples compared with GMAW samples. Sang-Jin Ko et al. [20] investigated the effect of corrosion in hot water on the mechanical characteristics of a welded pipe made from carbon steel. Potentiodynamic tests were carried out to assess the corrosion qualities, and a galvanostatic test was employed to speed up corrosion. Corrosion caused a decline in the mechanical properties of the welded carbon steel pipe, as observed by the microstructures and stress intensity factor estimates, with longer aging times, the mode of fracture shifted from ductile to brittle.

S. A. Sulaiman et al [21] studied the corrosion rates on different types of mild steel welding joints (lap joint, butt joint, and edge joint) using SMAW, after they were immersed in Sodium Chloride NaCl, HCl, natural seawater, and distilled water for periods ranged from 30 to 50 days. The results showed that butt joints suffered from the highest corrosion rate than lap joints and edge joints.

Shian and Razak [22] investigated the corrosion behavior of welded low-carbon steel joints in a synthetic seawater environment with 3.5 wt.% NaCl at various welding voltages and filler materials is presented in the study. The Metal Inert Gas (MIG) approach was used to weld samples in s butt joint form. After the corrosion test, iron oxides and pits were discovered on the exposed area's surface. Using MIG welding and heat-treated carbon steel, Ng and Abd Razak [23], looked at the corrosion behavior of the carbon steel. The corrosion behavior was tested using a synthetic seawater environment with 3.5 wt.% NaCl. The results showed that the amount of heat used during welding affects how quickly carbon steel corrodes, a high welding heat input resulting in a low corrosion rate. Majed et al.[24] studied the corrosion rate of (0.077 % C) low carbon steel weldments. The welded joints were fabricated using Arc, MIG, and TIG welding methods. The corrosion of low-carbon steel weldments was tested using a potentiostat at a scan rate of 3 mV.sec^{-1} in a corrosive medium containing seawater with 3.5% NaCl. They observed that as compared to low carbon steel that has not been welded, TIG welding increases anodic Tafel slop and corrosion current density while decreasing polarization resistance and TIG welding is more susceptible to corrosion than Arc and MIG welding. Mohammad [25] investigated the corrosion behavior of TIG weldments (0.2 % C) low carbon steel (1020AISI). The welded joints were carried out using the TIG welding technique using variable welding current keeping other welding parameters (voltage and speed) constant. The corrosion test of the welded joints was carried out utilizing the electrochemical method by immersion of all the samples in 3.5 % NaCl as a corrosive medium. The results showed that the corrosion rate decreases with increasing the welding DC current. Choi and H. Kim [26] studied the corrosion conduct of (0.1 % C) steel weldments for offshore constructions corroded in marine and Arctic low-temperature environments. The welded joints were fabricated using submerged arc welding (SAW) and flux-cored arc welding (FCAW) techniques. In seawater at low water and air temperatures, immersion tests, SST, and CCT were performed to determine the corrosion characteristics of the base metal and weldments. It was concluded that the base metal is corroded more than the fusion zone in weld joints under severe corrosion circumstances.

Katiyar et al [27] presented the immersion test results for mild steel corrosion activity with various water samples, the variance in terms of Total Dissolved Solids(TDS), pH, and Dissolved Oxygen (DO) of each water sample in order to determine the effect of these parameters with immersed, and atmospheric conditions. Three different types of water, ranging in corrosiveness from acidic to typical freshwater, as well as higher TDS water were used. Using the corrosion coupon weight-loss technique, the mild steel corrosion rate was determined. They found that the corrosion rate for submerged coupons was greater than the atmospheric rate.

Higher TDS content samples exhibited a sharp increase in corrosion rate, which supported the aggressive anions attack to cause corrosion as well as, they also discovered that corrosion had a significant impact on the parameter of water quality, which is good news for water storage tanks. According to their conclusions, mild steel is good for atmospheric applications but shouldn't be utilized without sufficient safeguards in more aggressive water. Royani et al. [28] studied carbon steel corrosion in freshwater for water distribution systems. The corrosion rate was rather consistent with the immersion duration, according to the weight loss analysis, carbon steel's corrosion rate in freshwater ranged between 0.41 to 0.76 mpy. Except for dissolved oxygen, the water characteristics are largely steady in the meantime. A reduction in DO suggests a corrosion interaction between oxygen and iron. These results revealed that the rate of corrosion of carbon steel on static fluid is basically consistent. Royani et al. [29] studied the corrosion of carbon steel in the Sukabumi River in West Java. The rates of corrosion of certain steels were determined using the weight loss technique after being exposed to varying periods in different depths of water (0 meters and 1 meter). SEM, energy dispersive spectroscopy, and X-ray diffractometer (XRD) were used to evaluate the surface shape and the corrosion product composition (EDS). After exposure, the corrosion product covered the whole surface of carbon steel in all depths of water. Based on the results, those steels had a higher corrosion rate at 0 meters of depth compared with steels at 1 meter of depth after 76 days of immersion, indicating that there were no protective oxides on the surface of carbon steel at 0 meters. These results showed that the corrosion rate of steel at the wet-dry level is greater than at full immersion.

This work observes the corrosion behavior of welded low-carbon steel by Friction Welding (FW), Shielded Metal Arc Welding (SMAW), and MIG welding techniques using immersion tests in tap water at different periods.

3. Experimental Procedure

3.1 Materials

Low-carbon steel rods of 12 mm in diameter were used in this research work. The chemical composition of the mild steel rod is shown in Table 1.

3.2. The Preparation of Weldments:

Mild steel rods were prepared in a mechanical workshop. The samples were machined and ground to 100 mm in length and 12 mm in diameter (Figure (1)). Before the welding process, the surface was cleaned using a metal grinder and finished with an emery paper. The welding types that were adopted in this study: were shielded metal arc welding (SMAW), metal inert gas (MIG), and friction welding (FW). four joints were fabricated using the above welding techniques. Table (2) above shows the welding parameters involved in the welding processes.

Table 1. Chemical composition of parent metal by emission spectroscopy.

%C	**%Si**	**%P**	**% Mn**	**%S**	**%Cr**	**%Ni**	**%Al**
0.244	0.336	<.002	1.46	0.014	0.204	0.016	0.064
%Mo	%Cu	%Ti	%Sn	%B	%Nb	%Co	%Fe
0.002	0.06	0.007	0.084	0.048	0.002	0.059	Balance

Table 2. Welding parameters of SMAW, MIG, and FW processes

Welding process	**SMAW**	**MIG**	**FW**
Welding Machine	Tazaka model MMA-300s	Miller	------
Welding Electrode	EWC 3235010 INGCO 3.2 mm	Weld 70 S-6	------
Welding Current	125 A	119 A	------
Rotation Speed –N (rpm)	---------------	-------------	1030
Friction pressure (kg)	---------------	-------------	0098
Friction time (s)	---------------	-------------	0005
Forging pressure (kg)	---------------	-------------	0560
Forging time (s)\	---------------	-------------	0008

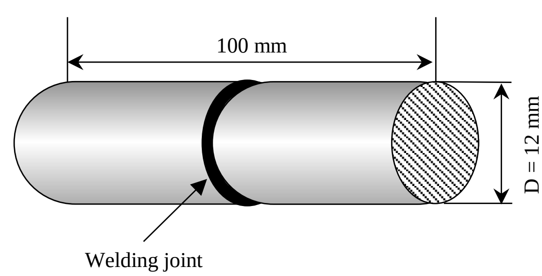

Figure 1. Welded sample dimensions before the immersion test

3.3. Immersion test

After the preparation of the welding joints and finishing the surface with emery papers (400 µm and 500 µm), all the samples were accurately weighed using a sensitive scale (Balance-Micro) with a sensitivity of (0.0001g.). Then, the samples were immersed in sixteen transparent, plastic containers containing 1750 mL tap water as selected corrosive media for this study. The containers were kept one meter away from any magnetic or electric field which may accelerate the corrosion rate [29].

Figure 2. Image of some corrosion compounds before the immersion test.

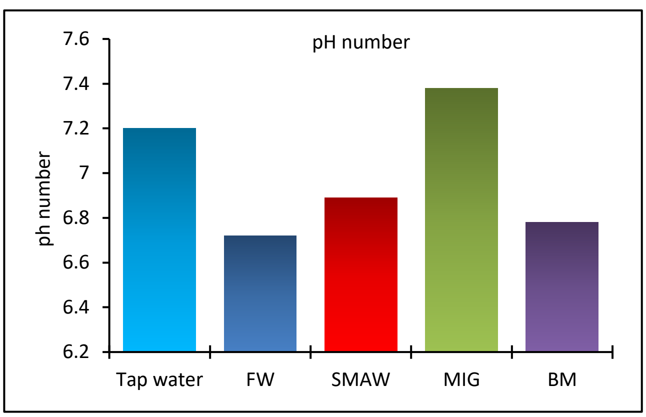

Figure 3. pH numbers for the tap water and the corrosive solutions after 1150 hours of the immersion of weldments

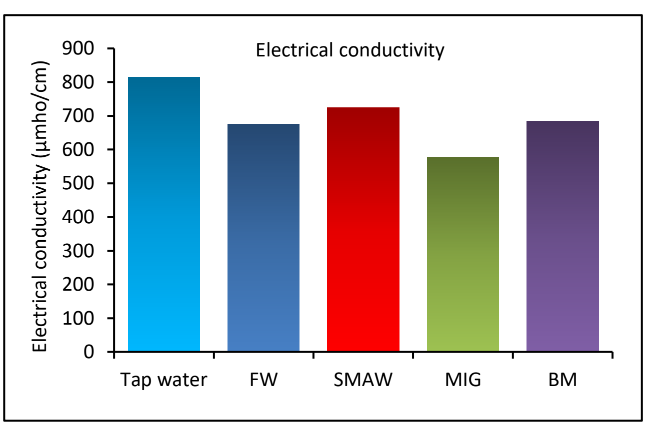

Figure 4. Electrical conductivity for the tap water (1) and the corrosive solutions after 1150 hours of the immersion of weldments:

3.4 The physical and chemical tests for the corrosive solutions

Figures (3, 4, and 5) show the results of physical and chemical tests before and after the immersion test. The following points can be observed from these figures: The pH number of the corrosive media of parent metal, friction-welded and SMAWsamples decreased to acidity (pH <7). However, the pH number of the corrosive medium of MIG samples increased to be alkaline (pH > 7) (see Figure 3). Compared with that of tap water. the water electrical conductivity (Figure 4) decreases by 89%, 84%, and 83% in friction-welded,, arc-welded samples corrosive solutions, and 71% in MIG samples corrosive solution. $CaCO_3$ and Ca^+ decreased for all of the corrosive media after the immersion tests. The level of Cl^- ions remains constant in parent metal and friction-welded corrosive solution, and raised in MIG and arc corrosive media. The Mg^{+2} ions slightly increased in the corrosive media of MIG-welded, arc-welded, and friction-welded samples, but it jumped from 18 (mg/l) to 43.3 (mg/l) in the corrosive medium of parent metal samples.

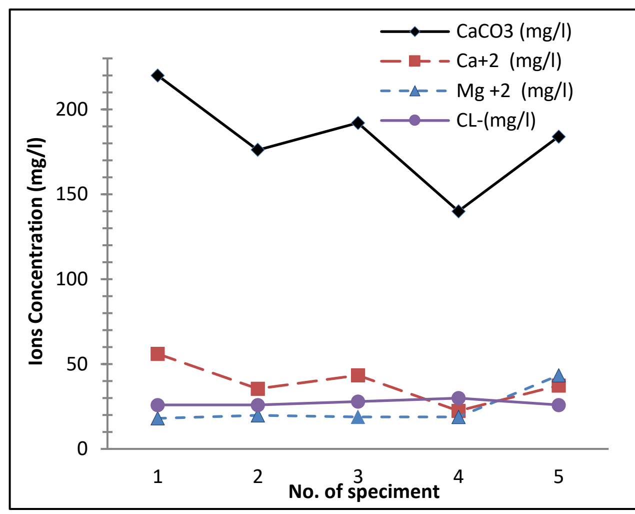

Figure 5. $CaCO_3$, Ca^{+2}, Mg^{+2}, and Cl^- ions concentrations for the tap water (1) and the corrosive solutions after 1150 hours of the immersion of weldments: (2) friction weldments. (3) SMAW weldments. (4) MIG weldments, and (5) base metal samples.

4. Calculations of corrosion rates

The corrosion rate was determined through an immersion test by taking the weights of the samples before and after the test. The specimens were immersed in the tap water in different timelines of 650, 815, 985, and 1150 hours respectively. The rate of corrosion was calculated using Eq. 3 [30].

$$Corrosion\ Rate\ (mpy) = 534\ \frac{w}{DAT} \quad (3)$$

w=Weight loss (mg)
A= Total area of exposure (in^2)
T = Exposure time in hours
D= density in grams per cubic centimeters

Depending on that's primary objective, which is the test subject's weight reduction. The metal's density and surface area constants [31].

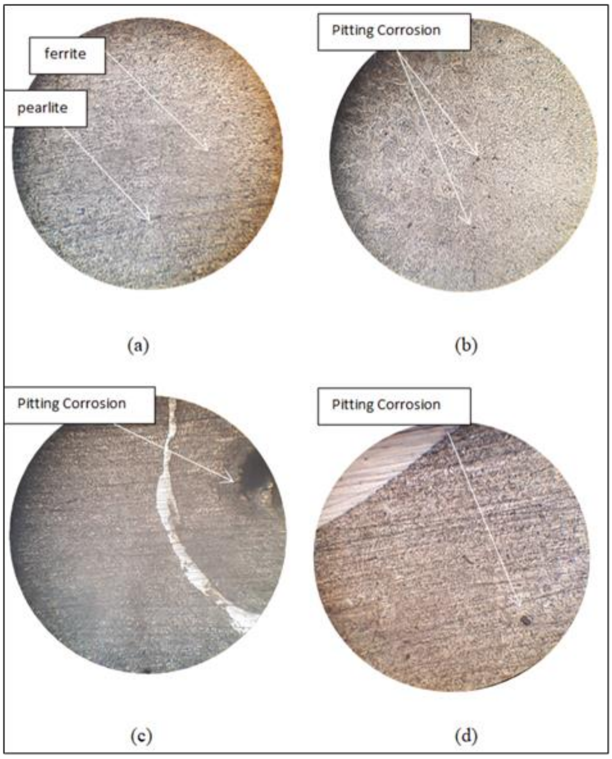

Figure 6. Microstructure of the parent metal and the different weldments at the nugget zone (X100). (a) parent metal; (b) friction weldments; (c) SMAW weldments; and (d) MIG weldments

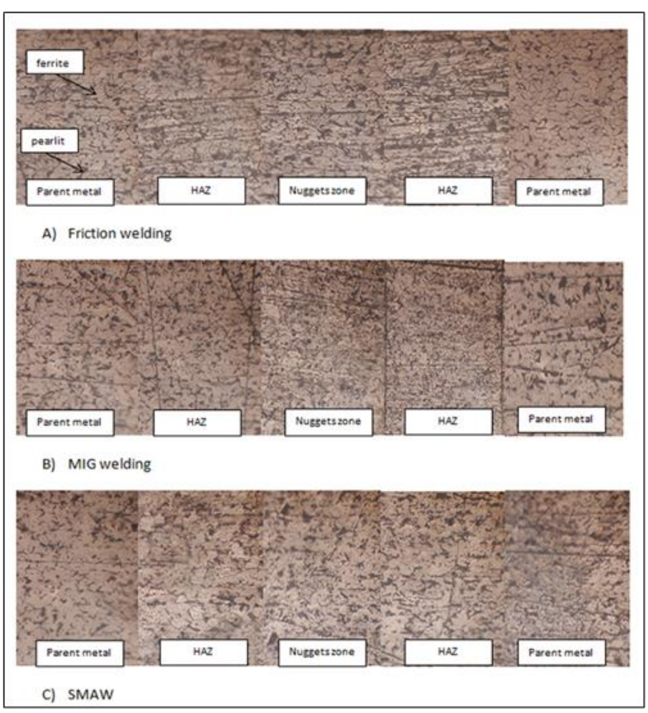

Figure7. Microstructure along the welded rod*s* at different welding zones (X164) for (a) friction weldments; (b) MIG weldments; and (c) SMAW

5. Result and discussion

Microstructures for *different* zones, Figs 6 and 7, were prepared to *observe* the corrosion process because *of* the microstructure. Nital solution, which contains 2% nitric acid and 98% alcohol, was used to etch the samples.Despite the fact that *the* proper selection of parent metal and filler material is essential to minimize corrosion failure[1]. *It* is not the sole factor to be justified. Plenty of factors found to play a role in the determination of the corrosion resistance of weldments [1]; these factors can be technical, and/or metallurgical. *Metallurgical*, the cycle of heating and cooling a welding joint undergoes an influence on the corrosion resistance of the weldment [1] (Figures 6 and 7). Balancing alloy composition is quite important to maintain corrosion resistance in the welding zone [32]. After 650 hours of being immersed in the corrosive medium, friction welded (FW) samples and arc-welded (SMAW) samples showed a close corrosion rate (Figures 8 and 9), MIG-welded samples had a lower corrosion rate in terms of mpy as it is clearly shown in Figure (10). Then, the corrosion rate of all the weldments decreased after 850 hours as *a* result of the precipitation of $CaCO_3$ which reacts with Fe (from the steel samples) to produce $FeCO_3$. *T*he latter can protect the surface of the samples from excessive corrosion. then, the rate of corrosion in FW samples and SMAW samples dropped by the same amount while MIG-welded samples kept showing better corrosion resistance. After 985 hours, friction welding and arc welding samples maintained their corrosion resistance showing close values of corrosion rates, but the corrosion rate of MIG-welded samples increased to hit the initial values of the samples welded by friction welding and arc welding.

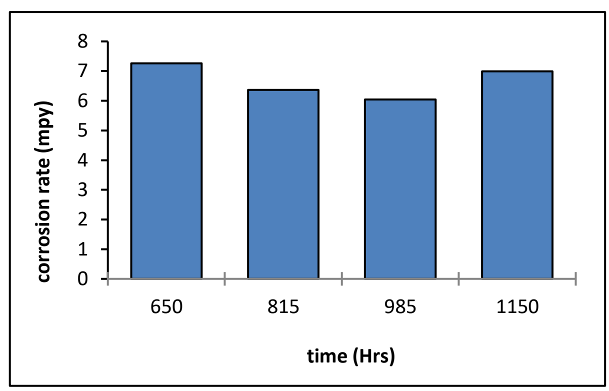

Figure 8. Corrosion rates for friction weldments

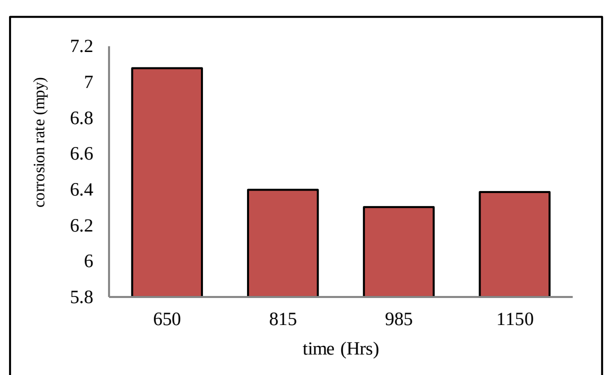

Figure 9. Corrosion rates for SMAW weldments

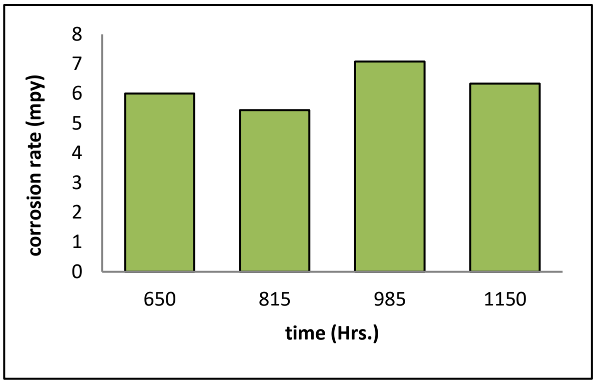

Figure 10. Corrosion rates for MIG weldments

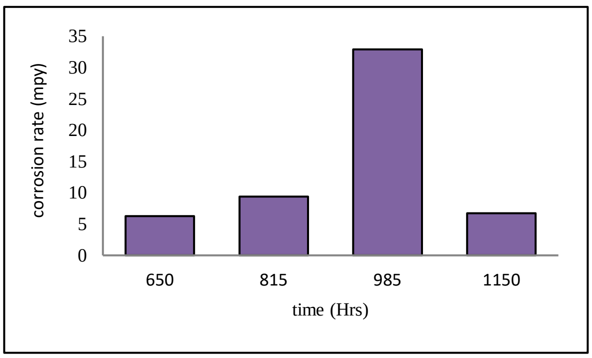

Figure 11. Corrosion rates for parent metal

The reason that the amount of $CaCO_3$ largely decreased in the corrosive media which means that high amount of the protective $FeCO_3$ formed on the samples and protected them from the propagation corrosion.[32-37]. For the parent metal, the corrosion increased gradually in the first and second periods, while it jumped to the highest corrosion rate in the third period due to the increase in the concentration of magnesium ions in the corrosion medium, which led to impeding the formation of the protective layer of calcium carbonate. (Figure 11).

Finally, for the samples that were removed after the completion of the period of 1150 hours; there was no change in the corrosion behavior of FW samples and SMAW samples while the corrosion rate of MIG-welded samples (Figure 10) decreased to its initial value (650 hours).

7. Conclusions

In this study, corrosion was observed on different welding joints of low-carbon steel and the following conclusions were made:

1. Friction welding and SMAW showed similar corrosion behavior.
2. The MIG Weldments sample had the lowest overall corrosion rate.
3. Low pH increased corrosion in SMAW, FW, and parent metal samples, while high pH protected MIG samples and decreased corrosion rates.
4. Water hardness as CaCO3 provides a protection layer and reduced corrosion rates.
5. Some of the metallurgical and/or technical factors play a role in the determination of the corrosion rates of a welding.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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