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Influence of Welding Techniques on the Corrosion Behaviour and Mechanical Integrity of Mild Steel in Hydrochloric Acid Medium

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Abstract

The research examined how Electric Arc Welding (EAW), Gas Metal Arc Welding (GMAW) and Spot Welding affect the corrosion resistance of mild steel when exposed to 2 M hydrochloric acid (HCl) solution. The corrosion tests used gravimetric (weight-loss) and thermometric methods to measure corrosion rates on welded specimens. The researchers performed impact testing to evaluate both the mechanical properties and the structural stability of welds that underwent corrosion. The research showed that all welded joints showed corrosion in the acidic solution, but the degree of damage depended on the welding process used. The research demonstrates that Gas Metal Arc Welding (GMAW) produces the most suitable mild steel joints for acidic environments, providing excellent corrosion protection and durability.

Keywords: Mild steel, welding techniques, corrosion resistance, gas metal arc welding, weight loss, microstructure, hydrochloric acid.

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1. INTRODUCTION

The natural process of corrosion leads to metal degradation through environmental electrochemical reactions (Harsimran et al., 2021; Li et al., 2022). The process of corrosion represents a major engineering problem because it weakens structures and shortens operational periods and requires additional expenses for maintenance and equipment replacement (Manu et al., 2025). The annual financial losses and safety risks from corrosion-related failures in oil and gas and petrochemical and construction, and transportation industries remain substantial (Prasad et al., 2020; Adesina et al., 2025). The continuous degradation of metallic materials, including mild steel, requires immediate solutions because this widely used material faces ongoing challenges due to its strength and ductility and fabrication simplicity. The most frequently employed metal in construction and pipeline, and machinery applications is mild steel, which contains less than 0.3% carbon (Zahner, 2020). The corrosion resistance of mild steel remains poor when exposed to acidic conditions despite its attractive mechanical properties and affordable cost (Kadhim et al., 2021). The material undergoes significant changes during welding because the process creates new electrochemical and metallurgical properties that increase its susceptibility to corrosion. The welding process produces two distinct zones in steel which become more prone to corrosion because their microstructures differ from the original material. The welding process produces two distinct zones in steel which become more susceptible to corrosion because their microstructures differ from the original material. The welding process in mechanical engineering requires essential fabrication because it enables metal component joining for building complete structures (Phillips, 2023). The final weld microstructure and mechanical properties depend heavily on the welding process parameters which include heat input and current and voltage and cooling rate. Research indicates that different welding methods produce different metallurgical changes which determine how steel materials will react to corrosion (Wang et al., 2020; Li et al., 2025). The wrong choice of welding technique produces microstructural irregularities which include grain enlargement and carbide formation and stress buildup that speeds up corrosion development of corrosion (Sivaraman et al., 2025; Shifler, 2022). The three most common welding methods for working with mild steel include Gas Metal Arc Welding

(GMAW) and Electric Arc Welding (EAW) and Spot Welding. The MIG welding process uses a continuous wire electrode which feeds into the weld pool while an inert gas shield made from argon or argon-carbon dioxide mixtures protects the weld area from environmental contamination (Singh et al., 2024). The technique yields a neat, robust weld characterized by elevated deposition rates and reduced slag formation. In contrast, Electric Arc Welding (EAW) relies on an electric arc established between an electrode and the workpiece to produce the necessary heat for fusion (Khoshnaw et al., 2023). While adaptable and extensively utilized, this method can lead to increased residual stresses and surface oxidation unless meticulously regulated. Spot Welding, a form of resistance welding, connects metal sheets by exerting pressure and channeling an electric current through the contact zone, creating heat and forming a weld nugget (Tanmoy, 2022). Although swift and economical for thin-sheet applications, it may introduce concentrated heat-affected regions and restricted joint integrity, influenced by material thickness and operational variables.

Research studies have primarily investigated microstructural and mechanical properties of materials but few have evaluated their resistance to hydrochloric acid (HCl) corrosion. The research investigates how different welding methods (Gas Metal Arc Welding (GMAW) and Electric Arc Welding (EAW) and Spot Welding) affect mild steel corrosion resistance when exposed to acidic conditions. The research uses weight loss measurements to determine corrosion rates and study how welding processes affect metal structure. It is consistent with literature of engineering (Adeleke et al., 2025; Okwu et al., 2024; Olaye et al., 2025; Oyejide et al., 2025), that science and parameter optimization when brought together would improve process understanding and decision making in a variety of engineering applications. The research seeks to determine which welding method provides the best corrosion protection for mild steel to help engineers select materials and design structures for corrosive industrial settings. The research findings will enhance existing knowledge about weld corrosion engineering, while promoting the application of more durable, reliable, and cost-efficient joining methods suitable for diverse industrial applications.

2. Materials and Methods

2.1 Materials and Equipment

The investigation utilized welded mild steel samples, abrasive papers, acetone, purified water, ethanol, storage vessels, and a 2 M hydrochloric acid solution as essential supplies. Key instruments encompassed an electronic weighing scale, assay tubes, glass beakers, volumetric cylinders, Erlenmeyer flasks, a rotary evaporator, a metal-cutting saw, filtration papers, funnels, a digital temperature probe, and aluminum foil.

2.2 Welding Procedures

Three distinct welding methods were selected for analysis, including Gas Metal Arc Welding (GMAW), Electric Arc Welding (EAW), and Spot Welding, to assess their effect on mild steel's corrosion resistance. The welding operations were conducted in a regulated laboratory setting at room temperature.

2.2.1 Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding, alternatively termed Metal Inert Gas (MIG) welding, stands as a prevalent fusion procedure. It entails generating an electric arc between a continuously fed consumable electrode and the workpiece while an inert shielding gas is supplied to guard the molten weld pool against air impurities. Recognized for its adaptability, rapid deposition rates, and straightforward mechanization, this approach suits both large-scale industrial projects and small-scale fabrication tasks.

2.2.2 Electric Arc Welding (EAW)

Electric Arc Welding is one of the oldest and most widely used welding techniques. It involves the generation of an electric arc between an electrode and the base metal. The intense heat produced melts the metals, and upon cooling, they fuse together to form a strong joint. EAW finds extensive applications in structural steel fabrication, repair work, and general welding tasks.

2.2.3 Spot Welding

Spot Welding is a fast and efficient welding process used to join metal sheets together. It involves applying localized heat and pressure to create a weld at discrete spots. Spot welding is widely employed in the automotive industry for fabricating vehicle body panels and other sheet metal components.

2.3 Specimen Preparation

The metals used for this research work is welded mild steel. Welded Mild steel was used because of its versatility as material of construction. The mild steel specimens were mechanically cut into dimension of 2.0 x 0.2 x 2.5 cm (with a surface area of 11.8 cm^2). Prior to all, the mild steel coupons were mechanically polished with series of emery paper from 400 to 1200 grades. The surface of the sample was ground in a grinding machine to obtain a smooth surface.

2.4 Preparation of 2 M HCl

Standard concentrated HCl (density = 1.18 g/cm^3, purity = 35%) was used as the stock acid. The molarity of the concentrated HCl was calculated (molar mass HCl =

35.5 g/mol) and found to be 11.63 M. Using the dilution relation $C_1V_1=C_2V_2$, 85.99 cm³ of the concentrated HCl was diluted to 500 cm³ with distilled water to obtain the 2 M HCl solution used as the corrosive medium. Inhibitor solutions (where applied) were prepared by dissolving accurately weighed inhibitor quantities into the prepared 2 M HCl to obtain concentrations of 0.1, 0.3 and 0.5 g/L. Figure 1 shows the preparation of the acid.

Figure 1. Preparation of Acid

2.5 Weight-Loss (Gravimetric) Measurements

The weight-loss method was used to evaluate corrosion. Each coupon was weighed (initial weight, W_b) then immersed in 2 M HCl (with or without inhibitor). The coupons were suspended with acid-resistant clips and retrieved at 3-hour intervals up to 15 hours total immersion. After each interval specimens were washed with distilled water, degreased with acetone, dried, and reweighed (final weight, W_a). The weight loss (W) was obtained using Equation 1 below.

$$W = W_b - W_a \quad (1)$$

Where,
W_b = specimen weight before immersion, and
W_a = specimen weight after immersion
The corrosion rate (CR) was calculated using Equation 2 below.

$$CR = \frac{\Delta W}{At} \quad (2)$$

Where, ΔW is weight loss (g), A is surface area (cm²), and t is the exposure time in hours.
The inhibition efficiency (IE%) was calculated using Equation 3 below.

$$\mathrm{IE}(\%) = \left(\frac{\mathrm{CR_1} - \mathrm{CR_2}}{\mathrm{CR_1}}\right) \times 100 \quad (3)$$

where CR_1 and CR_2 represent the corrosion rates in the absence and presence of the inhibitor, respectively.

2.6 Thermometric Measurements

Thermometric measurements were done to study corrosion reaction kinetics. Coupons were immersed in beakers that contained inhibited and uninhibited 2 M HCl. A digital thermometer probe was inserted through the stopper to record temperature variation until the system reached a steady maximum temperature. The reaction number (R), which reflects the rate of the corrosion process, was calculated using Equation 4.

$$\mathrm{R} = \frac{\mathrm{T_m} - \mathrm{T_i}}{\mathrm{t}} \quad (4)$$

where T_m and T_i are the maximum and initial temperatures, respectively, and t is the time (minutes) required to reach the maximum temperature.
The inhibition efficiency (%I) for the thermometric measurement was determined from the percentage reduction in reaction number shown in Equation 5 below.

$$\%\mathrm{I} = \frac{\mathrm{R_{aq}} - \mathrm{R_{wi}}}{\mathrm{R_{aq}}} \times 100 \quad (5)$$

Where R_{aq} is the reaction number of the aqueous solution and R_{wi} is the reaction number in the presence of each inhibitor.

2.7 Impact Testing on Spot-Welded Joints

The impact assessment on corroded spot-welded connections was performed employing an Izod impact apparatus to gauge the energy intake during rupture. The process commenced by quantifying the baseline energy, involving lifting and discharging the pendulum hammer to oscillate without hindrance, followed by noting the measurement. The hammer was once more elevated to the identical position, firmly locked, while the sample was correctly positioned on the anvil. Protective measures were adhered to, ensuring only the handler remained within the pendulum's arc. The hammer was then freed to collide with the specimen, inducing fracture, and the concluding energy datum was extracted from the gauge.

Each specimen's shock-absorption capability was derived from the disparity between the starting and ending energy figures, with outcomes documented for scrutiny. This protocol effectively evaluated the fracture endurance of rusted spot-welded joints, offering clarification on the welds' structural soundness following corrosion susceptibility. The Izod impact testing equipment is depicted in Figure 2

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Figure 2. Izod Impact Testing Machine

3. RESULTS AND DISCUSSION

3.1 Weight-Loss Analysis

Table 1 illustrates the outcomes of weight-reduction assessments for mild steel samples joined through Spot Welding, Electric Arc Welding (EAW), and Gas Metal Arc Welding (GMAW) following immersion in 2 M hydrochloric acid across varied durations (3, 6, 9, 12, 15 hours). The figures demonstrate a steady rise in weight loss as immersion time lengthens for all joining methods, signaling ongoing metallic dissolution within the acidic medium. During the initial phase (3 hours), the Spot-Welded sample exhibited the largest weight reduction (0.80 g), trailed by GMAW (0.75 g) and EAW (0.60 g). Upon extending the exposure period to 6 hours, every sample manifested greater mass depletion owing to quickened corrosive action; the GMAW specimen, however, displayed a pronounced surge (1.30 g), hinting at more vigorous early-stage surface reactions. Past 9 hours, corrosive degradation escalated noticeably, with the GMAW specimen revealing the utmost accumulated depletion (1.50 g), whereas EAW and Spot Welding each registered 1.20 g. Following extended exposure (12–15 hours), the weight depletion figures climbed substantially across all specimens, peaking at 3.70 g (Spot Welding), 3.30 g (EAW), and 3.90 g (GMAW) after 15 hours. This pattern suggests that GMAW sustained the heftiest overall material loss, potentially because of heightened vulnerability of reactive weld regions and focused acid assault. However, when evaluating corrosion rate computations (weight deficiency standardized by surface extent and duration), GMAW might nevertheless exhibit superior overall resistance to deterioration should variations in weld surface coverage or material compactness be factored in.

Table 1: Result of the weight loss measurements in (g)

Time	Spot welding	Electric arc welding	Gas metal arc welding
3	0.80	0.60	0.75
6	0.87	0.80	1.30
9	1.20	1.20	1.50
12	3.10	2.00	3.70
15	3.70	3.30	3.90

The corrosion rate results that were gotten from the weight-loss data further support this observation, as illustrated in Figure 3, where GMAW consistently showed the lowest corrosion rates over time.

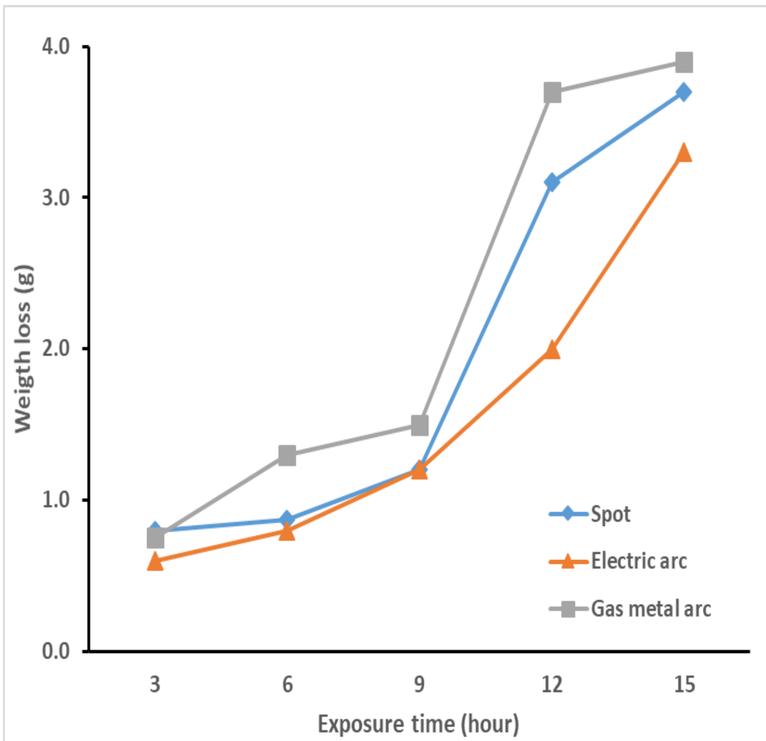

Figure 3. Graph of weight loss against the exposure time

3.2 Corrosion Rate Determination

The corrosion rate, estimated based on the data obtained from weight loss measurements, was found to reduce with an increase in immersion period for all welds. Both GMAW and Spot welding methods cause less heat input to the metal along with fast cooling rates compared to other methods. In GMAW, there is minimum heat input to the metal. The heat input to the metal due to GMAW results in smooth fusion between metals. In contrast to GMAW, other methods like EAW create a larger heat-affected zone with possible residual stresses or metal inclusions that can cause corrosion. In electrical arc welding methods like Spot Welding due to localized electrical resistance heating of metal leads to non-uniform metal structure. As a result, corrosion susceptibility increases.

3.3 Thermometric Measurements

Thermometric analysis was conducted to evaluate the reaction kinetics of the corroding systems in 2 M HCl. The temperature of the corroding medium increased with time until a maximum value was reached, after which it stabilized. The results, presented in Table 2, show the temperature rise for uninhibited and inhibited systems for each welding technique.

Table 2: Thermometric measurement (ºC)

Time	Spot welding	Electric arc welding	Gas metal arc welding
3	27.90	27.80	27.90
6	28.10	28.00	28.40
9	28.40	28.30	28.50
12	28.10	28.00	28.20
15	27.90	27.85	27.95

3.4 Impact Testing on Spot-Welded Joints

The impact properties of the Spot-Welded specimens after exposure to the corrosive medium are presented in Table 3. The results show that the impact energy increases as the weight fraction of the three different welding techniques decreases. The addition of 3% welded materials to the metal alloy increased the absorbed impact energy from 12.32J to 12.69J, and further increase in the percentage of the welded materials to 6% increased the impact value to 12.99J. The addition of 9% the materials also increased the impact value to 13.51J. Therefore, the observed drop in the impact energy of the reinforced mild steel could be as a result of the brittle nature of the welded materials when compared to the ductile metal matrix

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Table 3: Impact measurement (J)

Spot welding	Electric arc welding	Gas metal arc welding	Average
13.93	13.52	9.52	12.32
14.12	13.96	9.99	12.69
14.62	14.25	10.12	12.99
15.43	14.96	10.15	13.51

Corrosion attacks at the weld interface weakened the joint strength and promoted crack initiation sites, which led to premature fracture under impact loading. The deterioration of impact strength can therefore be attributed to the combined effects of material loss, microstructural embrittlement, and stress concentration around corrosion pits. This behaviour suggests that Spot-Welded joints, though easy to fabricate, are not suitable for service in strongly acidic environments where long-term corrosion resistance and mechanical durability are critical.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The corrosion on welded mild steel in 2M HCl was examined using weight loss, thermometric measurements and impact measurements. The weight loss with concentrated HCL in the absence of inhibitor increase as the exposure time increases and the weight loss with diluted HCL (2M) without inhibitor increase as the exposure time increases. The temperature increased with time and reach a maximum at approximately 190minutes and the decreased. However, the temperature efficiency decreases with rise in temperature. Therefore, the temperature of the sample in the system increases as the time increases till it reaches the steady temperature. Also, the observed drop in the impact energy of the reinforced mild steel could be as a result of the brittle nature of the welded materials when compared to the ductile metal matrix. However, as the weight ratio of welded mild steel increases with respect to the decreasing weight percentage in the composite, the toughness of the composite rise and thus, its ability to absorb impact load increased.

4.2 Recommendations

In this study, for future improvement to reduce corrosion of welded mild steel in acidic medium, the corrosion parameters should be checked with other measurement like Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) measurements. It is suggested that other researchers can make attempt to use cooling medium (like air, oil or water) for the cooling. The above research was carried out at room temperature (25^{0}C). However, future investigations can be done at more temperature-controlled environment.

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