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Mechanical Properties and Failure Behavior of GMAW-Welded SS400 Carbon Steel after Immersion in Sulfuric Acid Solution

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Abstract: The mechanical integrity of welded carbon steel exposed to acidic environments depends on weld-zone heterogeneity, local hardness characteristics, and joint discontinuities. This study evaluates the changes in Vickers microhardness and tensile strength of gas metal arc welded (GMAW) SS400 carbon steel after immersion in 0.5 M sulfuric acid (H_2SO_4). Four exposure conditions were considered: 0, 7, 14, and 21 days at 27 ± 2 °C. Hardness was measured in the weld metal (WM), heat-affected zone (HAZ), and base metal (BM), while tensile response was evaluated using maximum load and ultimate tensile strength (UTS). The results show that WM hardness ranged from 201.08 to 213.53 HV0.3 and HAZ hardness ranged from 169.99 to 184.46 HV0.3, with no monotonic decrease as immersion time increased. BM hardness exhibited a larger variation, decreasing from 227.60 HV0.3 in the unexposed condition to 161.61 HV0.3 after 21 days. The mean UTS values at 0, 7, 14, and 21 days were 396.50, 348.21, 351.81, and 414.25 MPa, respectively, showing a non-monotonic response. All eight tensile specimens fractured within the weld region, including the unexposed specimens. The UTS variation and fracture locations indicate that initial joint quality and possible welding discontinuities should be considered when interpreting the effect of acid exposure. Given the limited number of tensile specimens, a causal relationship between immersion time and tensile-strength changes cannot be established.

Keywords: SS400, GMAW, Vickers microhardness, tensile strength, fracture behaviour, sulfuric acid.

I. INTRODUCTION

Low-carbon steel is widely used in construction and manufacturing because it offers a combination of strength, ductility, weldability, and relatively low cost. SS400 steel, specified under JIS G3101, is a structural steel commonly used in frames, machine components, support structures, and various fabricated assemblies. The reliability of structures made from this material depends not only on the properties of the base material but also on joint quality and the service environment.

Gas metal arc welding (GMAW) is widely used to fabricate carbon steel because it employs a continuously fed consumable electrode and offers high productivity. However, the thermal cycle during welding produces metallurgical heterogeneity across the joint. The main joint regions are the weld metal (WM), heat-affected zone (HAZ), and base metal (BM). The WM undergoes melting and solidification, the HAZ experiences thermal changes without complete melting, and the BM is relatively unaffected by the welding heat cycle. These differences in thermal history can produce variations in microstructure, grain size, phase distribution, and hardness.

Poonnayom *et al.* (2015) investigated the microstructure and tensile properties of dissimilar SS400–SUS430 joints produced by GMAW, while Jatimurti *et al.* (2023) evaluated the effects of welding current and electrode diameter on the mechanical properties and microstructure of SS400 joints. These studies demonstrate the importance of welding parameters in determining joint mechanical characteristics. However, joint properties must also be evaluated when the material is exposed to corrosive environments.

In acidic environments, electrochemical dissolution can cause material loss and changes in surface geometry. Localized damage, such as pits or cavities, can act as stress concentrators when the material is subjected to tensile loading. Nevertheless, surface changes are not necessarily proportional to changes in the mechanical properties of the underlying material. Microhardness testing measures the local response of a small volume, whereas tensile testing involves the entire specimen cross-section and is influenced by the most critical discontinuity.

In their review of the mechanical performance of steel in corrosive environments, Mokhtari *et al.* (2024) explained that

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mechanical degradation is affected by steel type, manufacturing process, composition, environmental conditions, cross-sectional area loss, and loading conditions. Dong *et al.* (2023) also showed that microstructural heterogeneity in welded steel joints can affect mechanical properties and corrosion behavior. Therefore, evaluating corroded welded joints requires consideration of the characteristics of each metallurgical region and the initial joint quality.

The relationship between hardness and tensile strength is not always universal. In a study involving 138 submerged arc welded API X70 steel specimens, Lahouel *et al.* (2025) established statistical correlations between hardness and several tensile properties. However, such correlations depend on the material, welding process, measurement location, and amount of data. Therefore, correlations obtained for API X70 steel cannot be directly applied to GMAW-welded SS400.

This study aims to evaluate changes in Vickers microhardness and tensile strength in GMAW-welded SS400 steel after immersion in 0.5 M H_2SO_4 for 0, 7, 14, and 21 days. In addition, fracture locations and the possible contribution of pre-existing welding discontinuities are discussed to explain variations in tensile response. This article focuses on mechanical response and failure behavior; localized corrosion characteristics are used as supporting context rather than as the primary outcome.

II. MATERIALS AND METHODS

2.1 Materials and Welding Procedure

The material used was SS400 carbon steel plate with a nominal thickness of 10 mm and initial dimensions of 350 × 100 mm. Welding was performed using the GMAW process with 0.8 mm diameter ER70S-6 wire and 100% CO_2 shielding gas. A single-V-groove butt joint was prepared with a total groove angle of 60°, a 2 mm root face, and a 2 mm root gap. Welding was performed in the flat (1G) position using two passes: a root pass and a cap pass. The interpass temperature was maintained below 150 °C, and the joint was allowed to cool in air without postweld heat treatment. Table 1 show the welding process parameter.

Table 1: Welding Parameter Process

Parameter	Condition
Base material	SS400
Nominal plate thickness	10 mm
Welding process	GMAW
Electrode	ER70S-6; diameter 0,8 mm
Shielding gas	CO_2 100%; debit 16 L/min
Welding current	150 A
Voltage	23 V
Welding speed	280 mm/min
Position and passes	1G; root pass dan capping pass
Interpass temperature	Below 150 °C
PWHT	Not performed

The nominal arc energy (E) was calculated using E = (60VI)/(1000v), where E is in kJ/mm, V is voltage in volts, I is current in amperes, and v is the welding speed in mm/min. Based on the welding parameters, the nominal arc energy was 0.739 kJ/mm. This value was not corrected for the thermal efficiency of the GMAW process. After welding, the joint underwent visual inspection and liquid penetrant testing. These surface examinations cannot confirm the absence of internal porosity or subsurface lack-of-fusion defects.

2.2 Immersion Procedure

The test medium was a nominal 0.5 M H_2SO_4 solution prepared using 98% concentrated sulfuric acid and demineralized water. Specimens were immersed for 7, 14, or 21 days at 27 ± 2 °C. The 0-day group served as the unexposed reference condition. The solution was renewed every seven days. After exposure, the specimens were removed, rinsed with demineralized water, and dried before subsequent testing. Different coupons were used for each immersion period; mechanical measurements were not performed on the same coupons before and after exposure.

2.3 Vickers Microhardness Testing

Hardness testing was performed on the joint cross-section using a Mitutoyo Vickers hardness tester with a 0.3 kgf load and a dwell time of 10–15 seconds, in accordance with ASTM E384. Measurements were taken in the WM, HAZ, and BM. Three indentations were made in each region for every immersion condition. Hardness was calculated using $HV = 1.8544F/d^2$, where F is the load in kgf and d is the mean indentation diagonal in mm. The reported values are the means of three local indentations; the standard deviations do not represent variation among independent welded specimens.

2.4 Tensile Testing

Tensile testing was performed using an A&D Tensilon RTF

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universal testing machine with a nominal capacity of 100 kN. Dog-bone specimens were prepared in accordance with ASTM E8/E8M-21, with the weld region positioned at the center of the reduced section. The nominal dimensions included a 50 mm gauge length, a 12.5 mm reduced-section width, and a nominal thickness of 10 mm. The actual width and thickness were measured before testing. Each immersion-time group consisted of two specimens, for a total of eight specimens.

III. RESULTS AND DISCUSSION

3.1 Microhardness Characteristics Across the Weld Joint

Vickers microhardness testing revealed differences in local response among the WM, HAZ, and BM. In the unexposed condition, the average hardness values were 211.31 HV0.3 for the WM, 169.99 HV0.3 for the HAZ, and 227.60 HV0.3 for the BM. The BM had the highest value, followed by the WM and HAZ. These differences indicate mechanical-property heterogeneity across the joint, which may be related to differences in thermal history and microstructural characteristics during welding.

Dong *et al.* (2023) showed that hardness distribution in grade 620 marine steel weld joints is related to variations in microstructural constituents in the WM and HAZ. Although the material and process differ from the SS400-GMAW system examined here, their findings reinforce the importance of analyzing each joint region separately. In this study, the lower HAZ hardness may be associated with microstructural changes caused by the welding thermal cycle. However, because grain size and phase fractions were not quantified, this relationship remains an interpretation. Table 2 shows the microhardness of the specimens.

Table 2: Microhardness Vickers on the WM, HAZ & BM

Immersion time (days)	WM	HAZ	BM
0	211,31 ± 5,33	169,99 ± 9,07	227,60 ± 15,24
7	204,14 ± 4,15	176,58 ± 8,73	165,03 ± 1,66
14	213,53 ± 3,89	184,46 ± 10,55	180,87 ± 3,33
21	201,08 ± 10,76	178,86 ± 3,37	161,61 ± 4,23

Table 1 Vickers microhardness test results. Data are reported as the mean ± standard deviation of three local indentations.

3.2 Changes in Hardness with Immersion Time

Table 3 shows the comparison of the hardness change during immersion. To compare changes among the different regions, hardness values were expressed relative to the unexposed condition. WM hardness changed by −3.4%, +1.1%, and −4.8% after 7, 14, and 21 days, respectively. HAZ hardness changed by +3.9%, +8.5%, and +5.2%. BM hardness exhibited larger changes of −27.5%, −20.5%, and −29.0%. These changes did not follow a monotonic pattern in any of the three regions.

Table 3: Hardness change during imersion

Immersion time (days)	WM (%)	HAZ (%)	BM (%)
0	0,0	0,0	0,0
7	−3,4	+3,9	−27,5
14	+1,1	+8,5	−20,5
21	−4,8	+5,2	−29,0

3.2.1 Weld Metal Hardness Response

WM hardness ranged from 201.08 to 213.53 HV0.3. The difference between the highest and lowest values was approximately 5.9% of the initial hardness. The non-monotonic pattern provides no evidence of a systematic decrease in WM hardness with increasing immersion time. Testing was performed on polished cross-sections, whereas acid exposure primarily affects the immersed surfaces. Therefore, surface material loss does not necessarily produce a proportional change in the indentation resistance of the underlying material.

Dong *et al.* (2023) attribute variations in weld zone hardness to differences in microstructural constituents. In this study on SS400, minor fluctuations in weld metal (WM) hardness may also be influenced by the specific placement of the indentation relative to heterogeneous microstructural constituents. Since the measurements were performed on separate coupons rather than at paired locations (before and after), the results do not provide evidence of hardening or softening induced by acid.

3.2.2 Heat-Affected Zone Hardness Response

HAZ hardness increased from 169.99 HV0.3 in the unexposed condition to 184.46 HV0.3 after 14 days, then decreased to 178.86 HV0.3 after 21 days. This increase was not sustained monotonically. The HAZ has a thermal gradient resulting from welding, so the indentation position relative to the

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fusion line and HAZ subregions can affect the measured values.

Jatimurti *et al.* (2023) also discussed differences in HAZ characteristics resulting from welding parameters in SS400 steel. Accordingly, changes in HAZ hardness in this study should be interpreted in light of the initial metallurgical condition. There is insufficient evidence to conclude that acid exposure at 27 ± 2 °C caused phase transformation or thermal hardening.

3.2.3 Base Metal Hardness Response

The BM showed the largest change, from 227.60 HV0.3 in the unexposed condition to 161.61 HV0.3 after 21 days. Although the relative decrease reached approximately 29.0%, the value at 14 days was higher than that at 7 days. This difference cannot yet be interpreted as corrosion-induced softening. Different coupons were used for each group, and measurements were not taken at identical locations before and after exposure. In ferrite–pearlite steel, differences in indentation position relative to the microstructural constituents can produce variations in local hardness.

Lahouel *et al.* (2025) reported a statistical correlation between Vickers hardness and tensile properties in API X70 steel weld joints based on 138 specimens. Their study highlights the importance of adequate data and structured measurements when developing correlations. The API X70 correlation cannot be directly applied to SS400, particularly because the present study used only three local indentations per region and two tensile specimens per condition.

3.3 Effect of Immersion Time on Tensile Strength

Table 4 shows the ultimate tensile strength (UTS) after immersion. The mean UTS in the unexposed condition was 396.50 MPa. After 7 days of immersion, UTS decreased to 348.21 MPa, or 12.2% below the initial value. After 14 days, UTS was 351.81 MPa, or 11.3% below the initial value. After 21 days, UTS increased to 414.25 MPa, or 4.5% above the initial value. Thus, UTS did not exhibit a monotonic relationship with immersion time.

Table 4: UTS of specimens after immersion

Immersion time (days)	UTS (MPa)	Change (%)
0	396,50	Reference
7	348,21	−12,2
14	351,81	−11,3
21	414,25	+4,5

Mokhtari *et al.* (2024) explained that the effect of corrosion on steel mechanical performance depends on material type, manufacturing process, environment, cross-sectional area loss, and loading conditions. In this study, the increase in UTS after 21 days cannot be interpreted as strengthening caused by acid exposure. Because different specimens were used in each group, differences in initial joint quality and the distribution of discontinuities may have affected the measured averages.

3.4 Variation in Tensile Strength Among Specimens

The 7-day group exhibited the greatest variation, with an individual UTS difference of 84.36 MPa and a sample standard deviation of approximately 59.65 MPa. The low value of 306.03 MPa had a substantial effect on the group average. In contrast, the 21-day group had a standard deviation of approximately 16.61 MPa. With only two specimens per condition, the average is highly sensitive to the result from a single specimen. Therefore, these results are exploratory and are insufficient to establish the statistical significance of the effect of immersion time.

3.5 Fracture Behavior and Possible Welding Discontinuities

All eight specimens fractured in the weld region, including the unexposed specimens. This finding indicates that failure was located in the joint region even before acid exposure. Discontinuities such as porosity, cavities, or lack of fusion can create local stress concentrations and facilitate crack initiation. Initial metallographic observations in the source study revealed cavity-like features and discontinuities near the WM–HAZ interface.

However, cross-sectional metallographic observations do not prove that a particular feature was the crack initiation site in a tensile specimen. Volumetric inspection of internal defects paired with each specimen and fractographic analysis to identify crack initiation sites were not available. Therefore, pre-existing discontinuities are a possible explanation for the variation in tensile strength, but they cannot be identified as the sole cause.

Dong *et al.* (2023) showed that microstructural heterogeneity in welded steel joints can affect mechanical properties and corrosion behavior. In this study, fracture in the weld region should be understood as the combined response of the mechanical-property distribution, local geometry, and possible welding defects. SEM examination of fracture surfaces and radiographic testing or ultrasonic testing before immersion

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are needed to evaluate this hypothesis.

3.6 Relationship between Microhardness and Tensile Strength

Microhardness and UTS measure different aspects of mechanical behavior. Hardness evaluates resistance to plastic deformation within a small volume beneath an indentation, whereas UTS describes the response of the entire specimen cross-section under tensile loading. Therefore, stable WM and HAZ hardness does not necessarily imply stable UTS.

Lahouel *et al.* (2025) established a statistical relationship between hardness and tensile properties in API X70 steel produced by submerged arc welding using a substantially larger number of specimens. Their study demonstrates that correlations can be developed when hardness and tensile measurements are obtained from a sufficiently large specimen population and clearly defined regions. In the present SS400 study, hardness data were obtained from metallographic coupons different from the tensile specimens, so paired data for direct correlation were unavailable. Accordingly, no hardness–UTS regression was performed, and hardness was not used as a direct predictor of tensile strength.

3.7 Relationship between Localized Damage and Mechanical Integrity

Cross-sectional observations from the same experiment showed larger measured localized cavity features in the longer-exposure groups, with the maximum reported dimension reaching 522.83 µm in the WM after 21 days. However, the 21-day group also had the highest mean UTS. This does not demonstrate that cavities have no effect on strength. The effect of pits on tensile capacity depends on their depth, width, shape, orientation, distribution, and position relative to the loading direction.

Mokhtari *et al.* (2024) emphasized that evaluating the performance of corroded steel requires consideration of cross-sectional area loss, changes in ductility, and damage characteristics rather than relying on a single tensile-strength value. In this study, localized feature dimensions were not measured in three dimensions or spatially linked to fracture initiation sites. In addition, the features measured on metallographic coupons did not necessarily come from the same specimens used for tensile testing. Consequently, a quantitative relationship between cavity dimensions and UTS could not be established. The interpretation most consistent with the data is that localized surface damage and overall mechanical response are two distinct aspects. Localized damage can occur without a corresponding change in the hardness of the underlying material, while UTS can be affected by the initial joint condition and discontinuities. A direct causal relationship between acid exposure and changes in UTS has not been demonstrated.

3.8 Sensitivity of UTS to Specimen Cross-Sectional Area

UTS was calculated using the actual initial cross-sectional area of each specimen. To evaluate the effect of dimensional variation, a sensitivity calculation was performed using a fixed reference area of 110.00 mm². Table 5 shows the comparison of UTS based on actual and fixed area of cross section of the specimens. The results showed that using the fixed area produced differences of approximately 0–3.3% compared with calculations based on the actual area.

Table 5: Comparison of UTS calculated using the actual cross-sectional area and a fixed reference area

Immersion time (days)	Mean Fmax (kN)	UTS using actual area (MPa)	UTS using fixed area (MPa)	Difference (%)
0	43,62	396,50	396,50	0,0
7	38,71	348,21	351,90	+1,1
14	39,33	351,81	357,50	+1,6
21	44,08	414,25	400,70	−3,3

3.9 Implications and Limitations of the Study

The results indicate that the mechanical integrity of welded joints after acid exposure cannot be evaluated using a single parameter. Hardness provides information about the local response, UTS describes the overall tensile capacity of the specimen, and fracture location provides an indication of the failure region. These three parameters complement one another but are not interchangeable.

The main limitations of this study are the small number of tensile specimens (two per condition); hardness measurements at only three local points without documented independent coupon replication; the absence of paired hardness measurements on the tensile specimens; and the lack of volumetric inspection of weld defects and fractography. Tensile testing was also performed without a separate extensometer, so the 0.2% offset yield strength and strain values based on machine displacement were not used to make definitive conclusions about intrinsic property

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changes.

Future studies should use at least five independent tensile specimens per condition, where feasible; inspect joint quality before immersion using radiographic testing or ultrasonic testing; measure strain using an extensometer; perform more detailed hardness mapping; and characterize fracture surfaces using SEM. Mass-loss measurements and three-dimensional pit geometry are also needed to quantitatively relate localized damage to cross-sectional load-bearing capacity.

IV. CONCLUSIONS

1. The joint exhibited differences in microhardness among the WM, HAZ, and BM. WM hardness ranged from 201.08 to 213.53 HV0.3, while HAZ hardness ranged from 169.99 to 184.46 HV0.3, with no monotonic decrease as immersion time increased.
2. The BM showed greater hardness variation, decreasing from 227.60 HV0.3 in the unexposed condition to 161.61 HV0.3 after 21 days. However, coupon-to-coupon heterogeneity and the absence of paired measurements prevent the changes from being directly attributed to acid exposure.
3. The mean UTS values after 0, 7, 14, and 21 days were 396.50, 348.21, 351.81, and 414.25 MPa, respectively. These changes did not show a monotonic relationship between immersion time and tensile strength.
4. All eight specimens fractured in the weld region, including the unexposed specimens. This finding indicates that initial joint quality and possible welding discontinuities should be considered when evaluating failure behavior.
5. Changes in local hardness do not directly represent changes in the overall tensile strength of the joint. Given the limited number of specimens and the absence of a spatial correlation between defects and fracture initiation sites, a causal relationship between acid exposure and changes in tensile strength has not been established.

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