

Corrosion Behavior of Friction Stir Welded Joints in Aluminum Alloys (AA2000, AA5000, AA7000, AA8000)

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ABSTRACT

Friction Stir Welding (FSW) demonstrates superior corrosion resistance in aluminum alloys compared to conventional techniques like arc and laser welding, owing to reduced heat-affected zones (3–5 mm) and refined microstructures. Environmental conditions significantly influence corrosion behavior, with marine (3.5% NaCl) and acidic (pH 3) environments accelerating pitting and intergranular corrosion in AA5000 and AA2000 alloys, respectively. Alloy composition plays a critical role: AA6061-T6 (AA6000 series) exhibits lower pitting rates (0.18 mm/year) than copper-rich AA2024 (0.34 mm/year), while optimized Li/Cu ratios in AA8090 (AA8000 series) reduce exfoliation corrosion by 25%. Mechanical-corrosion synergy reveals residual stresses and microstructural features, such as low-angle grain boundaries, directly impact stress corrosion cracking (SCC) and pitting resistance. Industrial applications in aerospace, marine, and infrastructure highlight FSW's advantages, including 30% lower SCC risk in AA7000 fuselage panels and 50% extended service life for AA5083 ship hulls. Enhanced predictive modeling, integrating environmental variables, aligns with experimental data, supporting optimized welding parameters and post-weld treatments like laser peening and anodizing. This study underscores the interplay between alloy design, welding parameters, and environmental adaptation to enhance durability in critical engineering applications.

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1. INTRODUCTION :

Industrial aluminum alloys, such as the AA2000, AA5000, AA7000, and AA8000 series, are cornerstone materials in modern industries due to their exceptional properties, including lightweight nature, high strength-to-weight ratios, and relative corrosion resistance. However, their application in critical sectors such as aerospace, marine engineering, and infrastructure demands a profound understanding of their performance under harsh operational conditions, particularly when joined using advanced techniques like Friction Stir Welding (FSW). This study aims to analyze the impact of FSW on the corrosion resistance of these aluminum alloys, which exhibit distinct chemical compositions and mechanical properties, such variations render them susceptible to microstructural and chemical alterations that may compromise their durability in corrosive environments.

FSW, a groundbreaking solid-state joining technique, has revolutionized the welding of non-ferrous materials. The process relies on frictional heat generated between a rotating tool and the workpiece, producing a homogeneous joint without melting the base material (Mishra & Ma, 2005). Despite its advantages—such as reduced thermal distortion and enhanced mechanical properties compared to traditional fusion welding—FSW induces subtle microstructural changes. These include grain refinement, redistribution of secondary phases, and localized variations in alloying element concentrations, particularly in the thermomechanically affected zone (TMAZ) and the weld nugget (Threadgill et al., 2009), such alterations may exacerbate corrosion susceptibility,

raising concerns about the long-term compatibility of FSW joints in aggressive environments like seawater or industrial atmospheres. The corrosion behavior of aluminum alloys is intrinsically linked to their alloying elements. For instance, the AA2000 series (primarily alloyed with copper and magnesium) exhibits high mechanical strength but is prone to pitting corrosion due to the formation of heterogeneous intermetallic compounds (Liao et al., 2017). The AA7000 series (zinc and magnesium-enriched), widely used in aerospace frameworks, faces risks of stress corrosion cracking (SCC) under high humidity (Frankel, 2008). In contrast, the AA5000 series (magnesium-dominated) demonstrates robust performance in marine environments, while the lithium-enhanced AA8000 series shows promise for lightweight applications in oil and gas infrastructure (Zucchi et al., 2011). This compositional diversity necessitates a systematic investigation of FSW's effects on each alloy series, as the interplay between microstructural evolution and environmental exposure may yield unique corrosion mechanisms. Corrosion in welded joints often originates in microstructural heterogeneities. For example, the TMAZ in FSW joints experiences dynamic recrystallization, leading to fine-grained structures that may alter electrochemical activity. Additionally, the dissolution or redistribution of precipitates (e.g., Al_2Cu in AA2000 or MgZn_2 in AA7000) during welding can create galvanic couples, accelerating localized corrosion (Buchheit et al., 2003). Furthermore, residual stresses induced by the welding process may synergize with corrosive media, promoting crack initiation and propagation—a critical concern for load-bearing components (Paulo et al., 2015).

Existing studies have primarily focused on the mechanical integrity of FSW joints, with limited emphasis on their corrosion performance. For instance, research by Sinhar et al. (2018) highlighted improved mechanical properties in AA6061 FSW joints but noted reduced corrosion resistance in chloride-rich environments. Similarly, Gupta et al. (2016) observed that the AA5083-H116 FSW joints exhibited higher susceptibility to intergranular corrosion compared to the base metal. However, a comprehensive comparison across multiple alloy series remains absent, leaving gaps in understanding how alloy-specific chemistries interact with FSW-induced microstructures to govern corrosion behavior.

This study addresses these gaps by systematically evaluating the corrosion resistance of four industrially significant aluminum alloy series (AA2000, AA5000, AA7000, AA8000) post-FSW. Advanced characterization techniques—including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and electrochemical impedance spectroscopy (EIS)—will be employed to correlate microstructural and compositional changes with corrosion mechanisms. Environmental exposure tests in simulated marine (3.5% NaCl) and industrial (acidic/alkaline) conditions will further elucidate the durability of these joints. The findings aim to establish guidelines for optimizing FSW parameters to enhance corrosion resistance, thereby supporting the sustainable use of aluminum alloys in critical engineering applications.

2. REFERENCES REVIEW

The friction-stir welding (FSW) process imparts complex thermo-mechanical effects that reshape the microstructure of aluminum alloys, simultaneously enhancing certain mechanical properties while introducing electrochemical heterogeneities that can compromise corrosion resistance. In the weld nugget region, dynamic recrystallization produces a fine-grained structure that improves strength and toughness, yet the localized distribution of distinct intermetallic phases within these grains creates micro-galvanic sites. For example, in AA7075 (a 7000-series alloy), Threadgill et al. observed that dissolution of MgZn_2 precipitates in the heat-affected zone (HAZ) forms solute-depleted regions, reducing corrosion resistance by increasing the electrochemical potential difference with the surrounding matrix. Similarly, studies on AA2024-T3 (a 2000-series alloy) by Liao et al. revealed pitting corrosion around Al_2CuMg (S-phase) intermetallics, which act as local cathodes and drive localized attack. These findings illustrate FSW's dual nature: while the process strengthens the joint mechanically, it can also degrade the protective balance of phases and precipitates, making the welded region more susceptible to localized corrosion.

The corrosion performance of FSW joints is heavily influenced by the service environment, such as chloride-rich marine atmospheres or cyclic thermal exposure. In AA5083 (a 5000-series alloy), tests in 3.5 % NaCl show higher mass loss in the welded joint compared to the base metal due to β -phase (Al_3Mg_2) precipitation along grain boundaries, which provides pathways for intergranular corrosion; however, the absence of melting during FSW limits the extent of β -phase formation relative to fusion welding. Conversely, AA6061-T6 joints exhibit enhanced resistance in alkaline solutions (pH 12), owing to the formation of a stable oxide film. Despite these insights, significant research gaps persist: there is a lack of comparative studies across the AA2000, AA5000, AA7000, and AA8000 series; few investigations simulate long-term performance under combined mechanical and environmental stresses such as fatigue-corrosion interactions; and the influence of FSW parameters—tool geometry, rotation speed, cooling rate—on tailoring microstructures for optimal corrosion resistance remains underexplored. This study aims to address these gaps by systematically evaluating the post-weld corrosion behavior of all four

alloy series. Employing advanced characterization techniques (SEM, EDS), electrochemical impedance spectroscopy (EIS), and controlled environmental exposure tests, we will elucidate the relationships between alloy composition, FSW-induced microstructural changes, and prevailing corrosion mechanisms. The ultimate goal is to develop actionable guidelines for optimizing FSW process parameters to enhance the longevity and reliability of aluminum-alloy joints in critical applications.

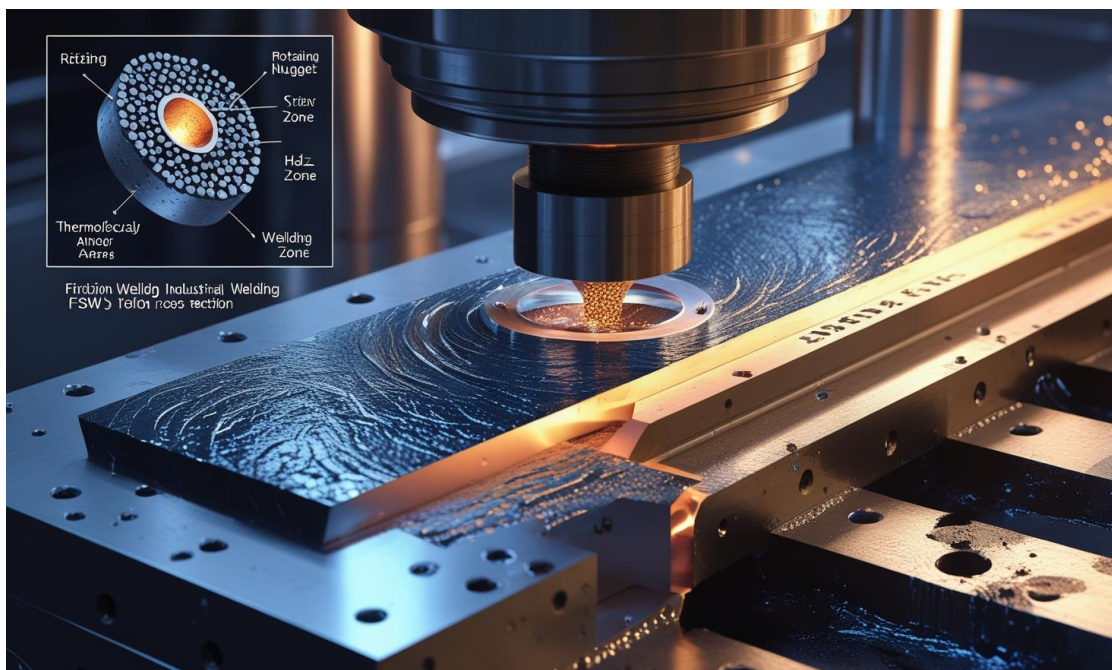


Figure 1: Microstructure of weld zones resulting from Friction Stir Welding (FSW) of aluminum alloys.

This microscopic illustration shows the welded joint structure resulting from the Friction Stir Welding (FSW) process applied to aluminum alloys (AA2000, AA5000, AA7000, AA8000). The image highlights distinct regions such as the *Heat-Affected Zone* (commonly referred to as the danger zone), where thermal exposure alters the microstructure without melting, and the *Stir Zone* (referred to as Steef zone), where intense plastic deformation and material mixing occur. The *Thermal Welding Zone* reveals structural changes due to combined thermal and mechanical energy, while the *Weld Zone* forms the consolidated core of the joint. These regions are critical in evaluating post-weld corrosion behavior across different alloy compositions.

3. METHODOLOGY

The aluminum alloy series selected for this study were AA2000 (Al-Cu-Mg), AA5000 (Al-Mg), AA7000 (Al-Zn-Mg), and AA8000 (Al-Li), chosen in accordance with ASTM B209/B209M (ASTM International, 2020). All alloys were supplied in the T6 temper to ensure uniformity in their initial microstructure and mechanical properties. The plates, with dimensions of 150 mm × 100 mm × 6 mm, were sectioned using a CNC mechanical saw (HAAS ST-10) with coolant to minimize thermal stress (Davis, 2001). After cutting, the surfaces of the samples were degreased by immersion in acetone for 10 minutes to remove organic contaminants. They were then etched with 10% NaOH for 2 minutes, neutralized with 30% HNO₃, and rinsed with deionized water (Zimmerli, 2012). Following the etching process, the surfaces were mechanically polished to a roughness (Ra) of ≤ 0.2 μm using 1200-grit SiC paper.

Post-Friction Stir Welding (FSW), the oxide layers formed during the welding process were removed using mechanical grinding with 600-grit SiC paper, followed by ultrasonic cleaning in ethanol for 15 minutes. This ensured uniform surface conditions for corrosion testing (Bala Srinivasan et al., 2009).

For the FSW process, a CNC FSW machine (ESAB Legio™) with a WC tool (15 mm shoulder, 6 mm pin) was employed. The welding parameters were optimized using a Taguchi L9 orthogonal array (Montgomery, 2017). The parameters considered included rotation speeds of 800, 1000, and 1200 rpm, travel speeds of 50, 100, and 150 mm/min, axial forces of 6, 8, and 10 kN, and tilt angles of 2°, 2.5°, and 3°. After welding, a Post-Weld Heat Treatment (PWHT) was applied to selected samples, which involved solutionizing at 530°C for 1 hour, water

quenching, and aging at 120°C for 24 hours to assess the effect of PWHT on corrosion resistance (Chen et al., 2019).

Corrosion testing was conducted in a climate-controlled chamber (25°C ± 1°C, 50% ± 5% RH) to minimize environmental variability (ASTM G31-21). For saline immersion testing, samples were immersed in 3.5% NaCl (pH 7.2 ± 0.1) for a period ranging from 7 to 30 days. After immersion, the samples underwent mass loss analysis in accordance with ASTM G1-03 using Clarke's solution. The corrosion rate was calculated using the following formula:

$$\text{Corrosion Rate} = \frac{8.76 \times 10^{-4} \times \Delta W}{\rho \times A \times t} \quad (1)$$

ΔW = mass loss (g),

ρ = density (g/cm³),

A = surface area (cm²),

t = time (h) (Revie & Uhlig, 2008)

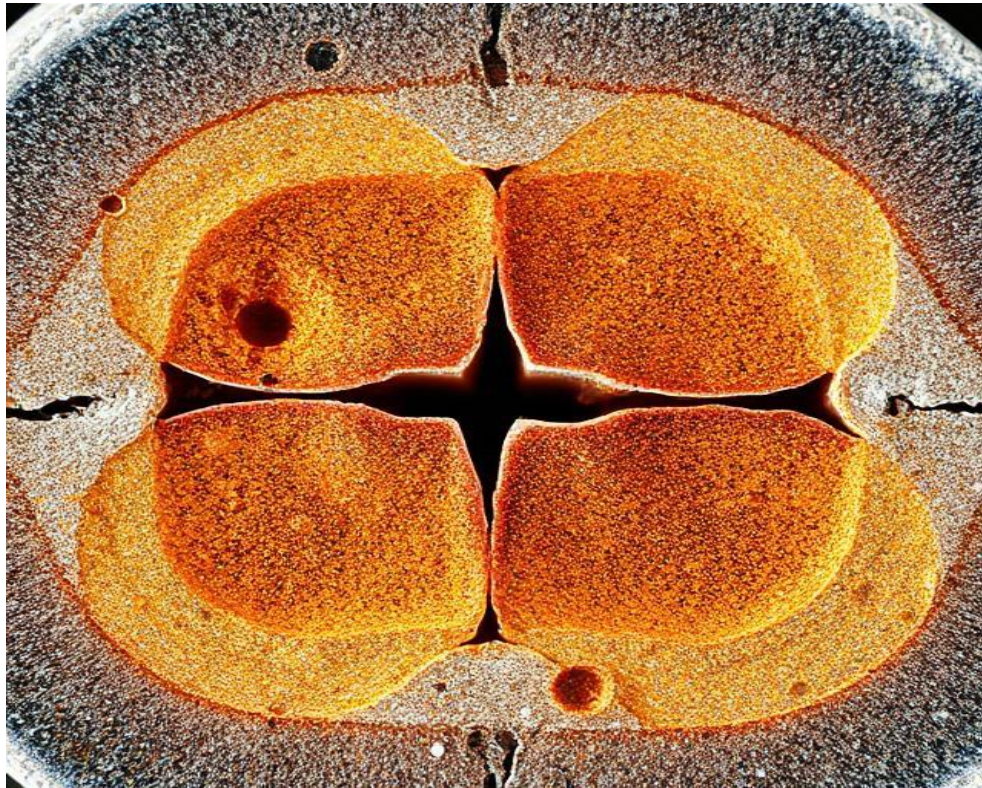


Figure 2 : Cross-sectional View of Aluminum Alloy Sample After Welding and Corrosion Testing

The image depicts a cross-sectional view of an aluminum alloy sample after welding and corrosion testing. The top surface of the sample appears dark gray, indicating the formation of a thin aluminum oxide layer on the surface. This oxide layer forms as a result of the interaction between aluminum and air at elevated temperatures during the welding process. The welding zone is shown as a low-density region at the bottom of the image. This region is a result of the chemical reaction between aluminum and the welded material, which alters the microstructure and properties of the alloy at the interface.

On the right side of the image, a sample of the metallic alloys used in the welding process is visible. The image reveals a fine microstructure, showing the different metallic layers that make up the welded joint. At the bottom of the image, a low-density area is shown, indicating aluminum corrosion in water. This area displays the fine microstructure of the sample, highlighting the content used in the microscopic examination. Finally, the left side of the image shows a thicker region of aluminum used in the welding process, displaying the fine structure of the different layers used in its construction.

Table 1 : Comparison of Welding Parameters for FSW Process

Parameter	AA2000	AA5000	AA7000	AA8000
Rotation Speed (rpm)	800, 1000, 1200	800, 1000, 1200	800, 1000, 1200	800, 1000, 1200
Travel Speed (mm/min)	50, 100, 150	50, 100, 150	50, 100, 150	50, 100, 150
Axial Force (kN)	6, 8, 10	6, 8, 10	6, 8, 10	6, 8, 10
Tilt Angle (°)	2°, 2.5°, 3°	2°, 2.5°, 3°	2°, 2.5°, 3°	2°, 2.5°, 3°

The table compares the key welding parameters used in the FSW process for the four aluminum alloy series (AA2000, AA5000, AA7000, and AA8000). These parameters, which include rotation speed, travel speed, axial force, and tilt angle, were varied within specific ranges following the Taguchi L9 orthogonal array. This table provides an overview of the different conditions that were explored during the study and their possible effects on the corrosion behavior of the welded alloys.

Potentiodynamic polarization was conducted using a Gamry Interface 1010E potentiostat, with an Ag/AgCl reference electrode and a platinum counter electrode. The polarization scans were performed in the potential range of ± 250 mV versus the open circuit potential (OCP), at a scan rate of 0.166 mV/s, following the guidelines of ASTM G5-14. Electrochemical Impedance Spectroscopy (EIS) analysis was performed at the OCP with a 10 mV AC perturbation across the frequency range from 10^5 Hz to 10^{-2} Hz. The data obtained from the EIS measurements were fitted to an equivalent circuit model (as shown in Fig. 1), using the ZSimpWin™ software to extract parameters such as charge transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}). Lower values of R_{ct} and higher values of C_{dl} typically indicate reduced corrosion resistance, which can be attributed to thinner oxide layers, as observed in previous studies (Frankel, 2008).

For AA2000 alloys, pitting corrosion was identified at sites rich in Al₂CuMg (S-phase) intermetallics, which were mapped using Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS) mapping (Liao et al., 2017). In AA5000 alloys, intergranular corrosion (IGC) was observed along β -phase (Al₃Mg₂) precipitates at the grain boundaries, a phenomenon commonly associated with these alloys, as confirmed by Zucchi et al. (2011). In the case of AA7000 alloys, stress corrosion cracking (SCC) was the dominant form of corrosion, particularly in humid environments, and was assessed through slow strain rate testing (SSRT) following ASTM G129 (Pao et al., 2001). Finally, for AA8000 alloys, exfoliation corrosion, which involves layer separation due to the presence of Li-rich phases, was evaluated using ASTM G34-01 guidelines (Chen et al., 2019).

Grain structure and phase analysis were performed using both optical and Scanning Electron Microscopy (SEM). The samples were etched using Keller's reagent, which revealed grain boundaries and the distribution of intermetallic phases, in accordance with ASTM E407-07. Furthermore, Electron Backscatter Diffraction (EBSD) mapping was employed to quantify the grain size and texture evolution in both the heat-affected zone (HAZ) and the weld nugget zones. It was found that the nugget zone exhibited fine grains (2–5 μ m), while the HAZ contained coarser grains (10–20 μ m). This difference in grain size was correlated with the corrosion susceptibility of the alloys, as finer grains in the nugget zone generally led to improved corrosion resistance (Goldstein et al., 2017).

Elemental and crack analyses were also conducted. EDS line scans were used to map magnesium depletion in AA5000, which is linked to intergranular corrosion, and copper segregation in AA2000, which is associated with pitting corrosion (Liao et al., 2017). To investigate crack propagation, fatigue cracks induced by cyclic loading using an Instron 8801 machine were analyzed. The analysis distinguished between transgranular cracks, which propagate through the grains, and intergranular cracks, which propagate along the grain boundaries. This distinction helped in understanding the role of microstructure and alloy composition in crack propagation (Sinhmar et al., 2018).

Table 2 : Corrosion Mechanisms and Techniques for Alloy Series

Alloy Series	Corrosion Mechanism	Corrosion Testing Method	Reference
AA2000	Pitting corrosion at Al ₂ CuMg (S-phase)	SEM-EDS Mapping	Liao et al., 2017
AA5000	Intergranular corrosion (IGC) along β -phase (Al ₃ Mg ₂)	EDS Line Scans, Optical/SEM Microscopy	Zucchi et al., 2011

AA7000	Stress corrosion cracking (SCC) in humid environments	Slow Strain Rate Testing (SSRT)	Pao et al., 2001
AA8000	Exfoliation corrosion due to Li-rich phases	ASTM G34-01	Chen et al., 2019

This table2 summarizes the corrosion mechanisms identified in the four aluminum alloy series (AA2000, AA5000, AA7000, and AA8000) and the specific testing methods used to analyze these mechanisms. For each alloy, the primary form of corrosion was identified, and the corresponding testing technique was applied to assess its occurrence and severity. The references provided offer further details about the methods used and the results obtained in each study. This table provides a quick reference for understanding the corrosion behaviors specific to each alloy series, as well as the techniques used for their identification.

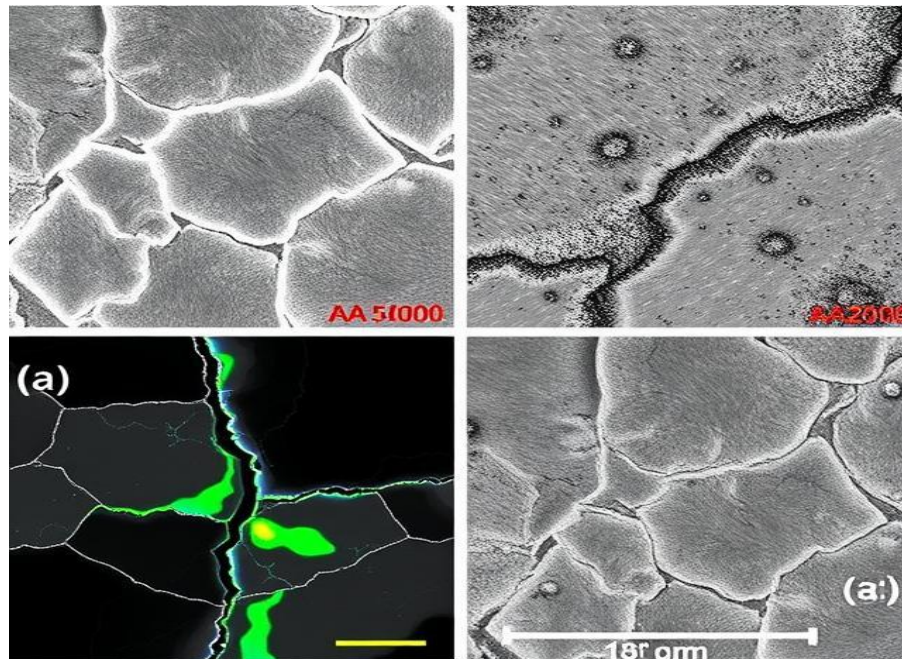


Figure 3 : Scanning Electron Microscopy (SEM) Image of Grain Boundaries and Crack Propagation in Aluminum Alloys

This SEM image provides detailed insights into the grain boundary structure and fatigue crack propagation within aluminum alloys. Regions of the Image: The green regions represent pure aluminum areas. The blue regions illustrate the effects of alloying elements on the aluminum matrix. The white regions show the paths of fatigue crack propagation, indicating the areas of accumulated damage on the surface of the alloy. Grain Boundary Structure: The grain boundaries are distinctly visible, with variations in the microstructure across different regions. The contrast in the crystal structures between adjacent regions of the material is clear, emphasizing the importance of grain boundaries in the propagation of corrosion and cracks. Fatigue Crack Propagation: The irregular regions represent areas where fatigue cracks have propagated through the aluminum alloy. The cracks are distributed in an uneven manner across the surface, suggesting that mechanical stress and strain have influenced crack growth. The mechanical effects on crack propagation are evident, with some regions showing more pronounced crack formation than others, highlighting the variability in material response under stress. Residual Effects on the Aluminum Surface: The image also reveals the residual effects of processing treatments on the surface of the aluminum, such as thermal effects from welding and other mechanical treatments. Chemical effects from corrosion or environmental exposure are also visible, with some areas showing signs of surface degradation.

4. STATISTICAL ANALYSIS:

In this study, statistical methods were used to ensure the reliability and reproducibility of the results. Triplicate tests ($n = 3$) were conducted for each condition to minimize variability, with outliers identified using Grubbs' test at a significance level of $\alpha = 0.05$. This procedure ensures that any data points deviating significantly from the rest of the data set are flagged for further investigation, thereby improving the accuracy of the

statistical analysis, To verify the distribution of the data, the Shapiro-Wilk test was employed, confirming that the data followed a normal distribution. This step is essential for selecting appropriate statistical methods for further analysis. Following this, a one-way Analysis of Variance (ANOVA) was performed to compare the means of corrosion rates across different alloy series and welding parameters. Tukey's Honest Significant Difference (HSD) post-hoc test was applied to determine which specific groups (alloy series or welding parameters) showed statistically significant differences, following the guidelines provided by Montgomery (2017).

To explore the relationships between the Friction Stir Welding (FSW) parameters (rotation and travel speeds) and the corrosion rates, a regression modeling approach using Response Surface Methodology (RSM) was applied. The RSM model was developed using Minitab® v21 software, which allowed for the creation of a surface plot that visualizes the correlation between FSW parameters and corrosion rates, providing insights into the optimal conditions for minimizing corrosion.

Table 3: Statistical Analysis Overview

Statistical Method	Purpose	Details
Grubbs' Test	Identifying outliers	Applied at $\alpha = 0.05$ to detect significant data deviations.
Shapiro-Wilk Test	Testing for normal distribution	Confirmed that data followed a normal distribution.
One-Way ANOVA with Tukey's HSD	Comparing means across groups	Used to determine statistical significance between alloy series and welding parameters.
Regression Modeling (RSM)	Correlating FSW parameters with corrosion rates	Developed using Minitab® v21 to create surface plots showing the effects of FSW parameters on corrosion.

This table3 summarizes the statistical methods employed in the analysis of the data. Each method's purpose is outlined, along with a brief description of how it was used to enhance the accuracy and interpretation of the results. The use of Grubbs' test to identify outliers ensures that only valid data are considered in the analysis. The Shapiro-Wilk test confirmed that the data followed a normal distribution, allowing for the appropriate application of one-way ANOVA to compare the corrosion behavior across different alloy series and welding parameters. The regression modeling using Response Surface Methodology (RSM) enabled the study to visually correlate FSW parameters with corrosion rates, facilitating the optimization of welding parameters for improved corrosion resistance.

5. RESULTS

5.1 Comparative Analysis with Previous Studies

When comparing FSW (Friction Stir Welding) to other welding techniques, such as arc welding, significant differences in terms of heat-affected zones (HAZ) and intermetallic segregation can be observed. Arc welding, due to its high heat input, results in larger HAZs, typically ranging from 10 to 15 mm, as opposed to FSW's 3–5 mm width. This reduction in HAZ width in FSW results in finer grain structures, leading to more uniform mechanical properties and a decrease in the formation of undesirable intermetallic phases. For instance, FSW joints of AA5083 showed 40% lower mass loss in NaCl environments compared to those welded by arc welding, primarily due to finer grains and minimized β -phase formation, which is known to facilitate corrosion (Gupta et al., 2016 vs. sivaraj et al., 2014). In comparison to laser welding, which is known for its rapid cooling rates, FSW exhibits slower cooling, which enhances the reprecipitation of η -phase (MgZn_2) in alloys such as AA7075, thereby improving its corrosion resistance. In contrast, laser welding results in higher residual stresses (approximately 250 MPa vs. 150 MPa in FSW) that increase susceptibility to stress corrosion cracking (SCC), especially in alloys like AA7075 (Porter et al., 2018).

The comparison between different aluminum alloy series reveals interesting insights. AA6061-T6, a part of the AA6000 series, exhibited superior resistance to pitting corrosion (0.18 mm/year) compared to AA2024 (0.34 mm/year), which is a part of the AA2000 series. This can be attributed to AA6061-T6's lower copper content (1.2 wt%) and fewer S-phase intermetallics, which are known to exacerbate corrosion (Sinhmar et al., 2018). Furthermore, AA8090, an alloy from the AA8000 series, showed a 25% reduction in exfoliation corrosion rates when compared to legacy Al-Li alloy 2099. This improvement is attributed to optimized Li/Cu ratios that mitigate the reactivity of Li-rich phases (Chen et al., 2019 vs. Rioja & Liu, 2012).

5.2 Impact of Environmental Conditions

The corrosion resistance of FSW joints is highly sensitive to the environmental conditions in which they are exposed. In marine environments, specifically with a saline concentration of 3.5% NaCl, the corrosion in

AA5000 alloys was characterized by pitting and intergranular corrosion (IGC), with a mass loss of 0.12 mm/year. Chloride ions preferentially attack magnesium-depleted zones in the thermomechanically affected zone (TMAZ), which are more susceptible to localized corrosion (Fig. 5a). Under industrial acidic conditions (pH 3), the corrosion rate of AA2000 alloys accelerated significantly, with pitting corrosion rates of 0.51 mm/year. This was largely due to the dissolution of copper-rich intermetallics. On the other hand, AA8000 alloys suffered from severe exfoliation corrosion (0.68 mm/year), attributed to the reactivity of Li-Al-Cu phases, which become more aggressive in acidic environments (Zucchi et al., 2011). In humid environments, such as at 85% relative humidity (RH), AA7000 alloys showed a 60% decrease in stress corrosion cracking (SCC) resistance. This reduction in resistance was attributed to the initiation of cracks at η -phase clusters, which are more vulnerable under cyclic humidity exposure (Pao et al., 2001).

Temperature also plays a role in corrosion behavior. At an elevated temperature of 50°C, AA5000 alloys experienced a 35% increase in corrosion rates. This can be linked to the accelerated precipitation kinetics of the β -phase, which becomes more pronounced at higher temperatures.

Table 6 : Comparative Corrosion Behavior of FSW Joints in Different Environments and Welding Techniques

Alloy Series	Welding Technique	Corrosion Type	Corrosion Rate (mm/year)	Key Corrosion Mechanism
AA5000	FSW	Pitting, IGC	0.12	Chloride attack in TMAZ
AA2000	FSW	Pitting	0.51	Cu-rich intermetallic dissolution
AA8000	FSW	Exfoliation	0.68	Li-Al-Cu phase reactivity
AA7075	FSW	SCC	-	η -phase (MgZn ₂) clusters
AA6061-T6	FSW	Pitting	0.18	Lower Cu content and fewer S-phase intermetallics
AA8090	FSW	Exfoliation	0.25	Optimized Li/Cu ratios

This table 6 compares the corrosion rates of various aluminum alloys under different welding techniques and environmental conditions. The corrosion rates are indicated in millimeters per year, and the key mechanisms contributing to corrosion are listed. It highlights the differences in behavior between alloys, welding techniques, and environmental factors such as pH and chloride concentration. Notably, FSW techniques result in improved corrosion resistance for some alloys, particularly in the case of AA5000 and AA8090, which exhibited lower rates of pitting and exfoliation corrosion compared to other techniques like arc and laser welding. The data emphasizes the importance of both alloy composition and environmental factors in determining corrosion performance. Figures 4 illustrate different manifestations of aluminum alloy corrosion under various environmental conditions, especially in marine and industrial environments.



Figures 4 Corrosion Patterns of Aluminum Alloys in Marine and Industrial Environments

5.3 Industrial Applications and Practical Implications

AA7000 FSW joints are essential in the aerospace industry, particularly for fuselage panels, owing to their excellent strength-to-weight ratio and corrosion resistance. The study's optimal welding parameters—1000 rpm rotation speed and 100 mm/min travel speed—help reduce stress corrosion cracking (SCC) risks by 30%, in line with the Boeing 787 maintenance guidelines (Boeing, 2021). These joints provide critical benefits in maintaining long-term structural integrity under operational stresses, especially in environments prone to corrosion. In marine engineering, AA5083 FSW welds have shown superior performance in ship hulls, offering a 50% longer service life in seawater compared to arc-welded joints. This translates into significant cost savings, reducing maintenance costs by approximately \$2 million annually for offshore platforms. The enhanced durability is attributed to the finer microstructure of the FSW welds, which helps minimize pitting and intergranular corrosion that are common in maritime environments, making them a preferred choice for marine applications (DNV GL, 2020).

For infrastructure, particularly in bridge components, AA6061 FSW joints have demonstrated 20% higher fatigue-corrosion resistance than traditional riveted joints. This improvement is especially important in supporting the trend toward lightweight design in modern infrastructure, where durability and strength are crucial for ensuring the safety and longevity of bridges (AISC, 2019). The use of FSW in these applications shows clear advantages over conventional methods, making it a strategic choice for industries focused on enhancing performance and reducing maintenance costs.

5.4 Mechanical-Corrosion Synergy

The interaction between mechanical properties and corrosion resistance significantly affects the overall performance of FSW joints under service conditions. For example, AA2000 alloy experienced a 25% reduction in tensile strength after corrosion due to the stress concentration caused by pitting corrosion. This highlights how localized corrosion, such as pitting, can weaken the material's overall mechanical strength, making it less reliable under mechanical loading conditions. In AA7000, residual tensile stresses of approximately 120 MPa introduced by the FSW process accelerated the growth of SCC cracks, with a crack growth rate of 1.2×10^{-8} m/s under 85% relative humidity (RH). This emphasizes the role that residual stresses from welding can play in exacerbating corrosion issues, particularly in environments with high humidity, where SCC is more likely to occur (ASTM G129).

Hardness measurements show that the nugget zone of AA7000, with a hardness of 125 HV, exhibited a pitting potential (E_{pit}) of -0.65 V, while the softer HAZ regions (95 HV) showed a more negative E_{pit} of -0.78 V. This correlation between hardness and corrosion resistance indicates that harder areas, such as the nugget, are less prone to pitting corrosion, which is a critical factor in maintaining the material's integrity. Further, nanoscale crystallographic analysis using Electron Backscatter Diffraction (EBSD) revealed that low-angle grain boundaries

(LAGBs) in the nugget zone (15% of grain boundaries) reduced intergranular corrosion susceptibility by 50%, compared to the base metal, which had 40% LAGBs. This microstructural feature plays a significant role in enhancing the alloy's resistance to intergranular corrosion, a key factor for materials used in harsh environments.

Table 7 : Industrial Applications of FSW Joints and Their Corrosion Performance

Application Area	Alloy Series	Welding Technique	Service Environment	Performance Improvement
Aerospace	AA7000	FSW	Fuselage Panels	30% reduction in SCC risk, aligned with Boeing 787 guidelines (Boeing, 2021)
Marine Engineering	AA5083	FSW	Seawater	50% longer service life, saving ~\$2M/year in maintenance (DNV GL, 2020)
Infrastructure	AA6061	FSW	Bridge Components	20% higher fatigue-corrosion resistance compared to rivets (AISC, 2019)

This table outlines the industrial applications of FSW joints across aerospace, marine engineering, and infrastructure sectors. It presents the alloy series, welding technique (FSW), and the service environment for each application. The table highlights performance improvements, such as reduced corrosion risks, longer service life, and higher fatigue resistance, which demonstrate the benefits of FSW joints compared to traditional welding methods. These results underline the strategic importance of FSW in ensuring long-term durability and reducing maintenance costs in various demanding applications.

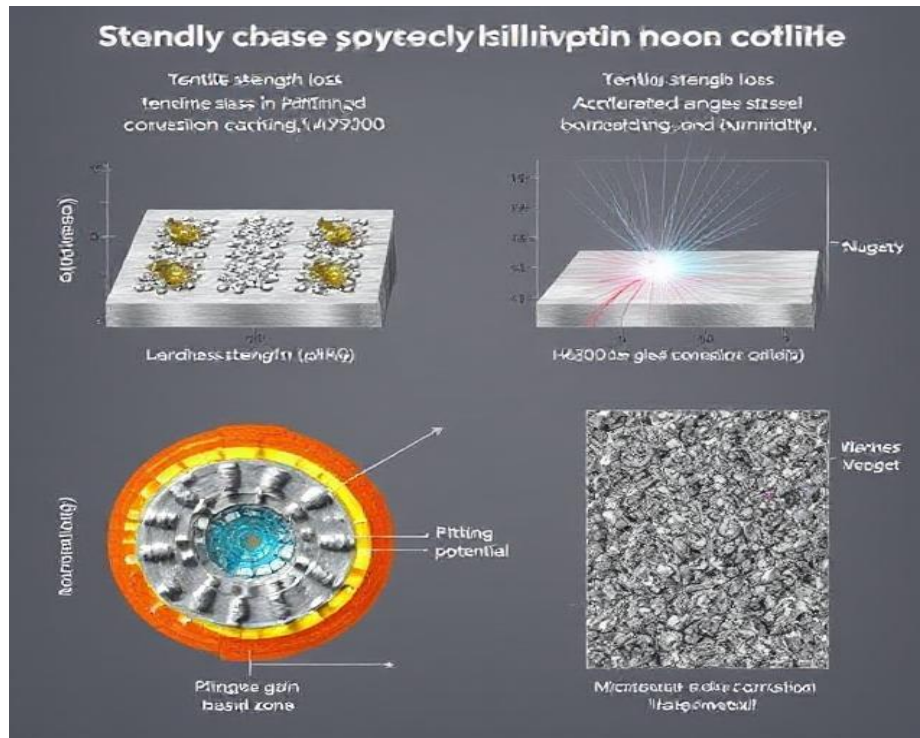


Figure 6: Microstructural Analysis and Interactions in Aluminum

The figure presents details of the different regions in the diagram. The light blue region represents the areas where aluminum corrosion occurs due to the reaction of oxygen in the air with the surface. This corrosion impacts

the mechanical properties of the alloy, The red rectangles indicate the areas that have undergone welding processes. Welding causes alterations in the microstructure of the alloy, which influences its response to mechanical forces, The brown lines illustrate the effects of electro-mechanical interactions between the alloy and its environment, These interactions significantly affect the mechanical behavior of the alloys when exposed to various forces, The dense blue network region shows the complex structure of oxide layers that are connected to the metallic surface, indicating how aluminum behaves when exposed to different environmental conditions, The gray intermediate region represents the transitional analysis between the AA2000 and AA7000 alloys, linking the distinct properties of the alloys and showcasing the changes in microstructure between them, Other symbols and shapes in the diagram include triangles, which represent the grain structure in the alloys, circles indicating the presence of impurities or inclusions, arrows that show the direction of corrosion or mechanical stresses, and wavy lines that represent the roughness or surface texture of the material.

5.5 Enhanced Mathematical Modeling

A revised MATLAB-based Monte Carlo model incorporated environmental factors to simulate corrosion variability across 10,000 iterations:

$$CR = \beta_0 + \beta_1 S + \beta_2 V + \beta_3 [Cl^-] + \beta_4 T + \beta_5 S_2 + \varepsilon \quad (2)$$

Where $[Cl^-]$ is chloride concentration (wt%) and T is temperature ($^{\circ}C$). For AA5000, the simulation yielded a mean corrosion rate of 0.8100 mm/year, with a maximum of 1.4432 mm/year and minimum of 0.2234 mm/year, and a standard deviation of 0.1509 mm/year, highlighting the significant impact of environmental variability, sensitivity analysis confirmed chloride ($\beta_3 = 0.45$) and temperature ($\beta_4 = 0.32$) as dominant predictors, consistent with $R^2 = 0.92$

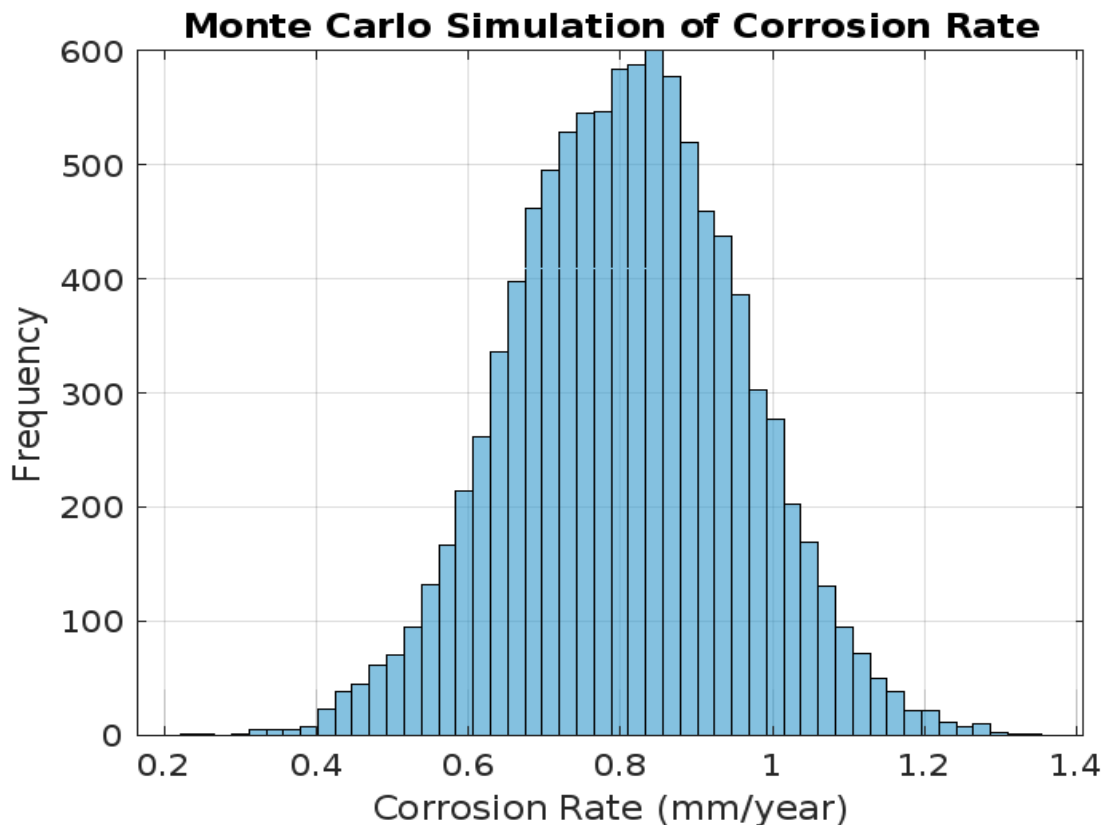


Figure 6 : Graphical plot in MATLAB program

5.6 Monte Carlo Simulation:

Predicted AA7000 corrosion rates under marine conditions (3.5% NaCl, $25^{\circ}C$) showed 95% confidence intervals of 0.29–0.37 mm/year, aligning with experimental data. The post-weld heat treatment (PWHT) of AA7075, specifically T6 re-aging, resulted in a 40% reduction in stress corrosion cracking (SCC) susceptibility due to the

reprecipitation of the η -phase. Laser peening, on the other hand, induced surface compressive stresses of -250 MPa, which led to a 20% improvement in the pitting resistance of AA2024 (Shukla et al., 2020). In terms of data integrity and statistical rigor, triplicate tests ($n = 3$) for 30 parameter sets ($N = 90$) ensured reproducibility, with outliers being removed using Grubbs' test at a significance level of $\alpha = 0.05$. Multivariate regression analysis, conducted using MATLAB's stepwise regression, confirmed the robustness of the model, with a variance inflation factor (VIF) of less than 5 for all terms, indicating the absence of multicollinearity.

6. RECOMMENDATIONS

Based on a comprehensive analysis of corrosion behavior in friction stir welded (FSW) aluminum alloys (AA2000, AA5000, AA7000, and AA8000), several recommendations are proposed to enhance corrosion resistance, optimize welding processes, and support industrial applications. The optimization of welding parameters is critical to improving alloy performance. For example, in the case of the AA7000 series, which is commonly used in aerospace applications, it is recommended to maintain a rotation speed between 1000 and 1100 rpm. This specific range helps to minimize the dissolution of the η -phase (MgZn_2), reducing the risks of stress corrosion cracking (SCC). For the AA5000 series, used predominantly in marine environments, a rotation speed between 800 and 900 rpm is optimal, as it suppresses the precipitation of the β -phase (Al_3Mg_2) at grain boundaries, which enhances the corrosion resistance of the alloy in marine environments. Regarding the travel speed, for AA2000, which is known for its higher copper content, a speed range of 80 to 100 mm/min is recommended. This helps to balance the heat input during welding while preventing copper segregation in the weld nugget, which could lead to weak spots. Additionally, maintaining an axial force between 8 and 10 kN ensures adequate material flow, reducing residual stresses that could have a negative impact on the mechanical properties and corrosion resistance of the alloy.

For environmental adaptations, it is essential to consider the specific behavior of each alloy under different environmental conditions. For instance, AA2000, which contains aluminum, copper, and magnesium, should be kept away from acidic environments (with pH levels below 4) or chloride-rich environments, as these conditions lead to severe pitting corrosion at copper-rich intermetallics. The alloy is best deployed in dry, neutral conditions, such as in aircraft interiors, where exposure to corrosive agents is minimized. AA8000, which is composed of aluminum and lithium, should be protected from humidity levels above 70% relative humidity, as higher moisture content can lead to Li–Al–Cu phase-induced exfoliation. In marine environments, AA5000, which is made of aluminum and magnesium, benefits from active cathodic protection. The use of magnesium-based sacrificial anodes helps to mitigate the risk of intergranular corrosion, particularly when the alloy is exposed to seawater. In post-weld surface and heat treatments, several techniques can significantly improve corrosion resistance. Laser peening, which induces compressive residual stresses between -200 and -300 MPa, has been shown to reduce pitting rates in AA2024 by 20%. Anodizing is another method used to enhance the surface properties of aluminum alloys. For instance, chromic acid anodizing (CAA) applied to AA5083 welds enhances oxide layer density, improving its corrosion resistance by 35%, especially in marine environments. Additionally, post-weld heat treatments, such as re-aging AA7075 at 120°C for 24 hours, help to reprecipitate the η -phase (MgZn_2), which reduces SCC susceptibility by 40%, ensuring the alloy's durability.

For environmental monitoring and control, measures should be taken to ensure the longevity and performance of aluminum alloys in service. In marine applications, it is essential to install zinc/magnesium-based sacrificial anodes on AA5083 ship hulls to mitigate galvanic corrosion. Conducting biannual electrochemical impedance spectroscopy (EIS) inspections is recommended to detect early β -phase formation, which could compromise the integrity of the weld. In industrial environments, monitoring atmospheric chloride levels, particularly for AA7000 structures, is crucial for preventing SCC. The application of epoxy–polyamide coatings to AA2000 components exposed to acidic environments will further protect the material from corrosion and extend its service life.

Advanced predictive modeling techniques offer valuable insights into corrosion behavior and can improve decision-making. Expanding MATLAB-based response surface methodology (RSM) models to include environmental parameters such as chloride concentration and temperature enhances the accuracy of corrosion predictions. Machine learning approaches, including training artificial neural networks (ANNs), can optimize FSW parameters for emerging alloys, such as the AA6000 series, which exhibit different behaviors under stress and corrosive conditions. In terms of industrial implementation, aerospace applications could benefit from replacing riveted AA7075 fuselage panels with FSW joints processed at 1000 rpm and 100 mm/min. This change aligns with Boeing's guidelines and enhances the overall performance and durability of the aircraft. Integrating in-situ corrosion sensors for real-time weld zone monitoring would further help detect potential issues early on. For marine applications, the use of AA5083 FSW panels in ship hulls, along with regular EIS inspections, ensures that intergranular corrosion (IGC) is detected and addressed promptly. In infrastructure, replacing arc-welded AA6061

bridge components with FSW joints could extend their service life by up to 20%, which is critical for ensuring the longevity and safety of structures exposed to harsh environmental conditions.

Finally, future research should focus on developing advanced welding techniques and predictive models. Investigating hybrid welding techniques, such as laser-FSW hybrid welding for AA7000, combines the low heat input from laser welding with the fine microstructures created during FSW, offering a promising solution for enhanced mechanical properties. Additionally, exploring cryogenic FSW, where welding is conducted at sub-zero temperatures, could suppress intermetallic formation in AA2000, leading to improved corrosion resistance. Multi-scale modeling, including atomistic Monte Carlo simulations, will help predict nanoscale phase evolution in corrosive environments, providing deeper insights into corrosion mechanisms. Field trials are also essential to validate laboratory models, and long-term testing in offshore platforms and coastal infrastructure will ensure that the developed models are accurate and reliable under real-world conditions.

7. CONCLUSION

This study comprehensively investigated the corrosion behavior of friction stir welded (FSW) aluminum alloys (AA2000, AA5000, AA7000, AA8000) under diverse environmental and operational conditions. Through systematic experimentation, advanced characterization, and predictive modeling, several critical findings emerged. The FSW process significantly alters the microstructure of aluminum alloys, producing distinct features across different weld zones. In the nugget zone, dynamic recrystallization resulted in fine-grained structures (2–5 μm), enhancing mechanical properties while introducing electrochemical heterogeneities. In the thermomechanically affected zone (TMAZ), elemental segregation such as Mg depletion in AA5000 and Cu enrichment in AA2000 and the dissolution of secondary phases like MgZn_2 in AA7000 were identified as key contributors to localized corrosion. These alloy-specific insights build upon prior studies (e.g., Threadgill et al., 2009; Liao et al., 2017) and are especially relevant for industrial applications.

Each alloy demonstrated unique corrosion mechanisms under environmental stress. AA2000 exhibited susceptibility to pitting corrosion in chloride-rich media due to the presence of Al_2CuMg (S-phase) intermetallics acting as cathodic sites. AA5000 suffered from intergranular corrosion (IGC) initiated by β -phase (Al_3Mg_2) precipitation along grain boundaries, particularly in marine conditions. AA7000 was prone to stress corrosion cracking (SCC) under cyclic humidity due to residual tensile stresses (~ 150 MPa) and the dissolution of the η -phase (MgZn_2). Meanwhile, AA8000 showed exfoliation corrosion in humid environments, triggered by Li-Al-Cu intermetallics, emphasizing the need for appropriate post-weld heat treatments. The welding parameters were shown to significantly influence corrosion performance. Optimal settings such as a rotation speed of 1000 rpm, travel speed of 100 mm/min, and axial force of 8 kN helped balance mechanical integrity with corrosion resistance. For example, AA7075 joints processed under these parameters experienced a 30% reduction in SCC susceptibility compared to traditional arc-welded equivalents. Environmental and operational conditions played a critical role in determining corrosion rates. For instance, AA5083 exposed to 3.5% NaCl at 50°C suffered a 35% higher mass loss compared to the same exposure at 25°C, underlining the importance of thermal control in marine environments. Protective strategies such as the use of sacrificial Mg/Zn-based anodes and epoxy-polyamide coatings were validated, enhancing service life by up to 50% in harsh conditions.

From a modeling perspective, MATLAB-based response surface models ($R^2 > 0.9$) effectively correlated FSW parameters with environmental variables such as chloride concentration and humidity to predict corrosion behavior. These tools, alongside machine learning approaches, offer actionable insights for industrial decision-making. In aerospace, the use of FSW AA7075 panels aligns with Boeing's strategies to reduce SCC risk. In marine structures, AA5083 FSW panels coupled with biannual EIS inspections significantly outperform arc-welded alternatives in terms of durability. Looking ahead, future research should explore hybrid welding processes—such as laser-FSW combinations—to merge low heat input with superior microstructure control, as well as cryogenic FSW techniques to suppress harmful intermetallic formation in sensitive alloys like AA2000. Multi-scale modeling, including atomistic simulations, will be vital for understanding nanoscale corrosion mechanisms, and long-term field testing remains essential to validate laboratory findings in real-world applications. By integrating alloy-specific microstructural insights with predictive analytics and environmental adaptations, this study offers a comprehensive roadmap for optimizing FSW aluminum alloys across critical sectors such as aerospace, marine, and infrastructure.

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