Corrosion Behaviour of Dissimilar Aluminium Alloys Joined by Friction Stir Welding – A Review

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Article Received: 25 April 2025 *Article Accepted: 29 April 2025* *Article Published: 10 May 2025*

Citation
R. Gokulakrishnan, "Corrosion Behaviour of Dissimilar Aluminium Alloys Joined by Friction Stir Welding – A Review", Journal of Next Generation Technology (ISSN: 2583-021X), vol. 5, no. 3, pp. 23-30, 2025. DOI: 10.5281/zenodo.15704840

Abstract

Friction stir welding (FSW) is a solid-state joining technique that enables the effective welding of dissimilar aluminium alloys without melting, making it highly suitable for aerospace, marine, and automotive applications. Despite its advantages, the corrosion behavior of dissimilar aluminium alloy joints remains a critical challenge due to differences in alloy composition, electrochemical potentials, and microstructural characteristics. This review explores the corrosion mechanisms that arise in dissimilar FSW joints, including galvanic corrosion, pitting, and intergranular attack. The effects of microstructural heterogeneity, welding parameters, and residual stresses are examined in relation to corrosion susceptibility. Additionally, the review discusses the impact of environmental exposure and highlights various mitigation strategies such as post-weld heat treatments, surface coatings, and process optimization. By analyzing recent findings, the review identifies knowledge gaps and suggests future research directions aimed at enhancing the corrosion resistance and long-term durability of dissimilar aluminium alloy FSW joints.

Keywords: Friction Stir Welding, Aluminum Alloys, Corrosion, Microstructural Heterogeneity

I. INTRODUCTION

Aluminium and its alloys are widely used in transportation, aerospace, marine, and structural applications due to their lightweight nature, excellent strength-to-weight ratio, corrosion resistance, and ease of fabrication. As modern engineering applications demand more efficient and multifunctional structures, joining different grades of aluminium alloys each optimized for specific mechanical or chemical properties has become increasingly important. Dissimilar aluminium alloy joints are typically required where cost, weight, corrosion resistance, and strength must be balanced within a single component or structure [1-2].

Conventional fusion welding techniques, such as Gas Tungsten Arc Welding (GTAW) or Metal Inert Gas (MIG) welding, often pose limitations when joining dissimilar aluminium alloys. These methods can lead to problems such as porosity, solidification cracking, residual stresses, and the formation of brittle intermetallic phases due to high heat input and melting.

To overcome these issues, Friction Stir Welding (FSW) has been developed as a promising solid-state joining technique. Invented in 1991 by The Welding Institute (TWI), FSW uses a non-consumable rotating tool that plastically deforms the material at temperatures below the melting point, resulting in a high-quality joint with minimal defects. FSW has demonstrated notable success in joining similar and dissimilar aluminium alloys with improved mechanical properties and fine-grained microstructures. However, a significant concern that limits the broader application of FSW in corrosive environments is the corrosion behavior of dissimilar joints. Unlike similar alloy welds, dissimilar joints are inherently more susceptible to corrosion due to the electrochemical potential differences between the base materials. This galvanic mismatch can lead to localized corrosion such as pitting, intergranular attack, exfoliation, and stress corrosion cracking (SCC), especially under marine or humid atmospheric conditions [3-5]. In dissimilar aluminium FSW joints, the presence of heterogeneous microstructural zones such as the stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) further complicates corrosion behavior. Each zone exhibits different grain structures, residual stress levels, and distributions of second-phase particles or precipitates, all of which can significantly influence the corrosion mechanism and rate. Additionally, process parameters such as tool geometry, rotational speed, welding speed, and the alloy positioning (advancing vs. retreating side) can influence the extent of corrosion susceptibility by altering material flow and thermal gradients. Although many studies have been conducted on the mechanical performance of dissimilar FSW joints, research into their long-term corrosion behavior is still limited and fragmented. Given the increasing use of FSW in critical structures that operate in aggressive environments, understanding the corrosion characteristics of dissimilar aluminium alloy joints is essential. This includes identifying key influencing factors, understanding corrosion mechanisms, and developing effective mitigation strategies [6-7].

This review aims to systematically present the recent progress in studying the corrosion behavior of dissimilar aluminium alloys joined by FSW. It explores the influence of metallurgical features, galvanic coupling, environmental exposure, and post-weld treatments. The review further identifies challenges and future research directions necessary for improving the durability and service performance of dissimilar FSW joints in real-world applications.

II. Friction Stir Welding of Dissimilar Aluminium Alloys

Friction Stir Welding (FSW) is a solid-state joining process that has revolutionized the welding of aluminium alloys, offering an effective method for producing high-quality joints without melting the base materials. In this technique, a rotating non-consumable tool with a specially designed pin and shoulder is plunged into the joint line of the materials to be welded. The frictional heat generated softens the materials without reaching their melting temperatures, allowing them to be mechanically stirred and forged together as the tool traverses along the joint. The resulting weld exhibits fine-grained microstructures, minimal distortion, and superior mechanical properties compared to conventional fusion welding techniques.

When applied to the joining of dissimilar aluminium alloys, FSW presents distinct advantages. Traditional fusion welding processes often encounter challenges when joining dissimilar alloys due to differences in melting points, thermal conductivities, and chemical compositions, leading to issues such as solidification cracking, porosity, segregation, and the formation of brittle intermetallic phases. In contrast, FSW, by operating below the melting point, mitigates many of these problems and enables the successful joining of alloys with dissimilar characteristics. Commonly welded dissimilar combinations include AA2024 with AA6061, AA7075 with AA5083, and AA2219 with AA6061, allowing for the integration of materials that optimize strength, corrosion resistance, and cost-effectiveness within a single structure [8-10].

However, the welding of dissimilar aluminium alloys using FSW is not without its challenges. A key concern is the asymmetric material flow that arises due to the differing properties of the base metals. The arrangement of the alloys specifically, which alloy is placed on the advancing side (AS) and which on the retreating side (RS) significantly impacts the weld quality. Typically, the alloy with higher strength or lower weldability is positioned on the advancing side to ensure better mixing and joint integrity. The resulting welded joint comprises several distinct zones: the stir zone (SZ), characterized by fine, dynamically recrystallized grains; the thermo-mechanically affected zone (TMAZ), where plastic deformation occurs without full recrystallization; and the heat-affected zone (HAZ), which experiences thermal exposure but no mechanical deformation. In dissimilar FSW joints, these zones often exhibit sharp transitions in microstructure and properties due to the different thermal responses and deformation behaviors of the parent alloys. Such heterogeneity can lead to variations in hardness, residual stresses, and corrosion susceptibility across the joint. Elemental migration and interdiffusion, especially of alloying elements like copper, magnesium, and zinc, can result in the formation of local microgalvanic cells, further complicating the joint's corrosion behavior.

Moreover, the FSW process parameters, including tool rotational speed, traverse speed, plunge depth, tilt angle, and axial force, play crucial roles in determining the joint's final properties. An optimal balance of these parameters is essential to achieve sound joints with uniform material flow and minimal defects such as voids, tunnel defects, or kissing bonds. Additionally, tool design and tool material selection are critical when joining dissimilar alloys, as the materials may exhibit different flow stresses and thermal responses, requiring tailored tool geometries to ensure effective stirring and mixing. Overall, Friction Stir Welding has demonstrated significant promise in enabling the joining of dissimilar aluminium alloys for high-performance applications. However, controlling the complex interplay of material flow, thermal exposure, and microstructural evolution is critical to ensuring not only the mechanical integrity but also the corrosion resistance of the welded joints. A deeper understanding of these factors is necessary to further optimize FSW for dissimilar alloy combinations and to fully exploit its advantages in demanding industries such as aerospace, automotive, and marine engineering.

III. Factors Influencing Corrosion Behavior

The corrosion behavior of dissimilar aluminium alloy joints formed by Friction Stir Welding (FSW) is complex and is governed by a multitude of interacting factors. These factors include the metallurgical characteristics of the base materials, the microstructural transformations induced by the FSW process, electrochemical potential differences, welding parameters, and environmental exposure conditions. Understanding these factors is critical for predicting and improving the corrosion performance of dissimilar joints in real-world applications.

A. Microstructural Heterogeneity

One of the primary contributors to corrosion susceptibility in dissimilar FSW joints is the presence of heterogeneous microstructures across the weld zones. The FSW process generates three main zones: the stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). Each of these regions experiences varying degrees of thermal exposure and mechanical deformation, leading to different grain structures and precipitate distributions. In dissimilar welds, the contrast becomes even more pronounced due to the differing physical and chemical properties of the base metals. For example, age-hardenable alloys like AA2024 or AA7075 contain copper-rich intermetallics, while non-heat-treatable alloys such as AA5083 or AA6061 are magnesium-rich. The dissolution, re-precipitation, or fragmentation of second-phase particles during welding can cause localized anodic or cathodic regions, thereby promoting selective attack such as pitting or intergranular corrosion. Moreover, grain refinement in the SZ may enhance corrosion resistance due to a uniform passive film, whereas the HAZ especially on heat-treatable alloys can suffer from over-aging or precipitate coarsening, making it more prone to corrosion.

B. Galvanic Coupling and Electrochemical Potential Differences

Galvanic corrosion is a major concern in dissimilar aluminium alloy joints. When two metals with different electrochemical potentials are electrically connected in a corrosive environment, the more anodic metal corrodes preferentially. In the context of dissimilar FSW joints, alloys like AA2024 or AA7075 (Cu-rich, high-strength alloys) typically act as the anode, whereas AA6061 or AA5083 (Mg-rich alloys) serve as the cathode. This galvanic interaction is further complicated by the formation of new intermetallic phases and compositional gradients at the interface, which can act as localized galvanic couples. For instance, the redistribution of Cu or Mg elements during FSW may create microgalvanic cells that accelerate corrosion on the anodic side of the joint. The relative area of the anode and cathode also plays a role—small anodic areas adjacent to large cathodic surfaces result in higher corrosion rates on the anodic side due to current concentration.

C. Welding Parameters and Thermal Input

FSW process parameters such as tool rotational speed, traverse speed, tilt angle, plunge depth, and axial force significantly affect the heat input and material flow during welding.

These parameters control the thermal cycles experienced by each alloy and influence the extent of intermixing and microstructural evolution. Excessive heat input can lead to over-aging, grain coarsening, or dissolution of strengthening precipitates in age-hardenable alloys, which negatively impacts corrosion resistance. Conversely, insufficient heat may result in poor bonding, voids, or tunnels defects that serve as initiation sites for corrosion. Tool design and alloy positioning (advancing side vs. retreating side) also influence corrosion behavior. For example, placing the more corrosion-resistant alloy on the advancing side can reduce the exposure of the anodic alloy to mechanical stresses and heat, potentially minimizing corrosion.

D. Residual Stresses and Distortion

Though FSW generally results in lower residual stresses than fusion welding, dissimilar joints are still subject to non-uniform thermal expansion and contraction due to different thermal conductivities and expansion coefficients of the base materials. These residual stresses can act synergistically with corrosive environments to promote stress corrosion cracking (SCC), especially in alloys like AA7075 or AA2024. In addition, residual tensile stresses near the weld interface can degrade the protective oxide film on aluminium, making it more susceptible to localized attack under tensile loads.

E. Surface Condition and Oxide Layer

Surface roughness, oxide layer characteristics, and surface contamination also play a role in the corrosion performance of FSW joints. Smooth surfaces typically support better formation of a passive aluminium oxide layer, whereas rough or damaged surfaces especially due to improper tool entry or exit may trap corrosive species and promote localized corrosion. The disruption of the native oxide layer during welding and its subsequent regeneration across different microstructural zones can lead to areas with varied protective capability, contributing to non-uniform corrosion behavior.

F. Environmental Exposure Conditions

The operating environment has a profound effect on corrosion behavior. Chloride-containing environments such as seawater or marine atmospheres are particularly aggressive toward aluminium alloys, especially those with copper or magnesium as major alloying elements. Temperature, humidity, pH level, and time of exposure influence the type and severity of corrosion. Pitting and intergranular corrosion are most common in chloride-rich environments, while SCC may occur in moist, tensile-stressed conditions. Accelerated testing methods like salt spray testing, immersion in NaCl solution, or cyclic corrosion testing are commonly used to simulate service conditions and evaluate long-term corrosion resistance.

G. Presence of Intermetallic Compounds and Particle Distribution

The distribution and composition of intermetallic particles formed during FSW can serve as either cathodic or anodic sites relative to the aluminium matrix. For instance, Al-Cu-Fe-Mn or Mg2Si phases are known to influence local electrochemical activity. These particles can initiate pitting or crevice corrosion, especially if they are incoherent or clustered at grain boundaries. The nature and location of these phases depend on both the base alloy composition and the thermal-mechanical conditions of the FSW process, underscoring the importance of alloy selection and parameter control.

IV. Corrosion Mechanisms

The corrosion mechanisms in dissimilar aluminium alloy joints formed by Friction Stir Welding (FSW) are complex and influenced by the microstructural and electrochemical heterogeneity introduced during the process. The primary forms of corrosion observed in these joints include pitting corrosion, intergranular corrosion, galvanic corrosion, exfoliation, and stress corrosion cracking (SCC), depending on the alloy combination and environmental exposure. Pitting corrosion is a common form of localized attack that initiates at microstructural defects or second-phase particles, such as Al-Cu-Mg or Mg_2Si precipitates. These particles act as cathodic sites, accelerating the anodic dissolution of the surrounding aluminium matrix [11-12]. The stir zone (SZ) often exhibits enhanced resistance to pitting due to grain refinement, while the heat-affected zone (HAZ) may become more susceptible due to precipitate coarsening or dissolution. Intergranular corrosion occurs when grain boundary regions are depleted or enriched with elements such as Cu or Mg, creating electrochemical gradients that favor attack along grain boundaries. This is particularly prevalent in age-hardenable alloys like AA2024 and AA7075.

Galvanic corrosion is a major concern in dissimilar joints, where alloys of differing electrochemical potential are in contact. The more anodic alloy (e.g., AA2024) corrodes preferentially when coupled with a more noble alloy (e.g., AA6061) in the presence of an electrolyte. Exfoliation and stress corrosion cracking may occur under specific conditions of high residual stress and aggressive environments, especially in the HAZ of high-strength alloys. The interaction of tensile stresses and corrosive agents facilitates crack initiation and propagation. Overall, the corrosion mechanisms in dissimilar FSW joints are the result of complex interactions between alloy chemistry, microstructure, residual stress, and service environment, making corrosion mitigation a critical aspect of joint design and application.

V. Corrosion Mitigation Strategies

Mitigating corrosion in dissimilar aluminium alloy joints produced by Friction Stir Welding (FSW) is crucial for extending service life and maintaining structural integrity, particularly in aggressive environments such as marine and aerospace applications. Several strategies can be employed to reduce the susceptibility of these joints to corrosion, focusing on material selection, process optimization, and protective treatments. One of the primary approaches is the optimization of welding parameters, including tool rotational speed, traverse speed, axial force, and tool geometry. Proper selection of these parameters can reduce thermal gradients and improve material flow, leading to more homogeneous microstructures and minimizing defects such as voids or kissing bonds that can act as corrosion initiation sites. Post-weld heat treatment (PWHT) is another effective method, particularly for age-hardenable alloys like AA2024 and AA7075. Controlled thermal cycles can help re-precipitate strengthening phases uniformly and relieve residual stresses, improving both mechanical and corrosion properties. However, care must be taken to avoid over-aging or sensitization, which may degrade corrosion resistance [13]. Surface modification techniques such as anodizing, chromate conversion coating, and organic or metallic painting can provide additional barriers against environmental exposure. These coatings help prevent direct contact between dissimilar metals and electrolytes, thereby reducing galvanic interactions. Corrosion inhibitors and sealing agents can be applied at critical locations, particularly in crevices and exposed weld zones, to protect against moisture ingress and chloride attack. Finally, strategic positioning of base materials placing the more corrosion-resistant alloy on the advancing side can reduce exposure of anodic materials to harsh thermal and mechanical conditions. Implementing a combination of these strategies, tailored to specific alloy pairs and service environments, is essential to enhancing the corrosion resistance and durability of dissimilar aluminium alloy FSW joints.

VI. Conclusion

The application of Friction Stir Welding (FSW) in joining dissimilar aluminium alloys has opened new avenues in lightweight structural fabrication, particularly in the aerospace, automotive, and marine sectors. By avoiding the melting of base materials, FSW offers a defect-free and mechanically superior alternative to conventional welding methods, especially for combinations of alloys that are otherwise difficult to join. However, the corrosion behavior of these dissimilar joints remains a critical challenge that must be addressed to ensure long-term reliability and performance. This review highlights the key factors influencing corrosion behavior in dissimilar FSW joints, including microstructural heterogeneity, galvanic potential differences, residual stress distributions, and the influence of environmental exposure. Corrosion mechanisms such as pitting, intergranular corrosion, galvanic corrosion, and stress corrosion cracking are common in such joints, particularly when age-hardenable alloys are involved. Effective corrosion mitigation requires a combination of approaches, including careful selection of alloy positioning, optimization of welding parameters, post-weld heat treatments, and the application of surface protection techniques such as anodizing or painting. Strategic design and process control can significantly improve corrosion resistance and extend the service life of welded components. Despite the progress made, further research is needed to develop predictive corrosion models, enhance understanding of micro-galvanic effects at the weld interface, and explore new material combinations and protective systems. Advancements in these areas will be essential for the broader application of FSW in critical structural components exposed to harsh environments. Ultimately, integrating corrosion resistance into the design and processing stages is key to realizing the full potential of dissimilar aluminium alloy FSW joints.

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