Microstructural Observations in Friction Stir Welding of Dissimilar Alloys: - A Critical Review

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Abstract- A promising method for combining incompatible metals, friction stir welding (FSW) allows for special material combinations that maximise performance in the automotive, marine, and aerospace industries. However, it can be difficult to achieve uniform mechanical characteristics and microstructural quality throughout the weld joint due to the intricacy of fusing different metals. The microstructural changes and defect forms in FSW of dissimilar alloys, such as magnesium-aluminum, aluminum- steel, and aluminum-copper combinations, are rigorously examined in this paper. Important elements that affect microstructure are covered in detail, including alloy composition, welding conditions, and tool geometry. Within the stir zone, thermomechanical affected zone (TMAZ), and heat-affected zone (HAZ), the development of intermetallic compounds (IMCs), grain refinement, and hardness fluctuations are highlighted. Understanding characterisation methods like energy-dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM) provide a thorough grasp of microstructural alterations and how they affect corrosion resistance and joint strength. Along with highlighting present issues including thermal incompatibility and IMC brittleness, the paper offers solutions for improving FSW procedures. In order to direct future research towards producing dependable and superior joints in challenging applications, this work attempts to expand our understanding of FSW in dissimilar alloys.

Keywords:- Friction stir welding (FWS),Intermetallic compounds (IMCs), heat-affected zone(HAZ), Dissimilar alloys.

1.INTRODUCTION

The efficiency of friction stir welding (FSW), a cutting-edge solid-state joining method, in connecting incompatible alloys has drawn a lot of interest. Since its debut, FSW has been widely used in the shipbuilding, automotive, and aerospace industries because of its capacity to fuse alloys that are otherwise challenging to fuse using traditional fusion techniques. FSW uses a rotating tool to create frictional heat, which softens the base materials and enables them to mix and join by plastic deformation, as opposed to fusion welding, which involves melting the base materials. Because of this feature, FSW is ideal for combining dissimilar alloys, which frequently pose problems because of variations in mechanical, chemical, and thermal expansion characteristics. Recent research have examined the microstructural alterations that take place in FSW of dissimilar alloys, with a particular emphasis on copper (Cu), magnesium (Mg), and aluminium (Al) as common base materials. In one study, for example, researchers used several tool profiles to examine FSW of dissimilar aluminium alloys and found that tool geometry has a substantial impact on joint quality and grain morphology [1]. According to the study, certain tool designs could enhance grain refinement, which is essential for improving the weld's mechanical qualities. The FSW of aluminium alloys AA5086 and AA7039 was investigated in another work, which focused on the significance of welding parameters in attaining a homogenous microstructure [2]. Their results demonstrated that, especially when combining dissimilar alloys, optimised parameters could reduce defects like voids and cracks that are linked to microstructural inconsistencies.

Because of the intricate interactions at the joint interface, microstructural evolution is a topic of great interest in FSW. Understanding dynamic recrystallisation is crucial, as demonstrated by one work that employed a cellular automaton technique to predict microstructural changes during FSW in the magnesium alloy AZ91 [3]. In a similar vein, a another study that looked at FSW between AA5083 copper and aluminium reported different microstructural zones at the interface, where substantial phase shift and grain refining took place [4]. These investigations demonstrate the intricacy of microstructural development in dissimilar alloy joints, where different grain structures and phase distributions are produced by mixing and heat input.

The development of intermetallic compounds (IMCs), which are frequently brittle and can compromise joint integrity, is one of the main problems in FSW of dissimilar alloys. According to research, ultrasonic assistance may improve mechanical performance by altering the grain structure of Al/Mg alloy joints and perhaps lowering the production of IMC [5]. The FSW of Al and Mg alloys was further investigated in another work, which shown that varying welding speed and rotation rates might affect IMC properties and improve joint durability [6]. Controlling process parameters is essential for lowering IMCs and creating stable microstructures, according to a thorough analysis of FSW of dissimilar alloys [7].

Studies have concentrated on improving mechanical properties by adjusting process parameters in addition to IMC production. One study, for instance, optimised FSW parameters for dissimilar alloys using Grey relational analysis, demonstrating that parameter adjustment may have a direct impact on the welded joint's microstructure and tensile strength [8]. Another study looked at the fractography and fatigue behaviour of FSW zones in two different aluminium alloys, AA5086-H32 and AA6061-T6, and found that improving fatigue life requires microstructural homogeneity [9]. Comparable patterns were noted in the FSW of AA6061 and AZ31B Mg alloys, where the application of an ER5356 filler enhanced the weld strength and microstructural cohesiveness [10].

Additionally, new developments in modelling and simulation methods have shed light on the behaviour of microstructures during FSW. Using simulation techniques to forecast microstructural changes and optimise welding conditions, one study looked at the connecting of duplex stainless steel with low-alloy structural steel [11]. Especially in intricate dissimilar alloy systems, these simulations can be very helpful in customising FSW methods to get particular microstructural and mechanical results. Further studies have demonstrated that the microstructural characterisation of different aluminium alloys is significantly influenced by tool design, particularly in tapered tools [12].

2. EXPERIMENTAL PROCEDURES AND TECHNIQUES IN FRICTION STIR WELDING OF DISSIMILAR ALLOYS

2.1 Tool Design and Materials

Tool design plays a pivotal role in determining the microstructure and mechanical properties of FSW joints, especially when joining dissimilar alloys. The tool geometry, material, and design must be optimized based on the base materials being joined.

2.1.1 Tool Geometry: The pin profile and shoulder size influence heat generation, material flow, and final weld structure. Variations in tool profiles, such as tapered, threaded, or conical shapes, can significantly impact the formation of the weld nugget and heat distribution. For instance, one study [13] investigated the effect of tool geometry on the welding of dissimilar titanium alloy and aluminum alloy, demonstrating that the pin design affects material flow and heat distribution in the weld zone.

2.1.2 Material Selection: To endure the harsh circumstances during FSW, the tool material needs to have strong heat conductivity and wear resistance. Tool steels, carbide materials, and tungsten alloys are examples of common tool materials. Tool life and heat transfer efficiency are directly impacted by the material selection. High-temperature stable tools are crucial for creating flawless junctions, particularly when combining incompatible alloys like copper and aluminium, according to another study [4].

2.2 Welding Parameters

FSW is highly sensitive to process parameters such as rotation speed, welding speed, and axial force. The control of these parameters is vital for controlling the heat generation and material flow, ensuring an optimized microstructure in the welded joint.

2.2.1 Rotation Speed: The quantity of heat produced at the tool-workpiece interface is influenced by the rotation speed. Increased speed can result in overheating, which can lead to undesirable intermetallic compounds (IMCs) or flaws such excessive stirring. Increased rotation speed in the FSW of aluminium alloys improved joint strength, according to research [14], but it needed to be carefully controlled to prevent excessive IMC development.

2.2.2 Welding Speed: The tool's translation speed has an impact on the joint's thermal history as well. Increased welding speeds may result in inadequate heat input, which could cause microstructural flaws and poor bonding. On the other hand, significant grain development or flaws may arise from slow welding speeds. Optimising the welding speed was essential for attaining the greatest mechanical properties in different magnesium and aluminium alloys, according to one study [5].

2.2.3 Axial Force: Controlling the material flow and the final weld shape is made easier by the force that the tool applies to the workpiece. While insufficient axial force might result in a weak joint, excessive force can cause material displacement and weld flaws. The impact of axial force on the interfacial microstructure and joint strength during the welding of duplex stainless steel to low-alloy structural steel was investigated in research [11].

2.3 Process Variations and Enhancements Various enhancements to the traditional FSW process have been proposed to improve the quality and properties of dissimilar alloy joints. These process variations involve modifications in the standard FSW setup, including the use of ultrasonic assistance, hybrid welding techniques, and other process parameters that aim to improve the weld's mechanical properties.

2.3.1 Ultrasonic Assistance: Ultrasonic-assisted FSW, which combines ultrasonic energy with FSW, has been demonstrated to enhance material flow and lessen the development of brittle IMCs, particularly in different Al/Mg junctions. According to research [5], by lowering the development of IMCs, ultrasonic aid in FSW of magnesium and aluminium alloys enhanced weld strength and encouraged finer grain size.

2.3.2 Hybrid Techniques: In order to more successfully combine disparate materials, hybrid methods like Friction Stir Spot Welding (FSSW) and Refill Friction Stir Spot Welding (RFSSW) are being investigated. The efficiency of hybrid FSW techniques for dissimilar alloy welding, including the use of refill tools and spot welding to improve material mixing and joint quality, was examined in another study [7].

2.3.3 Tool Tilt and Rotation Control: When combining alloys with different material qualities, it's crucial to optimise the heat distribution and material flow, which can be achieved by adjusting the tool tilt angle. The impact of tool tilt in the FSW of dissimilar aluminium alloys was investigated in research [15], which demonstrated that accurate tilt angle control enhanced weld quality by regulating material flow.

3. MICROSTRUCTURAL OBSERVATIONS IN FRICTION STIR WELDING OF DISSIMILAR ALLOYS

General Microstructural Characteristics

The joint microstructure in FSW of dissimilar alloys is usually separated into three separate zones: the heat- affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and weld nugget (WN). Because of the combined impacts of temperature, plastic deformation, and the alloys' material properties, each of these zones has distinct features.

1. Weld Nugget (WN):

The WN has a fine, equiaxed grain structure as a result of dynamic recrystallisation and severe plastic deformation. Material flow, rotation speed, and tool design can all have a major impact on the material mixing within the WN in dissimilar alloy welds. Because of elemental diffusion over the alloy contact, intermetallic compounds (IMCs) frequently occur in this zone, particularly in Al-Mg and Al-Cu joints.[2, 4, 16, 39]

2. Thermo-Mechanically Affected Zone (TMAZ):

With elongated grains aligned along the direction of material flow, the TMAZ displays a somewhat distorted microstructure. With a grain structure that progressively shifts from the HAZ to the WN, this zone can still contain traces of the basic materials.[17, 18, 39]

3. Heat-Affected Zone (HAZ):

The temperature cycle affects the HAZ, which is next to the TMAZ, but it doesn't change. This area frequently experiences grain coarsening, particularly for metals with high thermal conductivity. Variations in hardness and tensile strength result from the thermal gradient's impact on the HAZ's mechanical characteristics and grain structure.[5, 19, 20, 40]

Different Alloy Combinations Specific Observations for

1. Aluminum-Magnesium (Al/Mg) Alloys

Because aluminium and magnesium have very different melting temperatures and rates of thermal expansion, the FSW of Al/Mg alloys usually results in the development of brittle intermetallic compounds (IMCs) in the WN. According to studies, adding ultrasonic aid can improve the quality of the weld by reducing the production of IMC and refining the grain structure.[5, 21] While the TMAZ displays partial mixing with elongated Mg grains within the Al matrix, the Al/Mg junctions often display a refined grain structure in the WN. [22, 6]

2 Aluminum-Copper (Al/Cu) Alloys:-

IMCs like Al2Cu are frequently seen in the WN of Al/Cu joints. Usually brittle, these IMCs cause joint embrittlement and decreased ductility. The IMC layer thickness can be reduced and the weld strength increased by optimising process parameters, such as decreasing tool rotation speed. [4, 23, 24] The overall joint strength is increased by the noticeable mixing pattern in the TMAZ of Al/Cu welds, where Cu particles are distributed throughout the aluminium matrix.[8]

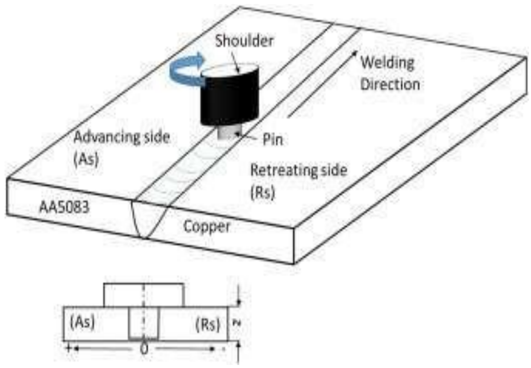

Fig.1 – Experimental setup [4]

3. Titanium-Aluminum (Ti/Al) Alloys

Because of the large variations in hardness and heat conductivity, the FSW of Ti/Al dissimilar alloys is difficult. According to research on Ti/Al junctions, the WN frequently features Ti-rich IMCs and a mixture of titanium and aluminium phases. It has been discovered that modifying the tool design—for example, by employing tapered or threaded pin profiles—improves material mixing and lowers the production of IMC in these connections. [13] The hardness distribution across the joint is influenced by titanium particles found in the aluminium matrix of the TMAZ. [13, 25]

4. Aluminum-Steel (Al/Steel) Alloys

The development of hard, brittle intermetallic phases such as FeAl3 and Fe2Al5 in the WN makes Al/Steel welding difficult. It has been demonstrated that process modifications, including preheating or employing tool materials with strong wear resistance, can regulate the development of these IMCs. Steel often has a wider HAZ than aluminium, which has an impact on the mechanical characteristics of the weld. [11, 26, 27] With steel pieces scattered throughout the aluminium matrix, the TMAZ in Al/Steel joints displays grain elongation, creating a gradient in strength and hardness along the weld cross- section.[28]

5. Aluminum-Aluminum (Al/Al) Dissimilar Alloys

A gradient in the microstructure and mechanical characteristics is visible throughout the weld zones in the FSW of different aluminium alloys, such as AA5083 and AA6061. Because of dynamic recrystallisation, the WN typically has a homogeneous, fine-grained structure, but the TMAZ shows a transition with zones of each alloy that are partially mixed. Grain structure and material flow are greatly influenced by process variables such as tool tilt and rotation speed.[3, 29, 30] The HAZ in softer alloys shows grain coarsening in Al/Al joints with varying temper states, which impacts the tensile strength of the weld.[14, 30]

4. MECHANICAL PROPERTIES

1. Tensile Strength

Material composition, tool geometry, and welding settings all have a major impact on the tensile strength of friction stir welded (FSW) connections made of dissimilar alloys. For example, a study that looked into how different tool profiles affected the tensile characteristics of different aluminium alloys found that a homogeneous mix of alloy elements was promoted by optimising tool pin profiles, which increased tensile strength [1].

Researchers discovered that carefully choosing the tool and welding speeds reduces fault development and increases tensile strength in another work on the FSW of AA5086 and AA7039 [2]. A tapered tool pin design improves joint strength by encouraging efficient plastic deformation and minimising voids, according to research on FSW of titanium and aluminium [13]. Similar to this, process parameters for tensile strength were optimised using grey relational analysis, emphasising the significance of managing temperature gradients to avoid joint interface weakening [23].

2. Hardness

Microstructural alterations during the welding process are intimately related to the hardness of FSW joints. According to a study on AA5083-copper joints, the distribution of hardness across the weld zone is influenced by thermal input; increased hardness is shown at the nugget zone as a result of grain refining [4]. Another study showed that ultrasonic aid during the welding of aluminum-magnesium alloy joints improves the hardness of the stirred zone by further refining the grains [5].

Hardness is also affected by the use of filler materials, as demonstrated in studies using ER5356 filler for AA6061-AZ31B alloy welds. By reducing softening in heat-affected areas, filler materials can assist keep hardness values closer to those of the base materials. In dissimilar joints, where hardness gradients may result in stress concentrations and failure under load, this is particularly crucial [10].

3. Fatigue Behavior

In load-bearing applications, fatigue behaviour is especially important for joints made of different aluminium alloys. Researchers showed that intermetallic compounds and residual stresses have a substantial impact on fatigue life in AA5086-AA6061 joints. Because intermetallics are brittle, their presence may cause early crack onset under cyclic loading [9]. Impulse-induced grain refinement improves fatigue resistance, according to another study that looked at the impact of impulses on Al-Mg-Si alloy joints [22].

The usage of interlayers is an additional strategy for enhancing fatigue life. In order to decrease intermetallic formation in Mg/Al joints, research used a Ni interlayer. This significantly increased fatigue life by reducing the joint's brittle phase and improving ductility and durability under cyclic stress [21].

5. ENVIRONMENTAL AND INDUSTRIAL IMPACT

Environmental Benefits of Friction Stir Welding (FSW)

Because of its solid-state technique, which reduces the need for extra consumables like filler materials and fluxes, friction stir welding (FSW) is known for its environmentally benign qualities. FSW has a far smaller environmental impact than traditional welding techniques since it emits little emissions and doesn't require shielding gases [7], [10]. Furthermore, FSW's reduced energy needs help to make it more sustainable by lowering the carbon emissions linked to high- temperature welding procedures [31], [28]. For example, FSW of magnesium and aluminium alloys reduces thermal input, which lowers energy consumption and related environmental effects [4], [5].

FSW joints' sustainability is further increased by their capacity to be recycled without sacrificing material integrity. Reusing high-performance materials while preserving natural resources and lowering landfill trash is made possible by recycling dissimilar junctions, especially those made of aluminium alloys [11], [32].

Industrial Applications

FSW has made a name for itself in a number of sectors, such as railroads, shipbuilding, automobiles, and aerospace. FSW's capacity to manufacture lightweight, flawless joints in magnesium and aluminium alloys—which are critical for structural dependability and fuel efficiency—benefits the aircraft industry [33], [2]. For example, using FSW in the production of fuel tanks and aeroplane fuselages guarantees fewer flaws, improving performance and safety [13], [16].

FSW is used to weld lightweight materials, like aluminium alloys, which are essential for lowering vehicle weight and increasing fuel economy in the automotive sector [6], [8]. Large panels of magnesium and aluminium alloys are joined by the shipbuilding industry using FSW, which offers superior mechanical integrity and corrosion resistance—two qualities crucial for maritime situations [34], [3].

FSW is used by the railway industry to build high-speed trains because it can attach long panels with great strength and precision, which guarantees dependability and safety [29], [36].

Future Trends and Sustainability

The goal of FSW's future advancements is to increase its industrial and environmental impact. By optimising process parameters for different materials, automation and the integration of artificial intelligence (AI) are poised to transform FSW by boosting productivity and cutting waste [37], [38]. To enhance joint quality and further lower energy usage, tool design innovations are being investigated, such as the use of ultrasonic assistance [5, 20].

In order to reduce the production of intermetallic compounds, increase joint endurance, and prolong the life cycle of welded structures, innovative interlayer materials including nickel and titanium are being developed for welding dissimilar alloys [21], [15]. Additionally, using FSW to recycle valuable materials like magnesium alloys and titanium will greatly cut down on material waste and encourage manufacturing that follows the circular economy [3], [23].

By combining conventional techniques with cutting- edge technologies like laser or impulse-assisted welding, hybrid FSW processes promise to increase its applicability to more difficult materials and complex geometries, guaranteeing sustainability in a wider range of industrial applications [18], [27].

6. CONCLUSION

When it comes to connecting incompatible alloys, friction stir welding (FSW) has shown enormous promise and can provide answers to problems that conventional fusion welding techniques cannot. The importance of welding settings, process improvements, and tool design in maximising microstructural changes and reducing defect forms has been emphasised in this paper. Important conclusions highlight the significance of attaining grain refinement, regulating the production of intermetallic compounds (IMCs), and preserving a balance between tensile strength and hardness across the weld zones. More precise control over FSW processes has been made possible by the richer understanding of microstructural behaviour offered by advanced characterisation techniques like SEM and EDS.

Addressing the brittleness of IMCs, enhancing thermal compatibility between dissimilar alloys, and using sophisticated modelling tools to forecast microstructural changes should be the main goals of future research. Technologies that promise to improve weld quality and increase the variety of incompatible material combinations include AI-driven parameter optimisation, hybrid welding procedures, and ultrasonic aid. Additionally, the creation of sustainable practices, such recycling FSW joints and cutting energy use, is in line with international environmental objectives.

FSW has industrial promise in the railway, automobile, shipbuilding, and aerospace industries, where strong, lightweight joints are essential. It is anticipated that further developments in FSW technology would spur manufacturing breakthroughs, making it possible to produce dependable and long- lasting parts for demanding applications. FSW may be further optimised to satisfy the changing demands of contemporary industries by tackling present issues and investigating cutting-edge methods, thereby solidifying its position as a revolutionary welding technology.

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