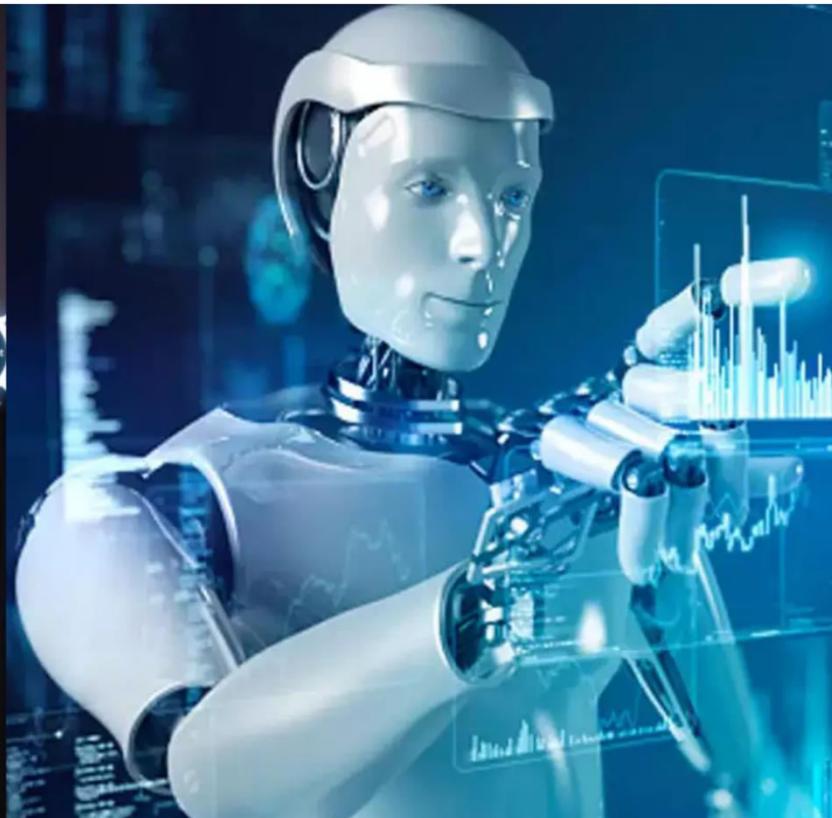




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# **A Review of Recent Advancements in Friction Stir Welding of Al-Mg Alloys for Various Industrial Applications**

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**ABSTRACT:** Friction Stir Welding (FSW) has emerged as a groundbreaking solid-state joining technique, widely adopted for welding aluminium and Magnesium in aerospace, automotive, and marine industries. This method has attracted significant attention for its ability to produce robust, flawless welds without requiring filler materials or melting. Current FSW research focuses on improving joint quality and efficiency, particularly for complex and dissimilar aluminium alloys. Progress in tool design, including the development of advanced wear-resistant materials and multiple-pin configurations, has enhanced FSW tool performance and durability. Furthermore, innovative approaches to process optimization, such as refining welding parameters like tool rotation speed, traverse speed, and axial force, have led to better control of weld microstructure and mechanical characteristics. Researchers have also explored hybrid FSW methods that combine FSW with other welding processes, such as laser and ultrasonic welding, to enhance productivity and joint integrity. The implementation of advanced numerical simulation models has provided deeper insights into process dynamics, enabling more accurate predictions of welding outcomes and improved process control. Efforts to adapt FSW for use in extreme conditions and thicker sections have been made to address challenges associated with welding high-strength, high-thermal-conductivity aluminium alloys. Despite these advancements, issues such as reducing thermal gradients, managing residual stresses, and welding high-strength dissimilar aluminium alloys remain. This review highlights recent advancements in these areas and examines both technological innovations and their industrial applications. The future of FSW for aluminium alloys depends on increased automation, improvements in process control, and the creation of new tools and techniques to meet the changing needs of industries relying on lightweight, high-performance materials.

**KEYWORDS:** Friction stir Welding (FSW), Solid State Joining, Aluminium Alloys

## **I. INTRODUCTION**

Nowadays a large demand for lightweight, fuel-efficient and low emissive structures has been fulfilled by the extensive application of aluminium and magnesium alloys (Al-Mg alloys) [1]. The application of both Al and Mg alloys provides a better design adaptability as well as improved strength and weight ratio [2]. Friction Stir Welding (FSW), developed by The Welding Institute (TWI) in 1991, has become widely adopted across various industries, including aerospace, automotive, and marine. Its popularity stems from its capacity to create robust, flawless welds without requiring filler materials or melting. In contrast to conventional fusion welding methods, FSW operates at temperatures below the material's melting point. This characteristic minimizes common issues associated with fusion-based techniques, such as distortion, porosity, and cracking. Consequently, FSW proves to be an excellent choice for joining materials that are challenging to weld using traditional approaches, particularly lightweight and high-performance alloys like aluminium. As per the statistics of consumption of materials in industries; steel is occupying first position due to their mechanical properties like hardness, strength, stiffness, etc., In the recent times, the usage of aluminium alloys is growing in many industrial applications instead of steel and steel-based alloys, due to its excellent properties such as corrosion resistance [3], light in weight as having one third density of steel, machinability, thermal and electrical conductivity, easy manufacturing methods, low cost of manufacturing, etc. Different aluminum alloys which are developed and widely used for various industrial applications are given in table 1.

Table 1. Various aluminium alloys and its major alloying elements [4].

Alloy series	Major alloying element
1xxx	Pure aluminum
2xxx	Copper (1.9–6.8%)
3xxx	Manganese (0.3–1.5%)
4xxx	Silicon (3.6–13.5%)
5xxx	Magnesium (0.5–5.5%)
6xxx	Magnesium and silicon (Mg 0.4–1.5%, Si 0.2–1.7%)
7xxx	Zinc (1–8.2%)
8xxx	Others

Friction stir welding (FSW) is an innovative welding methodology developed to join especially aluminium alloys [5] and other light-weight materials, economically [6] without any severe distortions which expected to influence mechanical and metallurgical behaviour of welded sample [7,8]. The weldability of various aluminium alloys by fusion welding methods like TIG and MIG welding, and FSW are shown in Figure 1.

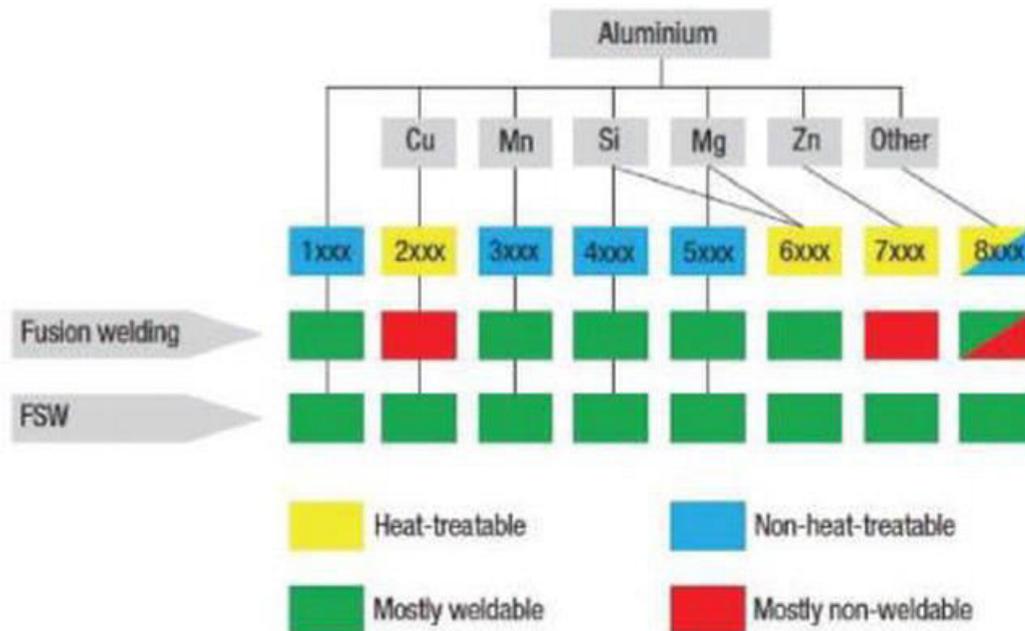


Figure-1 . Weldability of different aluminium alloys [9]

In brief, the FSW process involves two rigidly clamped work parts that are rotated along the thickness using a tool with a shoulder and a specially designed pin (probe), as depicted in Figure 2 [10,11] . FSW consists of four stages, which are plunging off the pin between the two workpieces, dwelling, welding, and retracting (Figure 3). To generate the requisite

heat when the pin penetrates the plates, the shoulder must be in contact with the top face of the work parts. Then, a linear movement of the tool across the abutting edges line should be employed. The friction between the tool and the workpieces will cause heat to be produced. Materials will undergo strict plastic deformation due to tool movement, which adds an additional heat source. In most circumstances, heat will weaken the workpiece material without melting it. The second component of the tool, the shoulder, which is positioned centrally at the top of the tool, releases necessary pressure and aids in the majority of the heat production process, after which the tool moves linearly, and the welding is completed. This method can be utilised for variable joint shapes, including lap, butt, and T-joints, among others.

Moreover, FSW shows promise for joining dissimilar aluminium alloys, as it can produce high-quality welds with favourable mechanical properties [12,13]Cao and Jahazi’s work focused on using FSW to join dissimilar aluminium alloys, specifically AA 2024-T3 to AZ31B-H24 alloys. The effects of tool geometry and welding parameters on weld quality are investigated, and the results demonstrate that FSW can generate defect-free welds in dissimilar aluminium alloys with satisfactory mechanical properties. The welds exhibit comparable tensile strength and fatigue strength to the base metal [14].

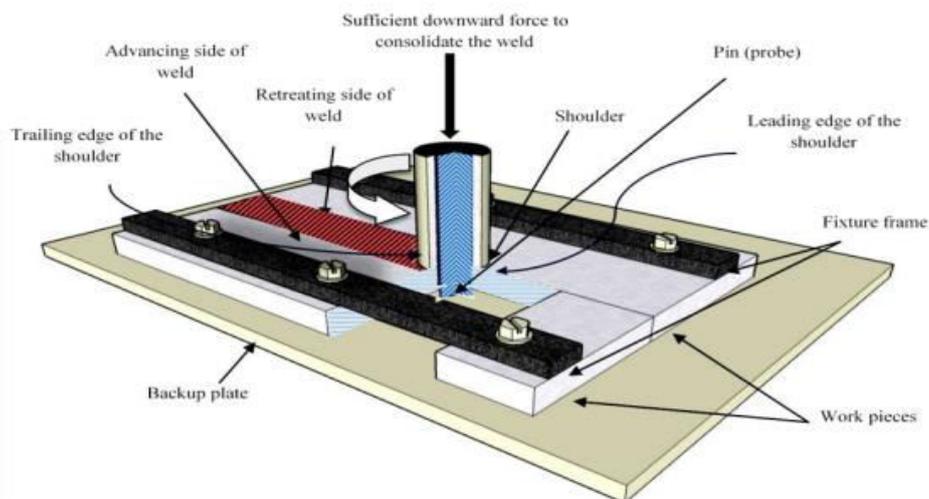


Figure 2. Schematic representation of friction stir welding

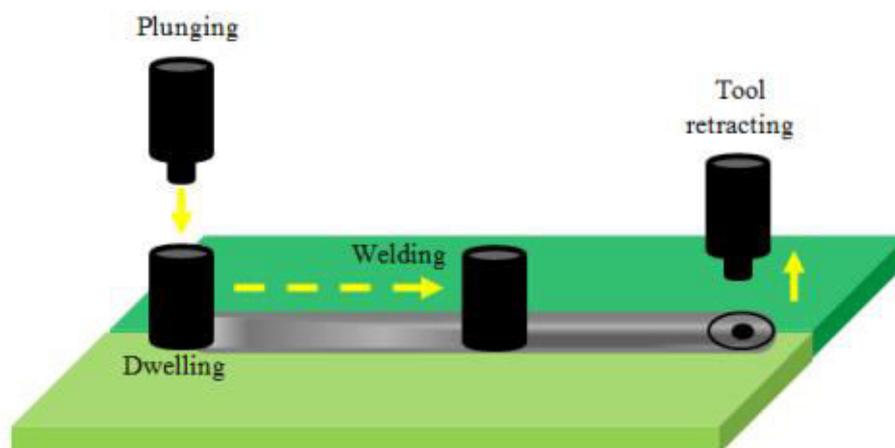


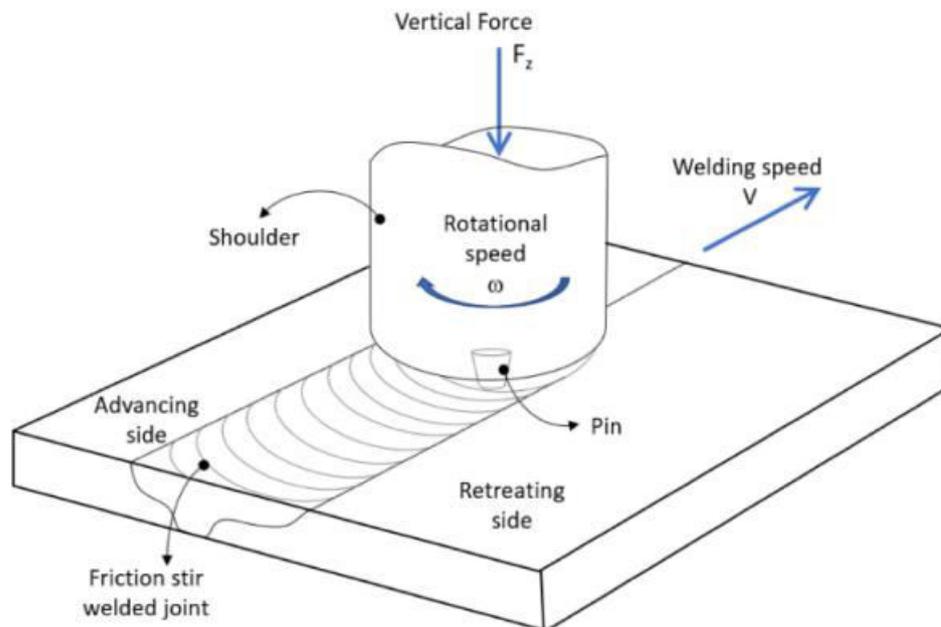
Figure 3. FSW process stages

Aluminium alloy welding is well known for its low tensile and fatigue strength at the weld zone. Friction Stir Welding (FSW) is currently the only effective method for welding the 2xxx and 7xxx series of Alloys [15]. The idea was originated by Thomas et al. [16] in 1991, and the welding institute was tasked with developing the concept. This marked the beginning of the development and adoption of various conventional joining techniques by businesses worldwide, particularly for aluminium and its alloys. Masithulela [17] reported that some companies and applications fully utilise FSW for their products, especially in ship construction, electrical applications, defence, automotive, and aerospace industries.

This review article examines the progress made in friction stir welding (FSW) for maritime applications, emphasizing its benefits compared to traditional techniques. The paper delves into enhancements in weld strength, resistance to corrosion, fatigue behavior, FSW machinery, material choices, corrosion prevention strategies, surface protection methods, and machine learning integration. It proposes areas for future study and stresses the need to consider environmental and economic aspects when implementing FSW technology.

## II. FSW- PROCESS AND WORKING PRINCIPLE

Developed by The Welding Institute (TWI) in 1991, Friction Stir Welding (FSW) is an innovative joining technique that operates in the solid state. Unlike conventional welding approaches, FSW doesn't rely on melting the materials to be joined. Instead, it utilizes mechanical friction and a stirring action to create the weld. This method is especially effective for joining materials that are challenging to weld using traditional techniques, including aluminium, magnesium, and certain other non-ferrous metals.. FSW is particularly useful for joining materials such as aluminium and other non-ferrous alloys, providing superior strength and minimal distortion and making it valuable in the aerospace and automotive industries alongside many others [18-21]. Figure 4 shows a schematic diagram of the FSW process.



**Figure 4.**Schematic of the FSW process.

FSW operates on a fundamental concept where a spinning tool is applied with force to the sides of two materials to be joined. As the tool rotates against the workpieces, it creates friction, producing heat that softens the materials at their point of contact without causing them to melt. The tool's movement then mechanically blends and combines the softened materials, forming a bond between them.

### 2.1 Tool Design and Material Flow in the FSW Process

The FSW tool consists of two main components, the shoulder and the pin; each is designed for specific welding processes. The shoulder, larger and flat, provides downward force for holding workpieces together, whereas the pin is suitable for thinner materials [22]. The shoulder is typically made from a wear- and heat-resistant material, such as tungsten carbide [23-25]. FSW tools often have cooling systems to dissipate the heat generated during welding, ensuring tool life and reducing the frictional forces and heat [26,27]. The pin is the smaller, threaded or profiled part of the tool that penetrates the joint. The size and profile of the pin are crucial for controlling material flow and ensuring the desired joint properties [28]. The pin, made from wear- and heat-resistant material, should be chosen based on the joint requirements and operating conditions. The pin rotates during welding, affecting the material flow and weld characteristics. Proper selection of profile, rotation direction, and speed is crucial for joint quality [29-31]. The FSW process significantly influences the quality and integrity of a weld by controlling the material flow within the plasticized zone, a region of the workpiece that becomes soft and pliable due to frictional heat generated by the rotating tool. This material flow can be described as shown in the Figure 5.

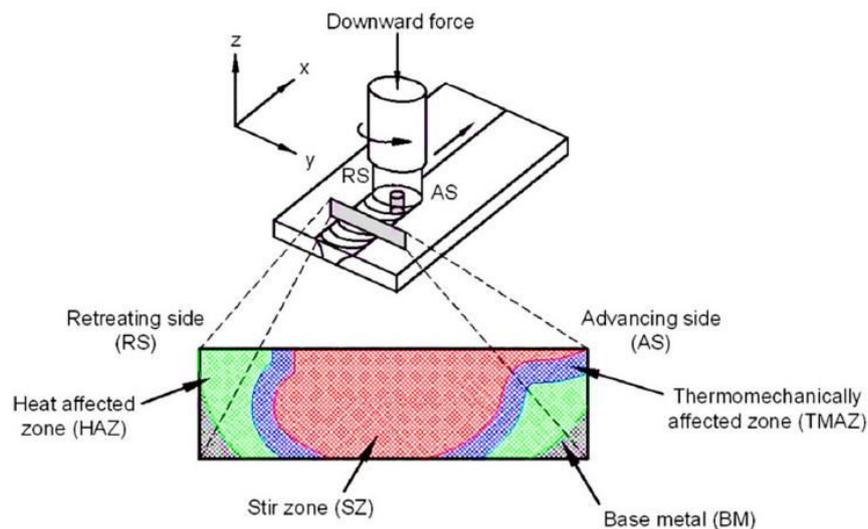


Figure 5. Different welding zones in the FSW process [32].

The rotating FSW tool generates frictional heat, softening material around it and creating a plasticized zone. This process breaks down grain structure, resulting in a finer weld zone and eliminating defects such as voids and inclusions, a common issue in traditional fusion welding. The FSW tool promotes metallurgical bonding, forming a strong, defect-free joint. As it progresses, the material solidifies forming the weld joint, with the “weld nugget” achieving highest strength [32].

### 2.2 Parameters Influencing the FSW Process

The FSW process is influenced by key parameters that determine the weld quality and efficiency. Optimizing these parameters for specific applications is crucial for producing high-quality, defect-free welds with the desired mechanical properties [33,34]. The design of the FSW tool, including the pin and shoulder shape, impacts the material flow, heat generation, and joint quality. The pin profile and shoulder size are customized for specific applications. Tilt angles can optimize welding processes for different materials and joint configurations [35,36]. The applied downward force that is exerted by the FSW machine affects the material contact and friction between the tool and the workpieces. It must be carefully controlled to ensure proper material flow and joint quality [37]. Each of these factors needs to be optimized for the specific material, tool and process used to ensure high quality welds in Friction Stir Welding.

### III. RECENT ADVANCEMENTS IN DISSIMILAR FSW OF AL–MG ALLOYS

Application of various Al and Mg grade are need to be highlighted such as ; Al grade of 2×××, 5××× and 6××× series is popular for commercial use, while, in Mg series, AZ31 is the most commonly used alloy [38,39,40,41]. These light weight materials are extensively used in aerospace and automobile industries, because of its excellent properties [42]. The various parameters and its consequences on joints are summarized in Table 2.

Table 2- Major FSW constraints [43-45]

Parameters	Significant contribution & effects
Rotational Speed	“Stirring action”, frictional heat, Plastic deformation and soft material inter mixing.
Traverse speed	Material and heat flow behaviour, weld appearance.
Tilt angle Tool offset	Bond formation, forging or stirring action Optimally distribution of heat and stresses during dissimilar FSW.
Downward force	Maintaining the contact between tool and workpiece, fraction of frictional heat sharing.

Developments have been seen in terms of tooling and fixtures, the welding technique (especially in-service repair), material combination for high-strength alloys and dissimilar metals, the optimization of welding conditions, improved corrosion resistance, the use of AI and robotics in marine applications, etc., [46,47].

#### 3.1 Mechanical Behaviour of Al-Mg alloys;

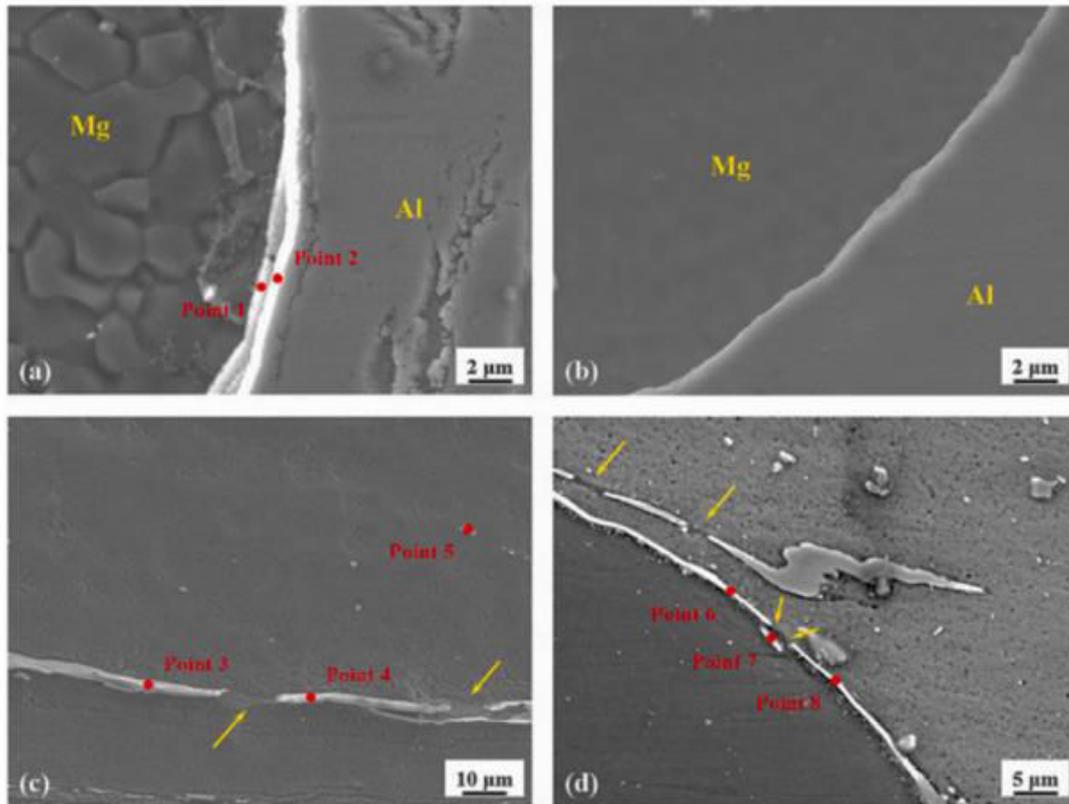
The mechanical behaviour of dissimilar Al–Mg FSW joints is influenced by various factors, including the microstructure, IMC formation, and residual stresses [48]. The joint strength, ductility, and fatigue performance can be evaluated through tensile testing, hardness testing, and fatigue testing. The presence of IMCs can affect the joint strength, with the potential for a trade-off between strength and ductility [49].PWHT or the addition of interlayers/fillers can be employed to modify the mechanical characteristics and enhance joint performance [50].

#### 3.2 Material mixing:

FSW promotes extensive material mixing between the dissimilar Al–Mg alloys, leading to a gradual transition region. The mixing of the materials can result in the redistribution of alloying elements, affecting the local composition and properties [51]. Proper material mixing is essential to achieve a sound joint with improved mechanical properties [52].

### 3.3 Residual Stresses:

FSW induces residual stresses in the welded joint, which can influence the mechanical behaviour and susceptibility to cracking [53].



**Figure 6:** (a) Al/Mg interface showing dual layers of IMC at 800 rpm and 50 mm/min, (b) diminishing of one layer of IMC due to ultrasonic vibrations (UV), (c) discontinued IMC in Mg matrix due to UV, (d) discontinued IMC at Al/Mg interface due to UV, Adopted from ref. [53] with permission. Copyright 2023 Elsevier. [Open Access under a Creative Commons License CC BY-NC 4.0 DEED]

Residual stresses are influenced by factors such as thermal gradients, material flow, and phase transformations during the welding process [54]. Understanding and managing residual stresses are crucial to minimize the risk of distortion, cracking, and premature joint failure [55]. It is important to note that the specific micro structural and mechanical behavior in dissimilar Al–Mg FSW joints can vary depending on the alloy compositions, process parameters, and post-weld treatments employed. Therefore, comprehensive characterization techniques, including microscopy, X-ray diffraction, and mechanical testing, are typically used to assess the microstructure and mechanical characteristics of dissimilar Al–Mg FSW joints in research and development studies [56].

## IV. INDUSTRIAL APPLICATIONS OF FSW OF DISSIMILAR AL-MG ALLOYS

### 4.1 FSW of dissimilar Al–Mg alloys for aerospace applications

The application of the FSW process for dissimilar Al–Mg alloys in aerospace industries offers several advantages and opportunities [57]. Here are some key aspects of the FSW process and its application in the aerospace industry:

- **Lightweight structures:** Aluminium and magnesium alloys are known for their lightweight properties, which are crucial for aerospace applications where weight reduction is a primary concern. FSW enables the joining of dissimilar Al–Mg alloys, allowing the construction of lightweight structures such as fuselage panels, wings, and fuel tanks

- **High joint strength:** FSW produces high-strength joints in dissimilar Al–Mg alloys due to the solid-state nature of the process. The absence of melting and subsequent solidification leads to a refined microstructure and a continuous grain structure, resulting in joints with excellent mechanical properties and fatigue resistance.
  - **Improved fatigue performance:** The FSW process helps in reducing stress concentrations and improving the fatigue performance of dissimilar Al–Mg joints. The homogeneous microstructure and reduced defect formation contribute to enhanced durability and increased service life of aerospace components.
  - **Corrosion resistance:** FSW joints in dissimilar Al–Mg alloys exhibit improved corrosion resistance. The absence of fusion-related defects and intermetallic formation in the joint region reduces the susceptibility to corrosion, making it suitable for aerospace applications exposed to harsh environments.
  - **Design flexibility:** FSW enables the joining of dissimilar Al–Mg alloys with varying thicknesses, allowing for design flexibility in aerospace structures. Complex joint geometries, including lap joints, butt joints, and T-joints, can be achieved using FSW, facilitating the construction of intricate aerospace components.
- Overall, the FSW process for dissimilar Al–Mg alloys in aerospace applications offers lightweight structures, high joint strength, improved fatigue performance, corrosion resistance, design flexibility, cost efficiency, and repair capabilities [58].

As discussed earlier, Al-Mg based alloys and FSW and FSP methods are used in various industries. Because Al-Mg based alloys have a high strength-to-weight ratio, they are extensively used in the automobile industry [59]. Thus, the fuel consumption of the vehicle is reduced using them [60–63,64,65]. On the other hand, these alloys possess suitable biocompatibility and are applicable as a biomaterial. In other words, it is a bio absorbable material such as those for stents and bone implants [66–71,72]. The applications of FSW/FSP technique in various fields could be observed in Figure 7 [73].



**Figure 7.** Applications of FSW/FSP technique in railway, aerospace, automotive, renewable energy, shipbuilding and marine, and defence industries (Reprinted with permission from ref. [73]. Copyright 2020 Elsevier Ltd.)

Other principal utilization of Al-Mg alloys, as well as the FSW/FSP technique could be illustrated as follows [62]:  
(a) Construction industries such as pipelines, bridges, reactors for power plants, and frames. (b) Railway industries such as container bodies, trams, wagons, and underground carriages. (c) Land transportations such as track bodies, engine chassis, tail lifts for tracks, wheel rims, body frames, fuel tankers, and mobile cranes.

- (d) Shipbuilding and marine industries such as marine and transport structures, panels for decks and floors, masts and booms for sailing boats, helicopter platforms, hulls and superstructures, and offshore accommodation.
- (e) Aerospace industries such as cryogenic tanks for space vehicles, wings, aviation fuel tanks, fuselages, and fuel tanks.
- (f) Other Industries such as motor housing

## V. CONCLUSION

The field of Friction Stir Welding (FSW) for Al-Mg alloys has seen notable progress in both its techniques and applications across diverse industrial domains. Al-Mg alloys, valued for their light weight, resistance to corrosion, and high strength, have gained increasing popularity in sectors such as aerospace, automotive, marine, and defence. Ongoing enhancements in FSW have facilitated of stronger, more resilient joints while addressing common challenges associated and conventional welding methods, including distortion, porosity, and cracking. A significant advancement in FSW of Al-Mg alloys has been the fine-tuning of process variable, including welding speed, tool rotational speed and axial force. These factors directly impact the thermal and mechanical conditions during welding, influencing the overall quality and integrity of the joint. Scientists have formulated methods to accurately regulate these variables, leading to improved weld strength, fewer defects, and enhanced micro-structural and characteristics.

Innovation in tool design have been crucial in enhancing the FSW process. Cutting-edge tool materials, coatings, and innovative geometries have reduced tool wear and improved the durability and effectiveness of the welding operation. These advancements have also contributed to cost reduction and increased scalability of FSW for large-scale industrial use. Furthermore, new tool design have aided in minimizing the occurrence of defects such as cracks, voids and excessive heat-affected zones, which can compromise the weld's integrity. The incorporation of sophisticated monitoring and control systems has been a key focus area to ensure consistent, high-quality welds. Technologies such as infrared thermography, acoustic emission, and process tomography enable real-time monitoring, providing better insights and control over the FSW process. These systems can identify parameter variation that might cause defects, allowing for immediate corrections during welding. This significantly enhances weld quality minimizes the need for post-weld inspection and repairs.

The increasing emphasis on sustainable manufacturing has also highlighted the environmental advantages of FSW. The process's solid-state nature, which doesn't involve melting the base materials, results in lower energy consumption and minimal distortion. Additionally, FSW's reduced environmental impact, due to the absence of harmful fumes and gases, position it as an eco-friendly alternative to conventional welding methods, aligning with global efforts towards mora sustainable manufacturing practices. Although significant progress has been made in FSW of Al-Mg alloys, several obstacles persist. These include ensuring uniform joint characteristics across diverse alloy composition, reducing residual stresses, and enhancing the effectiveness of welding thicker materials. Nevertheless, the advancements in this field indicate the FSW will remain a crucial method for joining Al-Mg alloys in industrial settings. Ongoing research and the development of innovative approaches suggest that FSW has considerable potential to facilitate more efficient, economical, and sustainable manufacturing processes for producing high-performance components across various industries. That outlook for FSW in L-Mg alloy application appears promising, with anticipated future developments expected to further expand its versatility and range of applications.

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