ADVANCES IN FRICTION STIR WELDING OF DISSIMILAR ALUMINIUM- MAGNESIUM ALLOYS: A COMPREHENSIVE REVIEW

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Abstract

The paper provides a comprehensive assessment of the advancements made in friction stir welding (FSW) involving dissimilar materials like aluminium and magnesium. It initiates by exploring the theoretical prerequisites, delving into the fundamental understanding of the joining mechanism and heat generation specific to aluminium-magnesium FSW. It proceeds to scrutinize the observed trends in microstructural characterization and mechanical properties. Furthermore, the paper meticulously discusses the intricate relationship between welding parameters, process variables, and material responses, offering insightful suggestions derived from these discussions to improve the practice and comprehension of dissimilar FSW involving aluminium and magnesium.

1. Introduction

Welding has consistently stood out as a pivotal enabling technology throughout various industrial sectors, offering distinct advantages over alternative joining methods like mechanical fastening and adhesive bonding. A fundamental aspect in any joint design is the necessity for achieving mechanical properties that ideally match those of the base materials. Solid state joining and processing technologies are emerging to be common place in industries to join softer metal alloys which are difficult to join using conventional fusion welding techniques. Friction stir welding (FSW), invented in 1991 at The Welding Institute[1].The primary requirements of any joint design will require satisfactory mechanical properties which are ideally comparable to the base materials [2]. Friction stir welding (FSW) is an environment friendly, solid state, and versatile welding technique which can be employed to weld most of the available engineering materials [3, 4]. Weight reduction in automotive and aircraft industries is a main concern in improving fuel economy and reducing environmental pollutions [5, 6]. Magnesium alloys, with a density of about two-thirds of Al alloys, are the promising engineering materials to boost fuel economy especially for the automotive industry [7, 8]. Aluminum alloys are widely used in engineering fields due to their unique properties including high strength, good formability and low density [9]. FSW does not use filler material, leading to considerable weight reduction. Within 26 years of invention, FSW has been proven to beat the forefront of joining high strength aluminium alloys, meant for application in automobile and aerospace sectors, while also savouring partial success in the joining of other metallic alloys [10-18]. Given the remarkable achievements of Friction Stir Welding (FSW), the concept of friction stir has undergone continual modification, enhancement, and revitalization. These advancements have led to the development of various innovative material joining and processing technologies. Consequently, this evolution is progressively facilitating the transfer of technological feasibility to a broader spectrum of high-strength structural materials and more intricate applications [19-28].

Frictions stir welding stands as an innovative technique that is reshaping the realm of material joining, driving its persistent advancement. The motivation behind the continual advances in friction stir welding lies in its unparalleled ability to fuse materials previously deemed challenging or impossible to weld. This innovative process not only offers superior structural integrity and mechanical properties but also mitigates traditional welding limitations such as distortion, porosity, and residual stress. Its versatility spans across a myriad of materials, including aluminum, steel, and even exotic alloys, catering to diverse industries from aerospace to automotive, maritime, and beyond. Dissimilar welding presents a multitude of benefits, including cost reduction, heightened energy efficiency, material optimization, and the capacity to customize material designs to achieve optimal properties in targeted areas. These advantages have been effectively leveraged in the automotive sector, notably through the utilization of stamped dissimilar sheet body structures, often termed as tailor-welded blanks [29-32]. Aluminium and magnesium base metals drive the increase in dissimilar welding demand. Each metal is widely used in the automotive and aerospace industries due to its advantages such as lightweight properties, high specific strength, and recyclability. Although aluminium and magnesium have their own merits, certain advantages favor aluminium, such as its superior strength and creep resistance, or magnesium, due to its superior damping capacity. These results in one metal being preferred over another in particular applications. Using dissimilar welding technology, the combined advantages of both metals can be harnessed according to localized priorities, offering the opportunity to utilize the advantages of both [33]. In spite of this, the formation of brittle intermetallic compounds (IMCs) based on Al-Mg is a significant challenge impeding the advancement of Al-Mg dissimilar welding. To address this issue, the literature has proposed three primary approaches: controlling thermal history by controlling time and temperature, limiting welding temperatures using solid-state welding techniques, and altering chemical reactions at the weld interface [33, 34]. Friction Stir Welding (FSW) stands out as a promising method to mitigate the adverse impacts of intermetallic compound (IMC) formation by utilizing the solid-state welding technique, thereby allowing control over the process's thermal history.

Due to its expanding integration across various industries, this paper conducts an appraisal of recent advancements in joining dissimilar aluminium-magnesium materials using friction Stir Welding. The paper commences with an overview of recent practical strides made in this specific domain. Subsequently, it delves into elucidating the prevalent joining mechanisms and heat generation dynamics. Following this, a comprehensive summary of the observations pertaining to microstructural and mechanical aspects is presented. Lastly, the paper rigorously evaluates the influence of welding parameters on process variables and the subsequent material responses, while also proffering noteworthy considerations for future endeavors in this field.

2. Friction Stir welding procedure and Stages

2.1 The FSW process commences with the initiation of rotation by a machine featuring a friction stir tool as shown in figure 2(a). This non-consumable tool, consisting of a pin and shoulder, is inserted into the joint between two firmly clamped materials supported by a backing plate. During the plunge phase, both the tool and the workpiece remain at ambient temperature, except for the immediate region surrounding the tool and workpiece interface. The rate of temperature elevation and the extent of plasticity largely depend on the insertion rate. This plunge phase concludes upon the tool shoulder's contact with the substrate. Friction and plastic deformation induce local heating, softening the material intended for welding [37, 38]. The tool shoulder generates more heat than the pin surface, and the tool's rotational motion further contributes to additional heat generation through deformation. As the metallic workpiece attains a critical temperature for plastic deformation, the applied force begins to decrease. For metals with higher melting points, the rotating tool can intentionally remain in this position for a predetermined duration, known as a hold time or dwell time, to reach the necessary temperature for plastic deformation. Upon reaching the designated plunge depth, the FSW machine initiates the traverse of the friction stir tool along the weld path. The continuous rotation of the tool, along with specific geometric features on the shoulder and probe, displaces and mixes (stirs) the material along the weld joint. The tool's shoulder restricts metal flow to a level corresponding to its position, typically close to the initial surface of the workpiece. Once the friction stir tool reaches the end of the path, it is retracted from the joint [39].

2.2 Figure 2(b) shows the different stages involved in the FSW process. • Plunging Stage: The tool, rotating at a constant speed, is inserted through the initial point of the workpiece joint line with a vertically downward axial force until the shoulder makes contact with the workpiece surface. This stage commences the deformation process.

• Dwelling Stage: The rotating tool, under axial force and with its shoulder in contact with the workpiece surface, dwells for 5–10 seconds, depending on the material and thickness. This dwelling generates ample frictional heat at the tool-workpiece interface, inducing plasticization of the workpiece. The plastic material ahead of the tool ensures smooth tool traversal during subsequent welding.

• Welding Stage: The rotating tool, under axial load and with its shoulder encompassing the plasticized region, moves consistently along the desired joint line at a constant speed due to traverse force. Tool rotation continues generating heat from friction and deformation. Moreover, the tool's rotation and traverse motions induce material stirring or flow, causing plastic material near the tool pin to move from the advancing side to the rear. The shoulder exerts a forging force on the material behind the pin, effectively filling the cavity created by the pin's forward motion. This promotes material intermixing through atomic diffusion or bonding, forming a joint behind the tool.

• Retracting/Cooling Stage: Upon completing the weld, the tool is retracted, leaving an exit hole. Methods to prevent this hole include refilling or using a longer weld length than intended. The primary functions of the tool are to: a) generate frictional or deformational heat; b) manage material flow; and c) confine plastic material under the shoulder. In thin sheet welding, the shoulder primarily generates heat, while in thicker workpieces; the pin is responsible for most of the heat. To enhance heat generation and material flow, special features on the tool shoulder and pin surfaces can be incorporated. Detailed principles of heat generation in friction stir welding can be found elsewhere. [40, 41]

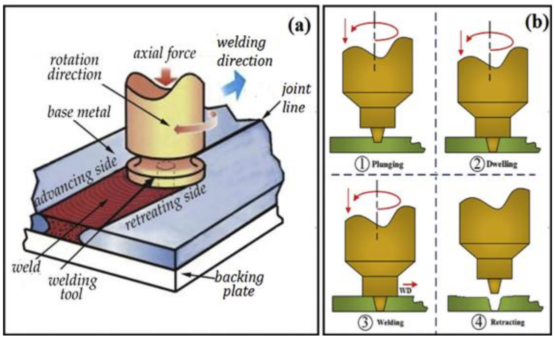

Figure 2(a) Friction stir welding Process and 2(b) stages in FSW

2.1.1 Frictions Stir welding Process parameters

The primary process parameters involved in the FSW (Friction Stir Welding) process include rotation speed, traverse speed, shoulder plunge depth, and tool tilt angle. Additionally, the tool geometry plays a crucial role in achieving reliable welds. Rotation speed and traverse speed control the generation of frictional heat, subsequent plastic deformation, and deformation heat. These factors, combined with plunge depth, significantly impact the axial force exerted on the workpiece, thereby influencing weld quality. The tool is deliberately tilted at a specific angle, and a known plunge depth is applied to the tool shoulder during welding, both aiding in material consolidation behind the pin. Generally, higher rotation speeds lead to increased heat input, while higher traverse speeds reduce heat input by decreasing the duration of tool-workpiece interaction at a given point. Moderate heat inputs are favorable for inducing plastic deformation, facilitating stirring and ensuring material flow in FSW, ultimately determining the formation and strength of the welded joints [42].

2.1.2 The microstructure of the joint

The formation of joints in FSW represents a multifaceted process influenced by the varying thermomechanical actions of the FSW tool. Consequently, the FSW joint demonstrates microstructural heterogeneity. Based on the tool's action and material movement, the welded area can be classified into three distinct zones: (a) the shoulder-affected zone (SAZ), (b) the pin-affected zone (PAZ), and (c) the weld bottom zone (WBZ) as shown in figure 3. Microstructure development within the TMAZ (Thermo-mechanically Affected Zone) primarily occurs due to dynamic recovery, as the levels of temperature and strain experienced are inadequate for recrystallization. Within the TMAZ, grains appear elongated, narrow, and relatively coarser compared to those present in the SZ (Stir Zone). The HAZ (Heat-Affected Zone) often witnesses grain coarsening due to heat influence. Additionally, there exists a variation in microstructure thickness-wise across the weld nugget center due to the presence of the SAZ (Shoulder-Affected Zone) and PAZ (Pin-Affected Zone), while the pin diameter may vary from the top to the bottom of the weld. These differences lead to alterations in the distribution of temperature and effective strain within the SZ.[43- 46]

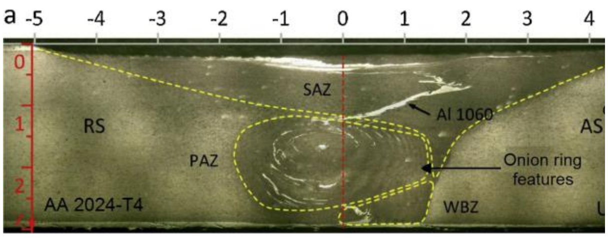

Figure 3: Macro-section of friction stir welded joint depicting SAZ, PAZ, WBZ and onion ring features

The microstructure of a weld significantly influences the mechanical properties of welded joints. For instance, the strength of aluminium alloy welded joints is reliant on factors such as grain size and precipitate. These strengthening elements can be managed, and mechanical properties can be enhanced through various approaches. These methods include meticulous selection of tool profile [47], utilization of composite backing plates [48, 49], implementing forced cooling during welding [50], post-weld heat treatment [51], applying ultrasonic vibrations [52], friction stir alloying among others. Extensive research documented in open literature explores the relationship between structure and properties. However, this paper's focus remains confined to the understanding of the process, its primary parameters, microstructure, and applications.

2.1.3 Feasibility and utilization of FSW

FSW, as a relatively low-temperature welding technique, resolves the drawbacks associated with fusion welding, particularly the formation of weld defects during molten metal solidification. Its successful industrial implementation has facilitated the production of commercial-grade welded joints in Al-alloys. Research findings suggest that FSW holds significant promise for commercially joining Mg alloys. Furthermore, by employing appropriate tool materials, geometry, and process parameters, FSW demonstrates technological feasibility for other alloys characterized by high strength and high melting points, including Fe-, Ti-, Ni-, and Cu-based alloys. Industries are progressively exploring and considering the implementation of FSW for these materials. Ongoing advancements indicate a swift transition from laboratory research to practical application. Moreover, FSW is under exploration for its efficacy in joining dissimilar materials, metal matrix composites, ceramics, polymers, and, more recently, wood-plastics [53, 54]. However, a detailed exposition and review of FSW's application across diverse materials fall beyond the scope of this paper.

3. *Progress in Dissimilar Friction stir welding of Al-Mg*

Various aluminium and magnesium metals are commonly utilized, with the 5xxx and 6xxx series being prevalent for aluminium-based materials, and AZ31 is emerging as the typical alloy for magnesium. This choice isn't unexpected given their widespread use in industrial sectors owing to their exceptional properties. The utilization of various aluminium and magnesium metals is notable, with the 5xxx and 6xxx series being the most commonly used for aluminium-based materials, while AZ31 stands as the typical alloy for magnesium counterparts. This prevalence is unsurprising given the widespread industrial use of these materials due to their exceptional properties. The ensuing analysis endeavors to extract insights from these studies to discern observable patterns. For instance, a meticulous examination reveals significant variations in key parameters like tool rotational speed, welding travel speed, and tool design across the reported literature. Therefore, it is crucial to meticulously analyze these FSW parameters to uncover trends in the resulting dissimilar Al–Mg welds. However, comprehending how these parameters impact the joint outcome necessitates understanding the fundamental aspects of the joining mechanisms and heat generation intrinsic to dissimilar Al–Mg FSW.

3.1 *Joining mechanism in Al–Mg FSW*

The joint strength in heterogeneous structures such as Al–Mg dissimilar welds primarily depends on two Mechanisms, namely; the chemical bonding by the presence of IMCs, and; the mechanical interlocking due to the tortuous weld interface [55, 56]. These metallurgical and mechanical mechanisms are addressed below.

3.2 *Issues related to incompatibility in Al–Mg FSW*

An overview of the basic properties and incompatibility issues between aluminium and magnesium is useful to understand the chemical bonding mechanism. The key problem relates to limited solubility between Al and Mg, which consequently promotes formation of IMCs as indicated in the binary phase diagram for these elements. Figure 4 depicts the equilibrium binary phase diagram of the Al–Mg system [56]. While acknowledging that welding processes are generally non-equilibrium processes [57], the equilibrium binary phase diagram serves as a standard reference for predicting stable phases and anticipated reactions during welding. In Figure 4, the shaded areas indicate the specific compositions of aluminium and magnesium where a single-phase (non-intermetallic) compound formation is feasible, signifying successful solubility between aluminium and magnesium. Notably, considering the solvus lines' trend, it's expected that the solubility of Al–Mg would notably decrease at room temperature (not illustrated).

Several crucial insights can be drawn from the phase diagram. The binary system presents two eutectic lines at 437 and 450°C, significantly lower than the individual melting points of pure Al and Mg. Furthermore, the diagram encompasses three stable intermetallic phases: the Al_3Mg_2 (complex cubic β) phase [54], $Al_{12}Mg_{17}$ (cubic of α-Mn type γ) phase, and rhombohedral R phase (also known as ε-phase) [55]. Due to the extremely restricted solubility between aluminium and magnesium, a blend of primary aluminium or magnesium phases can develop in equilibrium with Al_3Mg_2 and $Al_{12}Mg_{17}$ phases during Al–Mg dissimilar welding. The formation of intermetallic compounds (IMCs) predominantly relies on local temperature and composition, regardless of the chemical composition of the initial base metal alloys. Hence, predicting and interpreting microstructures and stable phases becomes challenging, given that the exact peak temperature during welding is typically unknown.

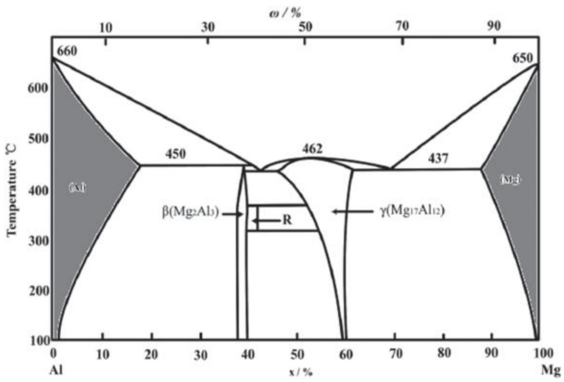

Figure 4: Equilibrium phase diagram of the Al–Mg system [57].

In the context of dissimilar Al–Mg FSW joints, the predominant theories presented in the literature to elucidate the formation of intermetallic compounds (IMCs) are grounded in either diffusion or eutectic reaction mechanisms. The ongoing debate about the dominant mechanism primarily revolves around whether the maximum temperature reached during welding surpasses the Al–Mg eutectic lines of 437°C (magnesium dominant side) and 450°C (aluminum dominant side).

According to Yamamoto et al. [59], they contend that the FSW process operates below eutectic temperatures, implying that the creation and expansion of such compounds occur through diffusion between Al and Mg atoms, consequently yielding eutectic layers.

3.3 *The Al/Mg welding interface*

As will be discussed in detail in the subsequent sections, the formation of these chemical and mechanical bonds in the welding interface varies significantly based on the material of workpiece, tool design and offset, as well as Welding variables and setup. From the arguments above, it can be suggested that an ideal joint should consist of thin, intercalated IMC layers and complex mechanical interlocking. The thin brittle IMC layer may reduce The presence of defects at the weld interface, while a complex mechanical bonding promotes better stress distribution during loading and a more complex crack propagation path [60].

3.4 *Heat generation in Al–Mg FSW*

In Friction Stir Welding (FSW), heat arises from three primary elements: plastic deformation (Ed), friction (Ef) occurring at the tool/workpiece interface, and viscous dissipation (Ev). In dissimilar FSW scenarios, such as Al–Mg welding, these components are influenced by three crucial factors: variations in friction coefficient, liquation susceptibility, and deformability [63]. Zettler et al. discovered that the friction coefficient at the Al-tool interface was higher than in the case of a Mg-tool interface, implying that augmenting interaction between Al and the tool, such as offsetting the tool towards the Al side, would increase the contributions of Ef and Ev during the process [61]. Meanwhile, Yang et al. calculated that the liquation susceptibility of AZ31 Mg is higher when compared to 6061 Al. Upon reaching the eutectic temperature in Mg–Mg FSW, liquid films generated from the eutectic reaction Mg+Al12Mg17 → L at the tool/workpiece interface could potentially lead to tool slippage and interfere with plastic deformation, subsequently reducing resistance to tool rotation. Consequently, the heat generated by Ed, Ef, and Ev decreases, resulting in lower heat input [63]. Additionally, Fu et al. proposed that constitutional liquation plays a dominant role in Al–Mg dissimilar FSW, leading to decreased heat input in contrast to similar Al and Mg FSW [63]. The dissimilarity in deformability between both metals finds its explanation in their respective crystal structures. Aluminium possesses a face-centred cubic (fcc) structure featuring twelve slip systems, while magnesium's hexagonal close-packed (hcp) structure offers only three slip systems. This structural dissimilarity allows better deformability for aluminium, resulting in increased heat generation through Ed and Ev [62, 63].Furthermore, Zettler et al. demonstrated in similar-metal butt joint FSW that the stir zone of Al 6040 alloy was approximately twice the size of the stir zone of AZ31 Mg alloy, indicating the superior deformability of Al [61].

4. *Summary*

A thorough review has been undertaken concerning Al–Mg dissimilar FSW. The aim of this review is to offer insights for future advancements in this particular field. However, due to the interplay of welding parameters and setup, these criteria can only serve as broad guidelines for reference.

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