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ARTICLE

FRICTIONS STIR WELDING OF MAGNESIUM AND ALUMINIUM ALLOYS: A REVIEW

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ABSTRACT

On account of the global warming problem, the emphasis is given on reducing the consumption of fuel in various industries. This problem can be reduced to a greater extent by using light weight Al and Mg alloys. It is essential to weld them properly to extract the specific properties of both the alloys. The evolution of the welding techniques of dissimilar materials is an advanced research topic that has drawn much attention in the recent past. Among many welding methods, friction stir welding (FSW) was considered to be feasible for adequate welding of dissimilar alloys. In this article, a comprehensive review of the FSW process used for adding Al alloy plates to Mg alloy plates and the strength of weld is presented. The effect of process parameters like tool rotational speed, traverse speed, tool inclination etc. on the weld microstructure and strength is also summarized. For the welding of Al/Mg plates, the development and innovative modification of FSW has also been addressed.

KEY WORDS
Aluminium, Magnesium, FSW, Alloys

INTRODUCTION

Recently, the focus has been shifted from traditional metal components to light metal components in several industries for weight saving purpose. The weight saving in the automotive sector might provide better fuel economy as the fossil fuel reserves are depleting with time, and alternative energy resources are not fully operational. In the construction of a lightweight structure, dissimilar lightweight materials have been extensively used as per requirement. The most frequently used materials are aluminium (Al) and magnesium (Mg) alloys. There is a significant amount of weight saving with considerable strength of a structure if these alloys are utilized in an adequate proportion. The joints of dissimilar alloys must be strong enough to bear the applied load. This could be ensured by the use of a suitable welding technique in conjunction with appropriate materials. In fusion welding techniques, the energy density is very high, which creates challenges in the joining of low melting point metals like Al or Mg. Near precise welding of Al to Mg alloys were achieved using TIG welding, which is expensive, slow and difficult to control process for the said materials. Additionally, the joint strength is marginal due to high process temperature, accelerated mixing and formation of brittle intermetallic compounds (IMCs) in the fusion region [1]. In view of these challenges, FSW is considered as an appropriate alternative for high strength welding of these alloys. Because of solid state processing and low operational temperature in FSW, the shape and size of brittle IMCs are almost insignificant. The applicability of FSW for different Al/Mg alloy joints was studied extensively [2–6].

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The present review aims to provide a lucid and systematic review of different Al/Mg alloy welding using FSW. The influence of the processing parameters on the weld strength as well as on weld quality was also incorporated.

SOLID STATE WELDING

In solid-state welding, a sound joint is established between two materials by the coalescence achieved in the solid state using pressure or temperature. However, the temperature must always be below the melting temperature of both the materials. The processes involved in this technique are providing localized plasticization effect, which is responsible for this type of joint. Solid state welding could be accomplished by friction welding, roll welding, forge welding, hot pressure welding, diffusion bonding, explosion welding, cold welding, and ultrasonic welding [7].

FRICTION STIR WELDING (FSW)

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FSW is a type of solid state welding. It was invented in 1991 by the researchers of The Welding Institute (TWI), UK, especially for Al alloys [8]. They named it friction stir butt welding. The tool used in FSW has a particular geometrical design consisting of pin and shoulder, as shown in [Fig. 1]. It must be made from the non-consumable and hard material so that it cannot be deformed or worn out during the process. The rapidly moving tool is inserted into the joint of two materials by applying a downwards force. After this operation, the quick rotating tool moves forward in the direction of the joint. In the contact area of materials and tool, heat generation will take place by friction locally, which will stimulate the plastic deformation in materials. Owing to the localized heating, the material around the pin becomes soft, and due to the rotation and horizontal motion of the tool, the material in front of the pin starts moving in the rear direction. This action occurs in the solid state, and the bond will be established on cooling. As the material comes under the intense plastic deformation in this process, the welded region consists of fine and equally distributed recrystallized grains [9, 10]. As per the Hall-Petch relationship, finer the grains better the mechanical properties [11]. Therefore, a joint established using FSW has better mechanical properties than its counterparts. FSW is considered as energy efficient, environment-friendly and a versatile material joining technique with comparison to traditional joining methods. As there is no need for filler material in FSW, almost all Al alloys can be joined using this technique irrespective of their chemical composition [12]. In this welding, there is no emission of harmful fumes, nor is the presence of solidification cranks in the welded region. Therefore, improved weld quality can be obtained by this method on the proper selection of process parameters. Additionally, this process makes less noise than other welding processes. The FSW processes are broadly classified into two groups, i.e., conventional and self-reacting FSW. The conventional FSW follows the same procedure explained beforehand. It is an advanced, high quality and efficient welding technique for longitudinal, circumferential and varied thickness (butt and lap) joints and commonly utilized in Al, Mg, Cu, Ti and steel alloys. The design of self-reacting FSW tool is unique [Fig. 2]. Unlike conventional FSW, the tool of self-reacting FSW consists of a pin, linked with top and bottom shoulders. It is also named as bobbin tool FSW. The self-reacting FSW tool can be designed for variable pin height as well as for constant force during the entire welding incident [13]. The advantages of self-reacting FSW over conventional FSW are negligible weld roots/root defects, fixture and machine experiences low Z force, no need of backing bar, minimum distortion owing to uniform heat input, and tolerance for thickness variation [14].

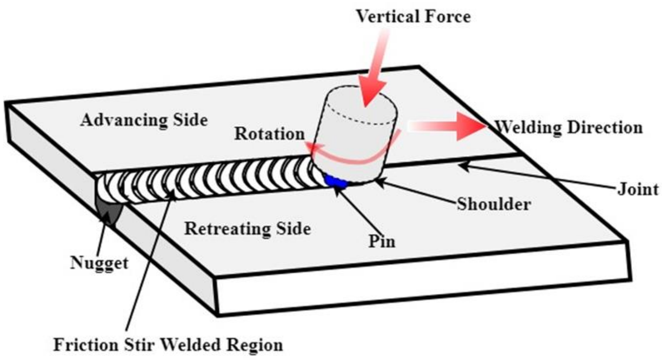

Fig. 1: Schematic drawing of the FSW technique [9].

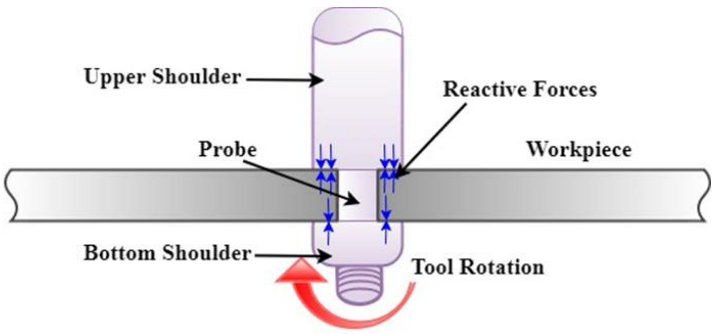

Fig. 2: Schematic of self-reactive or bobbin tool FSW [14].

COMMON CHALLENGES IN DISSIMILAR METAL WELDING USING FSW

It is an arduous task to successfully weld two dissimilar materials using FSW because the thermal characteristics, coefficient of friction and softening behavior of both materials will be different. Therefore, the production, distribution and dissipation of heat will vary in both materials and an unwanted temperature gradient will establish between the materials. Due to this uneven thermal distribution, bonding between the materials will affect, and undesirable defects will introduce in the central region of the weld. Additionally, selection of improper welding parameters will hamper the joint strength to a great extent. Another major issue which affects the welding strength is the formation of IMCs during dissimilar metal welding. The composition, size and shape of IMCs impose a more significant impact on weld quality. As the temperature is involved in the FSW, it cannot be avoided completely during the process. However, it can be mitigated by carefully chosen process parameters for FSW [15].

AL-MG DISSIMILAR ALLOY WELDING USING FSW

The utilization of lightweight metals and alloys like Al, Mg etc. has been extensively increased in several industries due to their specific properties, lightweight and die-castability. Using these light metal and

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alloys, designers get the freedom to build complicated, intricate and amazing yet strong structures. In the creation of complex structures, similar or dissimilar materials need to be fastened together. The requirement of joining two dissimilar materials is essential when two parts of the same structure exposed to different loading conditions or environments. Al and Mg alloys are wonderful materials with marvelous properties, and it is being successfully used in many industries. It has also been cited that they will be abundantly used in the future in automobile, aerospace and marine ventures. To date, their use in many industries is limited because the welding methods have not yet been fully developed. Fusion welding techniques are utilized to serve the purpose, but the joint made is undermined in strength. Usually, the strength of the joint made by fusion welding was reported well below the yield strength of the Al and Mg alloys. The formation and growth of brittle IMCs during this process is considered to be the main reason for the weakness of the joint. To avoid the formation of brittle IMCs in the welding zone, low-temperature pressure welding methods are gaining attention as an alternative to fusion welding techniques. FSW is an attractive welding method of this group and widely used for the welding of lightweight metal sheets. In Al/Mg hybrid structure, the control over brittle IMCs can provide improved welding strength. The temperature generated in FSW is well below the melting temperature of Al and Mg alloys, which effectively minimizes the formation of IMCs in the welding zone. The detailed research progress and parametric optimization of welding of Al and Mg alloys using FSW are reviewed and listed in [Table 1].

Table 1: An overview on research on Al and Mg alloys using FSW

S. No.	FSP Parameters	Material	Outcomes	Year	Ref
1	Plate thickness (PT): 12 mm Weld Length (WL): 160 mm Rotational speed (RS): 300-400 rpm Traverse speed (TS): 1-1.67 mm/s	AZ31B+5083	Sound weld but weld region has virtually no ductility	2003	[16]
2	PT: 2 mm RS: 800 rpm TS: 1.5 mm/s Tilt angle (TA): 1°	AZ31B-H24+6061-T6 AZ91D+6061-T6	Weld region consists of lamellar shear bands.	2004	[5]
3	PT: 6 mm RS: 2450 rpm TS: 1.50 mm/s TA: 3°	1050 (Al)+AZ31	The presence of $Mg_{17}Al_{12}$ IMCs increased the hardness of the weld region.	2004	[3]
4	PT: 4 mm RS: 200-1000 rpm TS: 0.32-1.25 mm/s	AZ31 (Mg)+1060 (Al)	Highest strength of the welded joints: 82.4 MPa Failure Mechanism: Cleavage Type	2005	[6]
5	PT: 2 mm RS: 800-1600 rpm TS: 5 mm/s	Annealed (AZ31B+A5252P)	Defect free weld were reported for 1000, 1200, 1400 rpm. Maximum tensile strength: 132 MPa at 1000 rpm Maximum ductility: 2%	2008	[2]
6	PT: 1.5 mm RS: 1400 rpm TS: 3.75 mm/s	AZ31+AA6040	The interface of FSW exhibited the presence of fine-grained $Al_{12}Mg_{17}$ and nanosized-grained Al_3Mg_2 IMCs.	2009	[4]
7	PT: 6 mm RS: 600 rpm TS: 0.67 mm/s	5052 (Al)+AZ31 (Mg)	Microhardness of weld region was almost double than the base Al and Mg alloys.	2010	[17]
8	PT: 1.2 mm (AA 5083) & 1.3 mm (AZ31) RS: 1500-2250 rpm	AA5083+AZ31	In friction stir spot welding (FSSW), lap share stress was higher when IMCs were mixed with α-Mg+$Mg_{17}Al_{12}$ eutectics.	2010	[18]

9	PT: 4 mm RS: 800 rpm TS: 0.58 mm/s	Al 6061-T6+AZ31	Weld tensile strength (max): 95 MPa	2011	[19]
10	PT: 3.25 mm RS: 900-2700 rpm TS: 1.69-6.4 mm/s Force: 14-30 kN TA: 1° or 3°	6065-T5 (Extruded)+AZ31B-H24 (Rolled)	Best mechanical strength were reported when rotational speed varied in between 900-1680 rpm and welding speed 1.69-4 mm/s	2012	[20]
11	PT: 3 mm RS: 300 rpm TS: 0.83 mm/s TA: 3°	5083 Al+AZ31C-O	Formation of IMCs was low in underwater welding due to less intermixing resulted in smooth surface.	2012	[21]
12	PT: 2 mm RS: 2000 rpm Tool shoulder plunge depth (TSPD): 0.2 mm TS: 3 mm/s	AZ31B-H24 (Mg)+5754-O (Al)	FSW of similar alloys (Mg-Mg) had better lap shear strength, failure energy and fatigue strength than dissimilar alloys weld (Al-Mg) due to the presence of IMCs like $Mg_{17}Al_{12}$ and Al_3Mg_2 in the dissimilar weld.	2012	[22]
13	PT: 2.5 mm RS: 1200 rpm TS: 1.33 mm/s	AA6013+AZ31	Sound joint is obtained using underwater FSW. Maximum Tensile strength: 152.3 MPa Maximum Hardness: 142 HV	2015	[23]
14	PT: 3 mm RS: 600-800 rpm TS: 0.5-1.0 mm/s	6061-T6+AZ31B	Sound and defect free joint, Tensile strength of the weld is 70% of Mg alloy	2015	[24]
15	PT: 3.1 mm (AZ31B) & 2.3 mm (6061) RS: 560-1400 rpm TS: 0.27-0.67 mm/min TA: 3°	AZ31B+Al 6061	Maximum mechanical interlocking and optimum tensile strength of the weld was obtained when rotation speed was 1400 rpm and welding speed 40 mm/min.	2015	[25]
16	PT: 3.1 mm (AM60B) & 1.5 mm (AA6022) RS: 1000-2500 rpm TSPD: 0.2-0.6 mm TS: 0.2 mm/s	AM60B (die-cast)+AA6022-T4 (Rolled)	Welded region was able to bear 2.5 kN shear force when welded at the rotational speed of 1000 rpm and shoulder depth of 0.9 mm.	2015	[26]

CONCLUSION

This manuscript represents the recent progress and research activities of dissimilar aluminum and magnesium alloys welding using FSW. Although the FSW is successfully being used in the welding of hard to weld materials, still its full potential is not being utilized commercially. This review will assist in understanding the use of FSW in the welding of dissimilar materials, especially the welding of Al and Mg alloys. The attributes of the FSW of Al alloys to Mg alloys are discussed. Other than this, the effect of various parameters on the strength of Al/Mg joints is also reviewed. It was noticed that even today, FSW is not widely used in Al-Mg welding because the strength of the joint is reduced due to the presence of IMCs. Owing to the presence of these IMCs, high hardness of the joints was reported. By selecting some process parameters, fragmental defects, voids, pores and cracks were also found in the weld region. The high hardness of the joint is also considered responsible for its brittle behavior and poor ductility. It is difficult to establish an appropriate analytic relationship among the various parameters to achieve the desired qualities from the joint. It was found that the quantity and size of IMCs are less in FSW than fusion welding. Finer grains were detected in the welded portion owing to dynamic recrystallization. At the same time, the joint hardness in fusion welding is much higher than that of FSW, which impairs the flexibility and strength of the joint. Consequently, FSW is a much better process than fusion welding to weld Al/Mg alloys.

CONFLICT OF INTEREST
None.

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None.

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