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Effect of process parameters on mechanical properties of friction stir spot welded magnesium to aluminum alloys

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ABSTRACT

Friction stir spot welding was applied to dissimilar cast magnesium (Mg) alloy AM60B and wrought aluminum (Al) alloy 6022-T4 under various welding conditions. The influence of tool rotation rate and shoulder plunge depth on lap-shear failure load was examined. Welds were made at four different tool rotation rates of 1000, 1500, 2000 and 2500 revolution per minute (rpm) and various tool shoulder plunge depths from 0 mm to 0.9 mm. The cross section of each weld exhibited the formation of intermetallic compounds (IMCs) in the stir zone. An increase in tool rotation rate decreased the width of the stir zone and resulted in lower lap-shear failure loads. The stir zone width increased and interlocking of IMCs was observed with an increase in tool shoulder plunge depth at 1000 rpm. High lap-shear failure loads were achieved in welds having a large stir zone width with formation of discontinuous IMCs at the tip of the interfacial hook. An average lap-shear failure load of 2.5 kN was achieved for welds made at 1000 rpm and 0.9 mm shoulder plunge. The present study suggests that the mechanical properties of friction stir spot welded dissimilar alloys are greatly influenced by the stir zone width, interfacial hooks and IMCs which are all weld process dependent.

1. Introduction

Automotive industries around the globe have increased the application of lightweight Mg and Al alloys in place of steel to produce more economical and better performing vehicles [1]. The traditional joining method used in automotive industry is resistance spot welding, which works well for steel but is not suitable for Al or Mg alloys [1–3]. Friction stir spot welding (FSSW) is a variant of the friction stir welding (FSW) process, a solid-state welding technique developed by The Welding Institute, UK in 1991 [4]. A typical FSSW setup consists of a rotating tool with a probe pin that is plunged into two sheets of metal to be joined. The downward force and rotational speed of the tool generates localized friction as the tool interacts with the sheets. The heat generated by friction and plastic deformation of sheet metals softens the materials adjacent to the tool and form a solid bond between upper and lower sheets [5]. Essentially the welding parameters such as the tool rotation rate, tool shoulder plunge depth and dwell time determine the heat generation, joint formation and mechanical properties [6,7]. In addition to welding parameters, the weld tool geometry plays a crucial role in material flow and mixing. Tools with concave tool shoulder designs are found to produce weld joints with higher static strength compared to tools with convex or flat tool shoulders [6,8,9]. The effect of tool pin design on the weld strength of the FSSW joints has been well documented [6,9–11]. FSSW are characterized by unique features known as the interfacial hooks formed at the faying surface. This hooking feature is a result of trapped oxide films that are displaced upward due to the plastic flow of the material resulting from the downward plunge of the pin into the lower sheet. The interfacial hooks have been shown to influence the failure load of the weld. A smaller hook height is observed to lead to better mechanical properties compared to welds with relatively large hook height [12–15]. The degree of oxide distribution at the faying surface is greatly influenced by the tool geometry and tool rotation rate [16].

Most research conducted on FSSW is relatively confined to joining of similar alloys of Al or Mg. To utilize the optimum physical, mechanical and chemical properties of these alloys, there is increased interest to use of Al and Mg in combination. The challenge of joining these dissimilar alloys lies in the formation of the brittle intermetallic compounds (IMCs) in the stir zone along with the geometrical features of the weld. With limited research conducted in solid-state joining of dissimilar alloys, most have reported about the formation IMCs and its effect on the weld joint strength [17–23]. Constitutional liquefaction occurred in the joints

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during the welding of Mg and Al alloys and the IMCs ($Al_{12}Mg_{17}$, Al_3Mg_2) were produced at the weld interface [19–23]. These IMCs are brittle and much harder compared to the base material and act as sites for easy crack growth. In FSSW of AA5083 to AZ31, presence of a thick layer of IMCs in a defect-free weld was reported. The thickness of the IMCs was observed to have negligible influence on the lap-shear strength of the weld but the distribution of these IMCs did affect the weld strength [17]. On the contrary, in FSSW of AA6K21 and AZ31, the lap-shear strength of welds decreased with increased thickness of the IMCs layer [19]. This reduction in strength was observed due to cracking in IMCs as the frictional heat increased with increase in tool rotation rate and dwell time. Similar relationship between lap-shear strength and the thickness of IMCs has been noticed in FSW of AZ31B and AA5083, due to weakened mechanical interlock between Mg and Al alloys [20]. In cyclic testing of FSSWed dissimilar AZ31 to AA5754, the failure occurred due to nugget debonding where the IMCs layer was present [23]. Yin et al. [24] observed that the distance from the tip of the hook to the keyhole periphery influenced the strength of FSSWed AZ91 to AZ31 Mg alloys. This distance greatly increased for welds made using tool having a triangular threaded pin compared to welds made using a non-threaded pin tool. In general, welds made with triangular pin tools have displayed larger bond width and better lap-shear strength compared to welds made using cylindrical pin tools [6,25]. While limited work has been done on FSSW of dissimilar Al and Mg alloys, and the fundamental understanding of critical role of IMCs on weld strength is still lacking, an effort has been made to explore the influence of the welding conditions on IMCs formation as well as lap-shear tensile properties between spot welded cast AM60B and rolled AA6022-T4.

2. Experimental procedure

A super vacuum die cast AM60B Mg plate having a thickness of 3.1 mm was FSSW to 1.5 mm-thick rolled AA6022-T4 sheet. The FSSW tool used in this study as shown in Fig. 1 was made of standard tool steel (H13) and constituted a concave tool shoulder and a triangular pin with threaded groove surface. The geometrical features and dimensions of the FSSW tool are listed in Table 1. FSSW was conducted in such a configuration that the Mg plate was always on top of the Al sheet with lap-shear tensile specimens having a 30 mm × 30 mm overlap between the two materials as shown in Fig. 2.

One of the research goals of this study is to identify the ideal welding parameters for optimal weld strength. The course of isolating the weld process parameters was carried out in two stages; stage I, the optimum weld tool rotation rate was quantified and in stage II, the ideal tool shoulder plunge depth was identified. In stage I, a set of FSSW coupons were prepared at different tool rotation rates, 1000/1500/2000/2500 rpm and tool shoulder plunge depth of 0.2/0.4/0.6 mm. The coupons were subjected to tensile testing and the optimum tool rotation rate was identified based on the weld strength. In stage II, the final set of FSSW coupons were prepared using the tool rotation rate quantified in stage I and then by varying the tool shoulder plunge depth. The process window indicating various welding parameters employed in this two-stage study is shown in Table 2. A constant tool plunge speed of 12 mm/min was maintained in both stages of the welding.

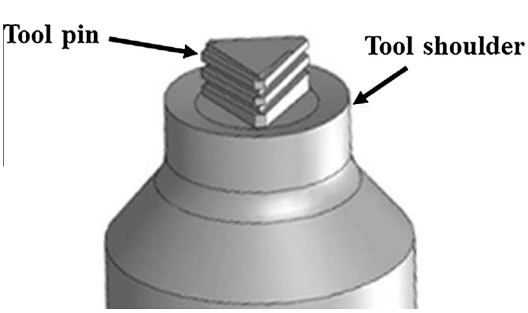

Fig. 1. Schematic of FSSW tool used in this study.

Table 1
Information of tool material and geometric features employed in this study.

Tool material	H13 tool steel	
Tool profile	Shoulder shape	Concave
	Shoulder diameter	12 mm
	Pin shape	Triangular
	Pin diameter	tri. = 5.4 mm (eq.)
	Pin length	3.5 mm
	Pin surface	Threaded groove

The lap-shear tensile tests were conducted at room temperature on an Instron screw-drive machine (Model 1123) with a constant cross head speed of 2 mm/min. At each stage of study, selected tested and un-tested coupons were cross-sectioned through the center of the welds and cold mounted in epoxy. The mounted specimens were mechanically ground and polished with 0.05 μm final finish for weld geometry, IMCs and failure mode analysis. In order to reveal the microstructure and IMCs, the AA6022-T4 was first etched with 20% NaOH solution (caustic etching) and then AM60B was etched using an acetic picral solution (4.2 g picric acid, 10 ml acetic acid, 10 ml H_2O, and 70 ml ethanol). The macro and microstructures of welds and failure modes were analyzed using the optical microscope. To further analyze the IMCs and its composition, untested FSSW coupons were examined under Jeol 7600F scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS) capabilities.

The microstructures of the as-received cast AM60B and AA6022-T4 are shown in Fig. 3. The microstructure of cast AM60B is comprised of a combination of irregular sized globular grains and large dendrites. Pores or voids were also observed all through the cast sheet. The AA6022-T4 Al alloy shows large globular grains on the surface and elongated grains along the rolling direction of the sheet.

3. Results and discussion

To isolate the ideal tool rotation rate, welded coupons were produced under different welding parameters and lap-shear tested. Fig. 4 presents the average failure load value with one standard deviation as a function of tool shoulder plunge depth at various tool rotation rates. The results show that welds made at 1000 rpm had higher failure loads compared to welds made at other tool rotation rates when the shoulder plunge depth is between 0.2 and 0.6 mm. Though there is slight scatter in the results for each individual welded coupon, the failure load

Table 2
FSSW process parameters employed in current study.

Tool rotation rate (rpm)	Tool shoulder plunge depth (mm)	Dwell time (s)	Plunge speed (mm/min)
Stage I			
1000	0.2/0.4/0.6	1	12
1500	0.2/0.4/0.6	1	12
2000	0.2/0.4/0.6	1	12
2500	0.2/0.4/0.6	1	12
Stage II			
1000	0.0/0.3/0.6/0.9	1	12