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Friction Stir Welding of Magnesium AZ31B and Aluminum Al-6062

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Abstract. Magnesium alloys, due to their attractive characteristics, are being utilized as lightweight structural materials in aerospace, automotive, and various other industries. Further design flexibility can be obtained by joining the Mg alloys to other materials with outstanding performance, such as aluminum alloys. In this study, Al-6062 and Magnesium AZ31B have been joined through friction stir welding (FSW) using the high-speed steel (HSS) tool. The impact of two important process parameters, including spindle speed and welding speed, has been evaluated on ultimate tensile strength (UTS). In addition, the effect of the advancing side has also been assessed. Analysis of variance has been performed based on full factorial design. For maximum UTS, the study suggests spindle speed and welding speed of 100rpm and 50mm/min respectively with magnesium on the advancing side. The weld strength is 110% higher than that of magnesium-magnesium weld joint.

Keywords: Intermetallic Compound (IMC), Friction Stir Welding (FSW), Microstructure

1. Introduction

Magnesium and aluminum alloys are used to build lightweight structures in aerospace, automotive, and construction [1-2]. Effectively combining these two materials creates a hybrid material that combines their properties, expanding their applications as design flexibility improves. Due to hard and brittle intermetallic compounds (IMCs), microcracks, and voids, joining dissimilar metals has always been difficult [3]. These defects limit the use of some solid-state welding techniques because they affect the joints' ductility and tensile strength. Friction Stir welding helps distribute IMCs uniformly, resulting in stronger welding junctions. Choosing the right FSW parameters like tool rotation speed, traversal speed, tool offset, metal advancing side, and metal position can increase joint strength. Researchers have developed techniques to reduce FSW faults. Dispersion of Al and Mg atoms removes or distributes IMCs however, eutectoid structure causes constitutional liquation, which increases IMCs [4]. Welding conditions and heat improve Aluminum alloy 6001-T6 and magnesium alloy AZ31B welded joints. Spindle and transverse speed affect heat. Al on the advancing side with an offset tool increases the heat effect [5]. Selvaraj at el. [6] performed Friction stir welding of 6mm AA6061-T6 alloy by varying rotational and traversal speeds. To produce a sound weld,

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increase rotational speed proportionally to welding speed. Verma at el. [7] studied welding parameters and reported Mg-AZ31B/Al-AA6061 weld joint tensile strength of 73% to base metal. Shuai at el. [8] reported that AL 6061/Mg NZ30K intermixed best at 900rpm and 120mm/min, increasing weld strength by 82%. Al on the advancing side and Mg on the reversing side can produce excellent joints with fine grain [9]. M. Azizeh et al. [10] studied the effect of rotational speed, pin positioning, and transverse rate on FS welding of Aluminum AA1100 and Magnesium AZ31 and achieved 70% base metal tensile strength. Several studies [11,12, 13] found similar results. In this study, weld strength of Al-6062 and Magnesium AZ31B joints is reported using different welding parameters and their effect on ultimate tensile strength (UTS), microhardness (MH), and microstructure.

2. Experimental Work

This study used ASTM E8/E8M-13a to prepare 5mm Al-6062 and AZ31B strips [14]. A 2mm-long, 12mm-shouldered 3mm HSS pin was used as a tool. After sanding off the oxide layer, the strips were dipped in 4% HCL, rinsed with distilled water, and then soaked in 91% isopropyl alcohol.

Figure 1 shows two smaller aluminum strips supporting Al and Mg on a CNC milling center. On the advancing side, the tool's rotation and transverse motion are in the same direction. 18 experiments were performed using a full factorial design of experiment (DOE) as shown in table 2.

Table 1. Chemical Composition and Mechanical Properties of Base Metals

Material	Chemical Composition, %wt									Mechanical Properties	
	Al	Mg	Si	Fe	Cu	Mn	Zn	Cr	Ti	UTS, MPa	MH($HV_{0.1}$)
6062-T6	Bal.	2.03	0.58	0.14	0.32	0.07	0.03	0.08	0.05	350	110 avg.
AZ31-B	3.05	Bal.	0.016	0.001	0.003	0.44	1.10	-	-	240	70 avg.

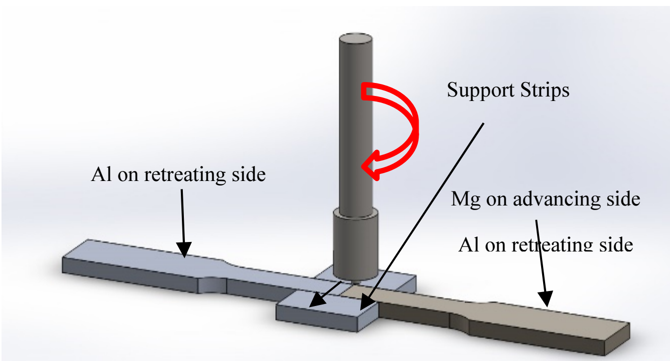

Figure 1. FSW Setup

Table 2. Design of Experiments (DOE)

Weld Factors	Level 1	Level 2	Level 3	Units	Advancing Side
Spindle Speed	1000	1100	1200	rpm	Al
Welding Speed	50	60	70	mm/min	Mg

Tensile tests are performed on the welded joints using a tensometer with a crosshead speed of 1mm/min. The specimens were sanded, polished, and etched for microstructure study. A scanning electron microscope (SEM) ISPECTS-50-FEI with tungsten filament was used to observe the weld zone's microstructure.

3. Results & Discussion

Tensile test results are presented in Table 3. Minitab 19.1 is used to perform ANOVA on process parameters. Both RPM (11%) and WS (86) are significant for Aluminum on the advancing side, but only WS (91%) for Mg. Control Al-Al and Mg-Mg joints had tensile strengths of 36.5 and 29.2 MPa. In our experiments,1000rpm, 50mm/min welding speed, and 20 rev/mm revolutionary pitch produced 32.40 MPa tensile strength. This value is 11% higher than Mg-Mg weld.

Table 3: Experimental Results

Sr. No	Spindle Speed (SS) (RPM)	Welding Speed (WS) (mm/min)	Revolutionary Pitch (Revolution per mm)	UTS (MPa) Al- Advancing	UTS (MPa) Mg- Advancing
1	1000	50	20.00	27.43	32.40
2	1000	60	16.67	24.22	27.50
3	1000	70	14.29	22.80	22.40
4	1100	50	22.00	25.22	28.60
5	1100	60	18.33	23.41	25.40
6	1100	70	15.71	20.95	22.50
7	1200	50	24.00	26.21	30.14
8	1200	60	20.00	23.20	26.20
9	1200	70	17.14	20.67	22.50

In this study, the tensile strength achieved is higher as compared to that reported in existing literature[5, 16]. For better strength, interlocking grain boundaries are desired in the mixing weld zone [16]. The weld is achieved by diffusion of metals or due to solidification of the liquid weld pool. In the case of weld pool solidification, weaker weld results due to micro-cracks that develop in the process of solidification[18-19].

Fig. 3 shows the cross-section of a typical FS welded joint at 1000rpm and 50mm/min, showing banded zone and inter-metallic compounds. Three zones were identified in the Nugget zone: the shoulder affected zone, the banded zone on the advancing side, and the intercalated zone in the bottom. In the shoulder affected zone, material swirls from advancing to retreating, revealing onion rings (Fig. 3). Friction stir welding's swirling tool rotation caused this. Al-Mg intercalations were both banded and severe. Al and Mg intermix in banded and intercalated zones with alternative Mg-Al strips and complex catholic flow patterns. FS welding shows fine Al-Mg mixing. EDX line analysis shows Al and Mg in the interference zone (Fig. 4). EDS confirms two IMC layers: Al2Mg3 and Al12Mg17.

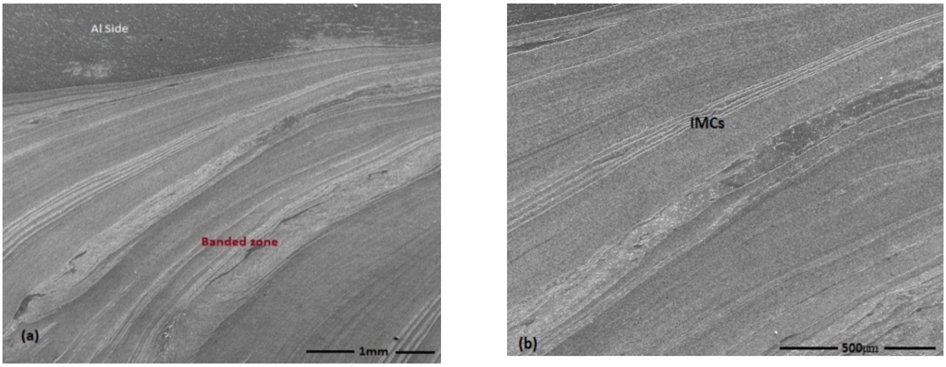

Figure 2. SEM of Weld Zone Showing Intermixing of Both Metals

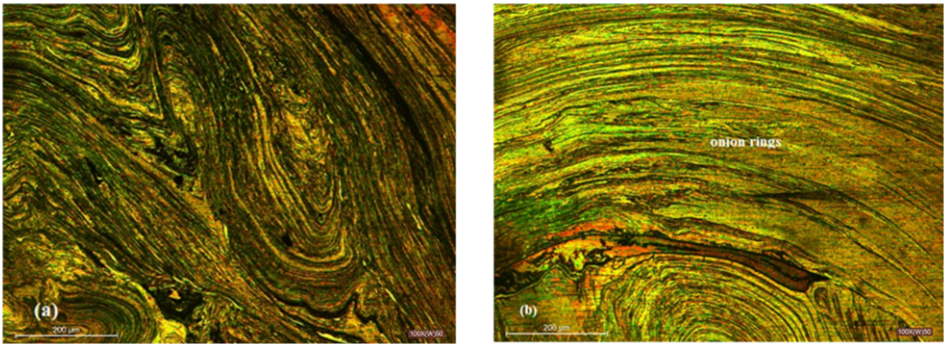

Figure 3. Optical Images for Interference of Weld Zone

Table 4. EDX Composition Details Taken Directly From SEM

Spot	Mg	Al	Others	Possible Phase
1	46.25	52.2	1.55	$Al + Al_2Mg_3$
2	56.36	41.28	3.48	$Al_{12}Mg_{17}$
3	63.53	33.14	3.45	$Mg + Al_{12}Mg_{17}$

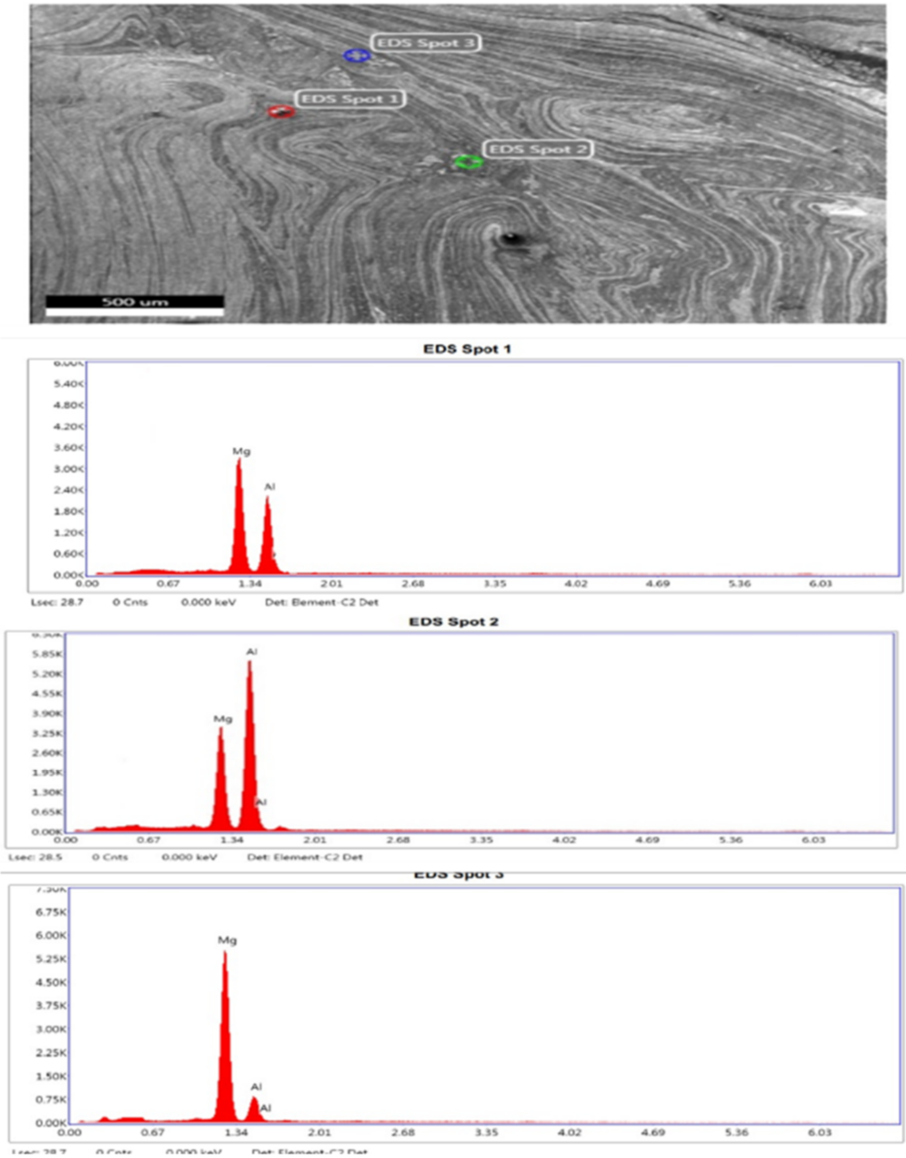

Figure 4. EDX Spectroscopy, Composition Graphs

Constitutional liquation forms Al2Mg3 and Al12Mg17, according to Sato et al. (2004) and Firouzdor & Kou [20]. As compared to Al, Mg shows intensive plastic deformation due to higher heat input generation on the Advancing side; tunnels and cracks were not observed on the weld surface, which increased weld strength. Due to insufficient heat generation, these defects were seen when Al was on AS and Mg on RS (RS). Due to excessive heat generation and plastic deformation in the thermo-mechanically affected zone (TMAZ) during FSW, Mg on AS had fine grain structure and dynamic recrystallization near the stir zone [3]. Al on AS has weak interface bonding between the banded zone and base metal, resulting in low tensile strength [21]. Constitutional liquation caused IMCs in the banded zone [22]. Hot cracks formed because liquid film couldn't withstand cooling stresses. Constitutional liquation forms Al2Mg3 IMCs [20][23]. These IMCs only formed when Al was on AS. In FSW, Al was transported from RS to AS by pin intermixing. Higher Mg IMCs formed due to more Mg reacting with Al.

EDX mapping, as shown in Figure 5, reveals that intermixing of Al/Mg in stir zone is sufficient and the constitutional liquation caused by the heat generation guarantees again proper mixing of Mg in Al when Mg is on AS as compared to mixing of Al in Mg when Al was on AS side during FSW.

Hardness was measured at the weld joint line and on 10 mm on each side joint line. Weld nugget zone (WNZ), heat affected zone (HAZ), and thermo-mechanical affected zone (TMAZ) hardness were measured (TMAZ). The WNZ showed 82Hv on both sides of NZ due to grain refinement and homogenous distribution/mixing of participants. Under the shoulder, microhardness plummets. HAZ on both sides of NZ has an average hardness of 57Hv due to the coarse grain structure and heat input during welding. Al and Mg alloy showed 107Hv and 100Hv, respectively. WNZ's maximum microhardness is

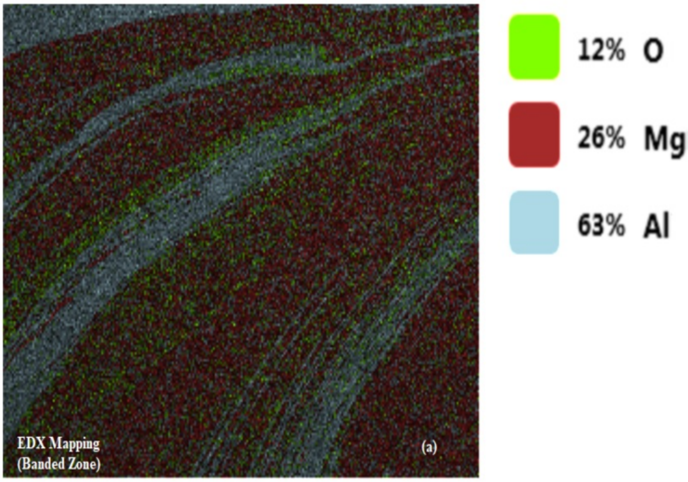

Figure 5. EDX mapping of banded zone

4. Conclusion

In current work, the effect of two process parameters (Spindle speed & Welding speed) has been evaluated on the friction stir weld joint of Al and Mg Alloy. Based on the experimental results, the following conclusions have been drawn:

1. Weld speed has shown a significant impact on UTS when both aluminum and magnesium were kept on the advancing side. Weld strength of 110% was achieved from the base metal (magnesium) weld joint when magnesium was on advancing side.

2. Low levels of both spindle speed i.e. 1000 RPM and welding speed i.e. 50mm/min weld speed have provided the highest values of UTS for advancing sides with both Al and Mg alloys.
3. Maximum hardness value (82Hv) was obtained at the weld nugget Zone, while the Heat effect zone has shown the lowest hardness (57Hv).

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