

Effect of tool offsetting on microstructure and mechanical properties dissimilar friction stir welded Mg-Al alloys

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Abstract. Automotive and aerospace industries are attempting to produce lightweight structure by using materials with low density such as aluminum and magnesium alloys to increase the fuel efficiency and consequently reduce the environmental pollution. It can be beneficial to join Mg to Al to acquire ideal performance in special applications. Friction stir welding (FSW) is solid state welding processes and relatively lower temperature of the process compared to fusion welding processes. This makes FSW a potential joining technique for joining of the dissimilar materials. In this study, Mg-Al butt joints were performed by FSW under different tool offset conditions, rotation rates (500-600 rpm) and traverse speeds (20 mm/min) with tool axis offset 1 mm shifted into AZ31B or Al6061 (T6), and without offset. During the welding process AZ31B was positioned at the advancing side (AS) and Al6061 (T6) was located at the retreating side (RS). Defect free AZ31B-Al6061 (T6) dissimilar metal FSW joints with good mechanical properties were obtained with the combination of intermediate rotation rate and low traverse speed pin is in the middle. When tool positioned in -1 mm or +1 mm offsetting, some defects were found in SZ of dissimilar FSWed joints such as cavity, tunnel, and crack. Furthermore, a thin layer of intermetallic compounds was observed in the stir zone at the interface between Mg-Al plates. The strength of the joint was influenced by FSW parameters. Good mechanical properties obtained with the combination of intermediate rotational speed of 600 rpm and low travelling speed of 20 mm/min by locating Mg on advancing side when pin is in the middle. Also, Joint efficiency of the welds prepared in the present study was between 29% and 68% for the different welding parameters.

1. Introduction

Nowadays, the automotive and aerospace industries are attempting to produce lightweight structure by using aluminum and magnesium alloys which have low density compare to other structure materials, to increase the fuel efficiency and consequently reduce the environmental pollution. Combination and assembly of these two alloys or with other metals through new design concept could results in better strength and performance. Thus, it can be beneficial to join Mg to Al in order to acquire ideal performance in special applications. However, the formation of intermetallic compound (IMC) in the interface of Al-Mg is unavoidable in the welding zone [1–6].

Until today, many researches have performed different joining methods to joint aluminum to magnesium alloys such as using laser weld bonding [7], TIG fusion welding [8], vacuum diffusion bonding [9], laser welding [10], etc. However, utilization of these methods for joining of Al-Mg alloys are limited because of lower strength of welded joint and particular process prerequisites. Recently, many researchers focused on friction stir welding to join aluminum to magnesium alloys [4,6,11].



Friction stir welding (FSW) is solid state welding processes invented by TWI in 1991 that can be performed to produce sound joint. FSW has lower temperature process due solid state nature compare to fusion welding such as MIG, TIG, and laser welding. So, FSW is believed that can be a potential method for welding of heterogeneous materials with reasonable mechanical properties. During FSW, high pressure accompanied by high shear strain can form metallurgical bands between bar metal surfaces which are positioned in close contact [11].

Many researches have been paid particular attention to tailoring the interfaces of dissimilar materials to enhance the mechanical properties. FSW is believed which has ability to make the complex nonlinear weld interface under certain welding conditions [11–13]. There are several reports about the joining of magnesium alloys to aluminum alloys by using FSW which some of the researches have mentioned about tool offsetting effect during the welding [6,11,12,14–21]. Venkateswaran and Reynolds [11] have reported which with 2 mm tool offset to Al6063, mechanical properties will decrease because of lower intermixing of Al and Mg in the interface and shorter zigzag line in the interface. Banglong Fu et al. [16] Believed that with tool offsetting about 0.3 mm to Mg side which has positioned in advancing side, sound Al–Mg dissimilar joints with welding efficiency of 70 % metal could be obtained. In other research performed by Firouzdor and Kou [21] have, they have reported mechanical properties of Al-Mg joint will be higher when the tool shifted 1.5 mm to AZ31 and Mg placed in advancing side by reducing the heat input and hence the detrimental formation of intermetallic compounds and liquid films. In another study which has been done by Firouzdor and Kou [19], they have mentioned that with tool positioned at the middle mechanical properties was slightly higher than tool had 1.5 mm offset to Mg side, in rotational speed of 1400 rpm when Al was in the advancing side. Dorbane et al. [22] showed with having aluminum on advancing side of the FSW of Al-Mg joints resulted in better welds with fewer defects in the stir zone and higher tensile strength when the pin was in the middle.

Therefore, the relationship between tool offsetting and welding properties for FSWed Mg-Al dissimilar metal need to be studied further. In this paper, Mg-Al butt joints were obtained by FSW under different tool offsetting and rotational speeds. The aim of this research was to evaluate the nature of dissimilar metal FSW of Al6061(T6)-AZ31B and effect of tool offsetting on joint strength.

2. Experimental Procedure

AZ31B magnesium alloy and commercial aluminum alloy 6061(T6) plates with dimensions of 75×50×4 mm used in this study as the base metal. The alloy compositions and mechanical properties of the materials used are mentioned in table 1. Prior to FSW, the surface oxides were removed by steel brush and then the surface was cleaned using ethanol. Figure 1 shows the joint configuration and welding parameters direction.

The welding direction is made perpendicular to rolling direction of AZ31B and Al6061 (T6) plates. The tool for FSW is a cylindrical threaded M5 pin made of a heat treated H13 tool steel with a hardness of 53-55 RC. Figure 2 shows the schematic view FSW tool pin with 3 degree tilted angle of tool axis. First, the tool was gradually pushed into the base metal sheet until the shoulder tip penetrated 0.2-0.3 mm to the base metal. During the welding process AZ31B was positioned at the advancing side (AS) and Al6061 (T6) was located at the retreating side (RS). Then, the tool started to be stirred along the joint. Tool rotation speed was varied from 500 to 600 rpm with tool axis offset 1 mm shifted into AZ31B, Al6061 (T6), and without offset. Figure 3 shows the tool position in different offsetting. +1 mm, 0 mm, and -1 tool position means tool shifted 1mm into AZ31B, tool in the middle, and tool shifted 1 mm into Al6061 (T6), respectively.

Table 1. Chemical compositions and mechanical properties of materials used

Material	Chemical composition (wt. %)						Yield stress (MPa)	Tensile stress (MPa)
	Al	Mg	Si	Mn	Cu	Zn		
Al6061(T6)	Bal.	0.8	0.4	0.03	0.18	-	258	293
AZ31B	2.5-3.5	Bal.	-	0.2-1.0	-	0.7-1.4	166	229

The workpieces were clamped down tight with four steel pads located 20 mm away from joint line. The fixture was used to minimize gap opening during the FSW as shown in figure 1. The sheets were held tightly against each other by tightening three bolts against the Al part in addition to being clamped tightly against the steel base by the hold-down clamps. Also, steel band with thickness of 3 mm was welded to the backing steel plate instead of using three bolts in AZ31B side. Microstructure observation was performed perpendicular to the welding direction. Then, samples were cold mounted, manually ground from #600 to #2000 and polished by using Al₂O₃ with the particle size of 1, 0.3, and 0.05 μm , respectively. An etching solution consisting of 10 ml acetic acid, 6 g picric acid, 10 ml distilled water, and 100 ml ethanol was used to reveal the microstructure of AZ31B. The second step was to etch sample with a solution consisting of 10 g NaOH in 50 mL distilled water for 45 seconds to reveal the phases in different colors. Microstructures of stir zone (SZ), thermo-mechanically affected zone (TMAZ) were observed by optical microscope (OM). Average grain size was measured based on the ASTM Standard E112-10. Tensile test was performed in ambient temperature (25 °C) with speed of 0.1 mm/min using specimen with length and width of 100 mm and 10 mm, respectively, which were cut perpendicular to welding direction.

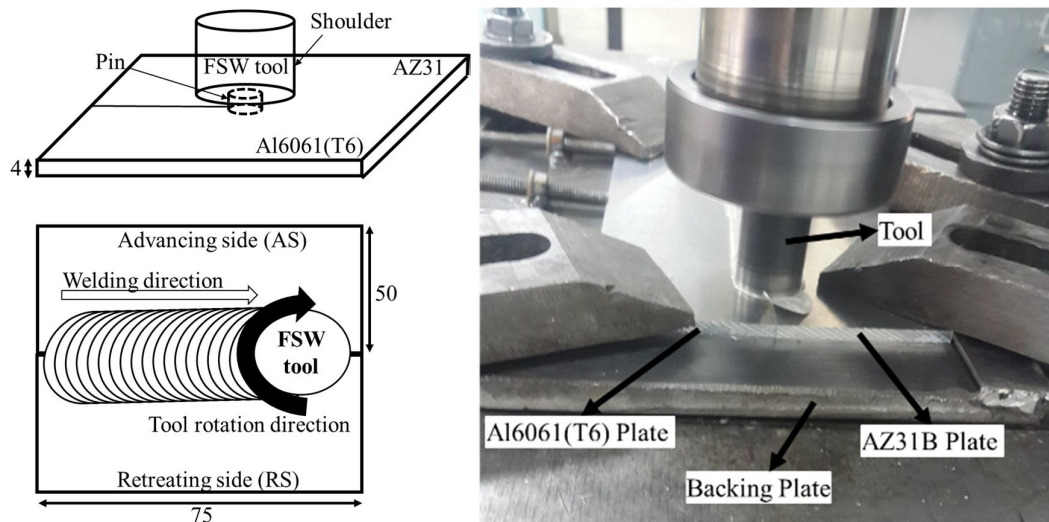


Figure 1. Joint design and dimensions (millimeter).

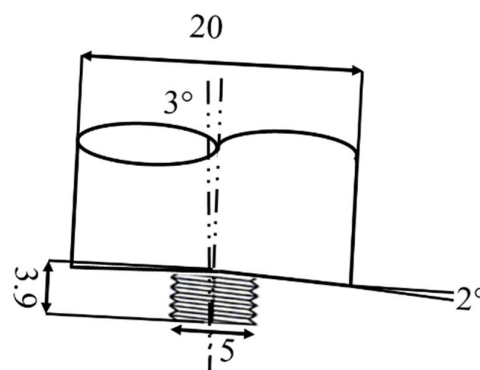


Figure 2. Schematic representation of welding tool (millimeter).

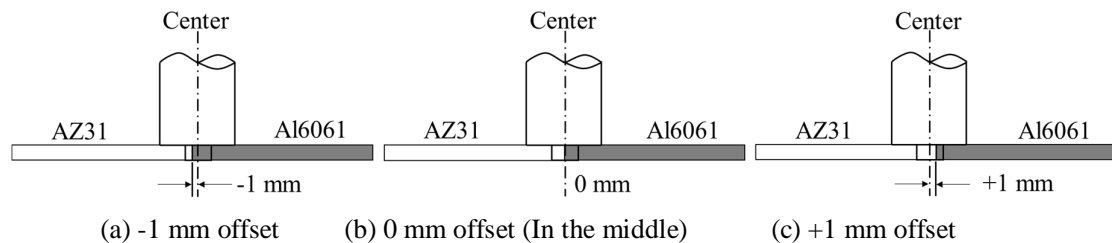


Figure 3. Tool position at different offset.

3. Results and Discussion

3.1. Appearance and macrostructure

Figure 4 shows the typical cross section macrostructures of dissimilar friction stir welding (FSW) of AZ31B and Al 6061(T6) in rotation speed of 500 and 600 rpm and travelling speed of 20 mm/min with pin offsetting. The AZ31B was in advancing side and Al6-061(T6) was in the retreating side. For Mg-Al dissimilar joint when tool positioned in the middle, the weld appearance was smooth semicircular traces and less flash was formed and pushed out from the welding zone during the welding. With tool shifting into Al or Mg, the weld appearances were acceptable but the amount of flash formed were higher in compare to tool position in the middle. Moreover, the amount of the flash formed in -1 mm tool position was more than +1 mm tool position. Also, increasing the rotational speed from 500 rpm to 600 rpm was caused the increasing amount of flash expelled out from the welding.

In the macroscopic photo in figure 4, the left side is AZ31B and the right side is Al6061(T6). The boundary between the stir zone (SZ) and the thermo-mechanical affected zone (TMAZ) is clear and sharper on the Mg side. In the macrograph, there is zigzag line which shows the intermixing of Al and mg in the stir zone. When tool was in the middle of welding line, sufficient intermixing was observed in compare to tool shifted into Al or Mg sides. Moreover, with shifting of tool to Al side, the zigzag line was more irregular in compare to -1 mm tool position. Furthermore, the free defect joint was formed in when the tool was in the middle.

When tool was shifted into Al or Mg, the different welding defects which included of crack, cavities, and tunnel, were formed in the welding zone. Figure 5 displays the defects formed in rotational speed of 600 rpm and +1 mm tool position. The defects volume in +1 mm tool position was bigger than in the -1 mm tool position. The defects were made just in the 1 mm from the bottom side, and only in the one condition, crack was made in the middle of the thickness in the rotational speed 600 rpm and 20 mm/min of travelling speed as shown in Figure 5.

Rotational Speed	Tool offset (mm)		
	-1	In the middle (0)	+1
500 rpm			
600 rpm			

Figure 4. Cross section macrostructures of dissimilar FSW of AZ31B and Al 6061(T6) at travelling speed of 20 mm/min and rotational speed.

3.2. Microstructure

Figure 6 shows the transvers cross section macroscopic photo and microstructure of dissimilar friction stir welded Mg-Al sample with welding parameters of 600 rpm and 20 mm/min and tool in the middle. In the micrograph the left side is AZ31B and the right side is Al6061(T6). Figure 6(a) revealed the

microstructure of AZ31B base metals on the advancing side. Microstructure of AZ31B revealed typical rolled microstructure of Mg alloys with inhomogeneous grains and numerous twins. The average grain size of the AZ31B was evaluated about 84 μm .

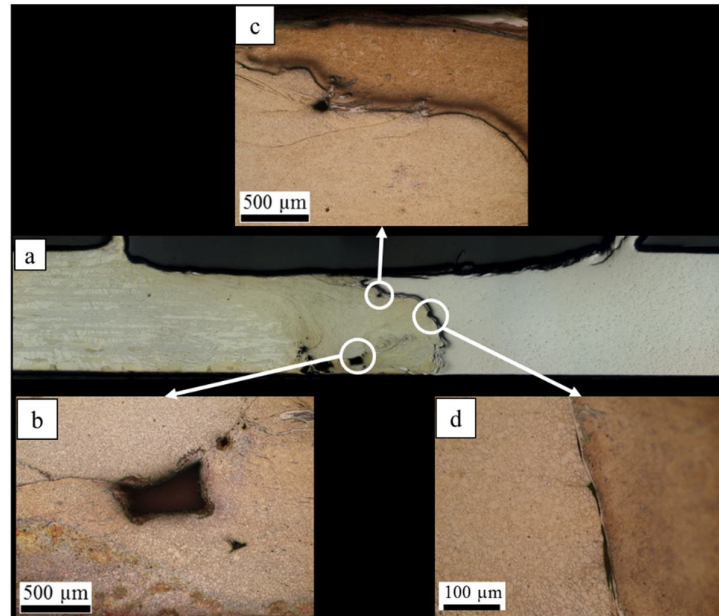


Figure 5. Magnified view of different defects in welded sample of 600 rpm, 20 mm/min, and +1 mm tool position: a) cross section, b) Tunnel volumetric defect, c) Cavity volumetric defect, d) Crack defect along the interface.

Microstructure of Mg-Al FSWed sample is divided in 3 zones which are heat effected zone (HAZ), thermomechanical effected zone (TMAZ), and nugget zone (NZ) or stir zone (SZ) as shown in figure 6b). Furthermore, Three distinct zones were defined in nugget zone of dissimilar friction stir welded Mg-Al samples; the shoulder affected zone (figure 6(c)) which was just below the shoulder during welding, the banded zone (figure 6(f)) which was in the upper and middle parts of the joints on AS, and severe intercalated zone (figure 6(g)) which was in the bottom which have been reported in recent researches [23] and involved lamellar-like shear bands. It also can be seen that intercalated structures formed no matter at the upper part of the joint or at the lower part of the joint are all sound without defects.

In the magnesium side, the TMAZ shows a larger number of twins and is distinguished with more elongated, bigger grains and partially equiaxed grains compared to the AZ31B base metal. Extreme plastic deformation and frictional heating during FSW lead to the generation of fine recrystallized grains in the SZ which was shown in figure 6(e). It will produce a finer grain structure, either decreasing the temperature or raising the strain rate.

Material flow in the shoulder affected zone was dominated by the plastic flow of material on AS with the direction of tool rotation, in this case, Mg penetrated into Al side under the mechanical stirring action of tool shoulder. Figure 6(d) shows the element of Al6061(T6) in SZ of AZ31B side which is a good evidence for intermixing of Al and Mg in SZ at Mg side. Furthermore, EDS mapping analysis was performed on the location of (I) as shown in the figure 7. It shows the main elements distribution of Al and Mg in that zone. Also, figure 6(h) shows a typical microstructure of dissimilar Mg-Al weld interface. The white line at the middle of interface clearly shows of intermetallic Compound (IMC) which have been formed in the interface of joint by mechanical stirring and frictional heat [6,16,20]. Constitutional liquation and solidification are caused to form intermetallic compound $\text{Mg}_{17}\text{Al}_{12}$ during FSW [13].

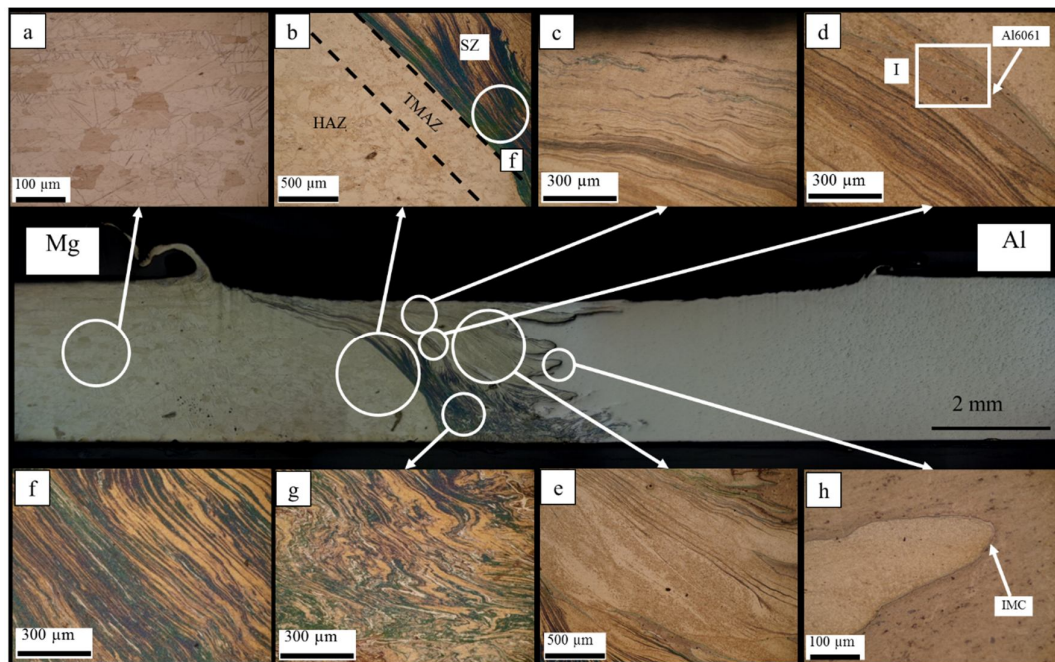


Figure 6. Micrograph photos of FSW of AZ31B to Al 6061(T6) in welding parameters of 600 rpm, 20 mm/min, and tool in the middle.

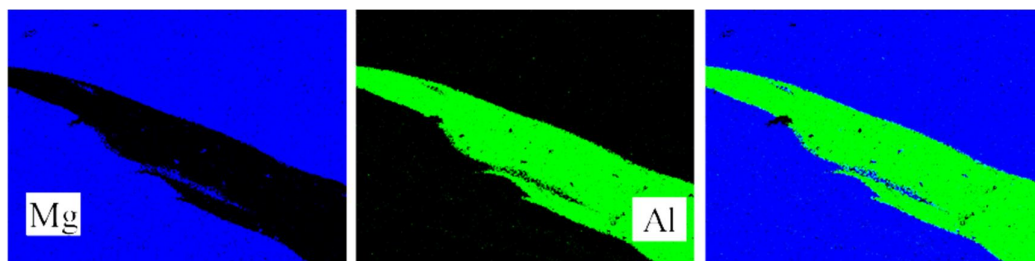


Figure 7. EDS mapping analysis of location (I) in figure 5(d)

3.3. Tensile properties

The transverse tensile properties of FSWed joints were obtained to evaluate the tensile strength, elongation, and welding efficiency under different welding parameters. The specimens display before tensile testing in Figure 8. In each condition, three specimens were tested and the average of three results are presented in table 2. As can be seen, the tensile strength of Mg-Al dissimilar FSW joints were lower than Al and Mg base metal which has mentioned in Table 2.

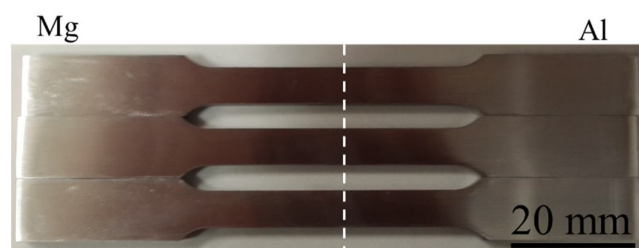


Figure 8. Tensile sample before test

The tensile strength of welded samples was varied by shifting of tool. When pin was in the middle, the highest tensile properties was achieved and tensile properties were decreased with shifting of tool into

Al6061(T6) or AZ31B. Also, the lowest tensile strength was obtained when tool was in +1 mm tool position. It was mentioned by recent research[16] where tool offset more than 0.3 mm/min, the tensile strength will decrease. It is due to lower heat input by shifting tool in Al6061(T6) or AZ31B and lower heat input is caused less mixing of Al and Mg in the stir zone in compare to tool in 0 mm tool position. Furthermore, distribution of intermetallic on the welding zone is effective on mechanical properties of Mg-Al joints[24] as shown in figure 5(d) which was caused a defect and reduced the tensile strength. When tool is at the middle, it is produced higher heat input and better mixing of Al and Mg in the welding zone. When tool shifted into AZ31B, mechanical properties of welded samples were increased by increasing of rotation speed, similar to -1 tool position [16].

Table 2. Transverse tensile properties of FSWed joints (MPa)

Welding Parameters		Tool offset (mm)		
		-1	0	+1
500 rpm	20 mm/min	108	130	65
600 rpm	20 mm/min	111	154	71

The increasing of tensile strength were due to better mixing of Al and Mg in welding zone and in top of that less welding defect in the stir zone. However, Firouzdour & Kou [19] have mentioned that there was not significantly different in tensile strength in constant rotation speed of 1400 rpm and welding travelling speed less than 75 mm/min when tool shifted into AZ31B and AZ31B was in advancing side.

A ratio between tensile strength of welded samples and ultimate stress of AZ31B base metal is called welding efficiency. The welding efficiency was varied from 29 % to 68 %. The minimum welding efficiency was related to sample in rotational speed of 500 rpm and pin at the -1 mm tool position which had lowest tensile strength and maximum efficiency was evaluated in sample when tool was in the middle in 600 rpm and 20 mm/min of welding traveling speed.

4. Conclusion

The following conclusions can be made based on the current study on FSW of dissimilar metals Mg-Al alloys:

- 1) Defect free AZ31B-Al6061(T6) dissimilar FSWed joints with good tensile strength was achieved with the combination of rotational speed of 500 and 600 rpm with travelling speed of 20 mm/min by locating Al on retreating side.
- 2) When tool positioned in -1 mm or +1 mm offsetting, some defects were found in SZ of Mg-Al dissimilar FSW joints such as cavity, tunnel, and crack. Also, weld defects were caused to reduce the mechanical properties of FSWed joints.
- 3) Mg side of SZ was separated into 3 regions; shoulder affected zone, banded zone and severe intercalated zone. The last two regions were in the middle and bottom of SZ which showed Mg-Al intercalated structures. Also, a thin and brittle layer of IMC was found in the interface of Mg-Al joints at stir zone.
- 4) Uniaxial tensile testing was carried out at room temperature and the ultimate tensile stress of welded joints was influenced by rotational speed and tool offsetting. Joint efficiency of the FSWed samples performed varied between 29% and 68% for the different parameters.

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