

On the Characteristics of Friction Stir Welding Lap Joint of Magnesium and Aluminum

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Abstract: Lap joints of commercially pure magnesium plates to aluminium plates (Magnesium plate on the top, and Aluminium plate, grade 1100, on the bottom side) were conducted by friction stir welding using various traveling and rotation speeds of the tool to investigate the effects of the welding parameters on the joint characteristics and strength. Defect-free lap joints were obtained in the welding traveling speed range of 40-80 mm/min, and rotational speed range of 1200-1600 rpm. The shear tensile strength of Mg/Al joints increased as a result of decreasing the welding speed from 120 to 40 mm/min at constant rotation speed of 1600 rpm. Defects such as surface grooves, excessive flash, tunnels, and voids were observed if the joints prepared out of the mentioned range. The effects of the welding parameters are discussed metallographically based on observations with optical and scanning electron microscopes.

Keywords: Frictions stir welding, Mg/Al, Dissimilar, Lap joint, Defects, Intermetallic.

1. INTRODUCTION

Magnesium and Aluminum are two light engineering metals widely used in the aerospace, automotive and marine industries. In order to extend the application of Mg-Al alloys in these industries, the dissimilar joining of Mg to Al alloys becomes essential [1]. For joining these two light metals, conventional fusion welding processes, such as gas tungsten arc welding [2], laser beam welding (LBW) [3], electron beam welding (EBW) [4], and diffusion bonding [5] has been applied. Other joining methods like compound casting has also been used for joining Al to Mg [6]. The joining methods, however, have limitations especially if increase the possibility of the formation of solidification related defects and/or formation of vast area of Al₁₂Mg₁₇ and Al₃Mg₂ intermetallic compounds in the fusion zone [7]. These two intermetallics are very brittle and have low fracture toughness [8].

Friction stir welding (FSW) is a solid state joining process which can avoid many problems associated with fusion welding of Magnesium and Aluminum. In friction stir welding of Mg and Al alloys, welds have higher strength [9], more fatigue life [10], and less and thinner intermetallic compounds as compared to the welds produced by fusion welding

methods [1]. Important issues in FSW of Al and Mg are the heat input [7] and the material flow profiles [11] which are affected by FSW parameters such as tool geometry [12], alloy type [13-14], tool rotation speed [15], welding line speed [16-18], and tool position [7].

Various investigation have been conducted on different Mg and Al alloys to understand how to control welding parameters and the final structure of the weld joint. Venkateswaran et al. [11] welded 6063 aluminum and AZ31 magnesium alloys. They reported that higher strength in Mg-Al dissimilar alloys can be promoted by mechanical interlocking. Firouzdor and kou [7] welded sheets of 6061-T6 Al and AZ31B-H24 Mg in lap and butt design. They reported that the window for selecting the welding and rotation speeds for optimizing the joint strength is considerably larger when Mg alloy is on the advancing side in butt joints. It was also reported when the AZ31 plate is on the top, shear tensile strength can be higher (1.07 kN) and the fracture location was out of the joint. They noticed that macroscopic intermetallic compounds could be formed during FSW and its limited time of the process. As the solid state diffusion is very low; therefore, the presence of thick intermetallic layers was attributed to the solidification of the liquated

material in the interface of lap joints when aluminum alloy were placed on top [7, 19]. Chen and Nakata [16] lap welded AC4C Al alloy and AZ31 Mg alloy. They selected AC4C Al alloy as top plate and kept the pin tip at a close distance above the AZ31. Even though the pin never touched the AZ31, it was reported that a conversion zone, containing eutectic Al₁₂Mg₁₇ and Mg matrix, has been formed at the friction stir lap joints. AZ31 top joint was not investigated in their research. Chowdhury et al. [10] investigated lap shear strength and fatigue properties of Friction Stir Spot Weld (FSSW) of dissimilar AZ31B-H24 Mg and Al (AA 5754-O) alloys. They reported that FSSW induced an interfacial layer in the stir zone (SZ) composed of intermetallic compounds of Al₃Mg₂ and Al₁₂Mg₁₇, leading to increasing of hardness.

Most of the published works on dissimilar joints of Mg/Al have been carried out on the alloys of these two metals. There has not been any significant research on commercially available pure Mg and Al. This work examines the effect of various operational parameters on the characteristics of the interface and also strength of commercially pure Mg/Al lap joints.

2. EXPERIMENTAL PROCEDURE

2. 1. Materials and Tools

The alloys used in this study were 1100 aluminum alloy rolled plate and commercially pure magnesium with thicknesses of 3 mm. The nominal chemical compositions of both metals are listed in Table 1 and Table 2.

The sheets were cut and sized, in to rectangular plates (110mm*65mm*3mm) and longitudinally

lap welded. The surfaces of both plates were brushed by stainless steel brush at first, and then cleaned by acetone, before welding to rectangular plates (110 mm * 65 mm*3 mm)

The tool used in the present study had a concave shoulder with triangular pin (equilateral), and was made of H13 steel. Schematic illustration and dimensions of the tool are depicted in Fig. 1. Tool profile and dimensions were chosen based on the literature [20-21] and preliminary welding trials. In all tests, Mg sheet was put on the top having a 40 mm overlap with Al plate. The schematic view of the joint design is illustrated in Fig. 2.

2. 2. Welding Process

Plates were fixed, each time, rigidly on the horizontal table of an automatic milling machine (Tabriz FP4M milling machine -2.2 kW or 3 HP) used as seen in Fig. 2. The tilted angle of the rotating tool, with respect to vertical axis of milling machine, was 3 degree and the rotating tool was in contact with the top surface of Mg plate. The rotating tool was plunged, from the Mg plate, into the surface of Al plate while the tool shoulder came in contact with the Al plate having an insertion of nearly 0.3 mm deep. All the welds were configured in such a way that the retreating side of the probe was always located near the top plate edge. Lap joints were produced by rotational speeds of 400, 800, 1200, 1600 and 2000 rpm and welding line speeds of 40, 80, 120 and 160 mm/min, respectively. Other parameters including the threaded geometry and plunging depth of the stir pin were kept constant. Finally,

Table 1. Chemical composition of magnesium alloy

| Composition (wt-%) | | | | | | | |
|--------------------|--------|-------|-------|-------|-------|-------|-------|
| Element | Mg | Al | Zn | Cu | Si | Mn | Fe |
| wt-% | 99.447 | 0.056 | 0.139 | 0.018 | 0.024 | 0.033 | 0.002 |

Table 2. Chemical composition of aluminum alloy

| Composition (wt-%) | | | | | | | |
|--------------------|--------|-------|-------|-------|-------|-------|-------|
| Element | Al | Si | Fe | Zn | Mg | Ni | Pb |
| wt-% | 99.447 | 0.073 | 0.335 | 0.012 | 0.053 | 0.023 | 0.027 |

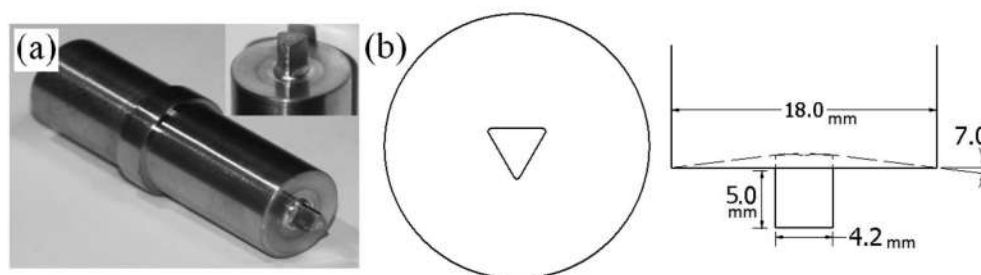


Fig. 1. Tool used: (a) Schematic illustration of the tool and its dimensions, (b) A magnified cross sectional view of the tool.

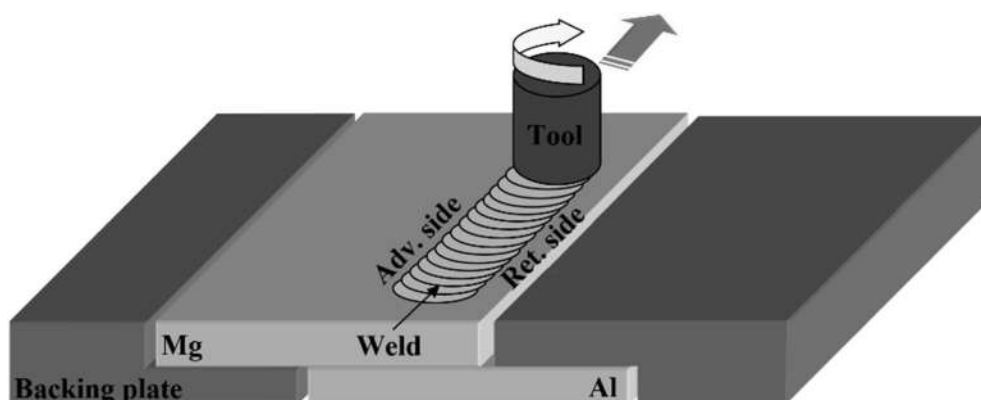


Fig. 2. Schematic view showing plates position and welding direction, advancing side (AS) and retarding side (RS).

the effect of welding line speed was investigated in the rotation speed of 1600 rpm.

2.3. Characterization of Welds

2.3.1. Weld Microstructure

After welding, firstly the joints were investigated by visual inspection for surface defects, such as groove or excessive flash. Then, joints were cut perpendicular to the welding direction and polished. Finally, they were etched in three steps: the first step was to etch the samples for 10 s in a solution of 5 mL acetic acid, 10 mL distilled water, and 4-g picric acid in 100 mL ethanol to reveal the microstructure of Mg part. The second step was etching them for 40 s in a solution consisting of 20-g NaOH in 100 mL distilled water to reveal the grain structure of Al. The third step was to dip samples, for 20 s, in a solution consisting of 4-g KMnO₄ and 2-g NaOH

in 100 mL distilled water to make Al colorful. Also a two-step etching procedure introduced by Somasekharan et al. [30] for color metallography of lap welds between Mg and Al was used. Finally the third step of a three-step etching procedure, reported by Firouzdar [7] was performed for showing Al, Mg, Al₃Mg₂, and Al₁₂Mg₁₇ in different colors, to take macro image from cross section. Both optical microscopy (OM) and scanning electron microscopy (SEM), equipped with an energy-dispersive spectroscope (EDS), were applied to examine the microstructures at the interface.

2.3.2 Mechanical Properties

The mechanical properties of the welded joints were evaluated using shear tensile tests performed by Galdabini shear tensile machine. The rectangular specimens were cut into 15 mm width and the edges of tensile test specimens

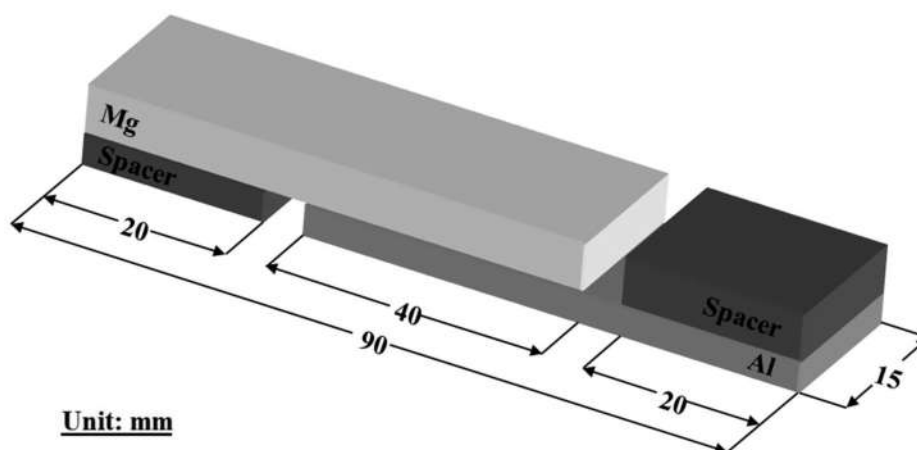


Fig. 3. Schematic illustration and dimensions of tensile specimen

were polished by 320-grit grinding paper. Spacers were attached onto both ends of a specimen prior to testing to make sure that an initial pure shear load is applied to the interfacial plane, and the bending effect is avoided (Fig. 3). The speed of the crosshead movement was adjusted to 1 mm/min and each shear failure load reported are representing an average of 3 measurements.

2. 3. 3 Hardness

The hardness of the weld samples was measured at different points along horizontal lines in two directions, at 1 mm above and below the primary interface line as shown in Fig. 4. Vickers microhardness testing was performed with a Bareiss Germany digital microhardness tester. For this purpose, a load of 100 gf was applied for 15 s.

3. RESULTS AND DISCUSSION

3. 1. Surface Appearance

The surface appearance of friction stir lap welded Mg/Al joints, having different rotating and traveling speed, are shown in Fig. 5. Other parameters during the experiments were kept constant. Two kinds of defects could be observed from the surface appearance. First type was the excessive flash, which existed on the surface of the top magnesium plate at the traveling speed of 80 mm/min and tool rotating speed of 800 rpm (Fig.5 b). This defect can be due to the excessive penetration during friction stir welding. Second type was the groove-like defect, which existed at the welding speed of 120 mm/min and the tool rotating speeds of 800 and 1000 rpm.

As shown in Fig. 5, at lower tool rotation speed and higher welding line speed, the surface of welds show defects, such as surface groove

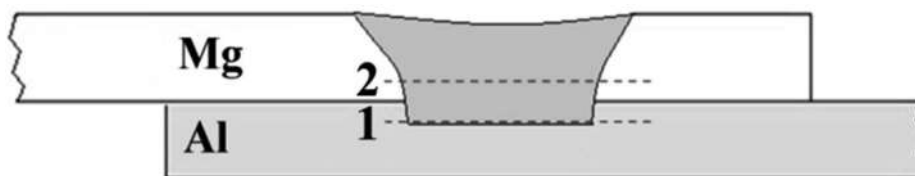


Fig. 4. Schematic drawing showing position of hardness test measurement at 1 mm above and below the primary interface line

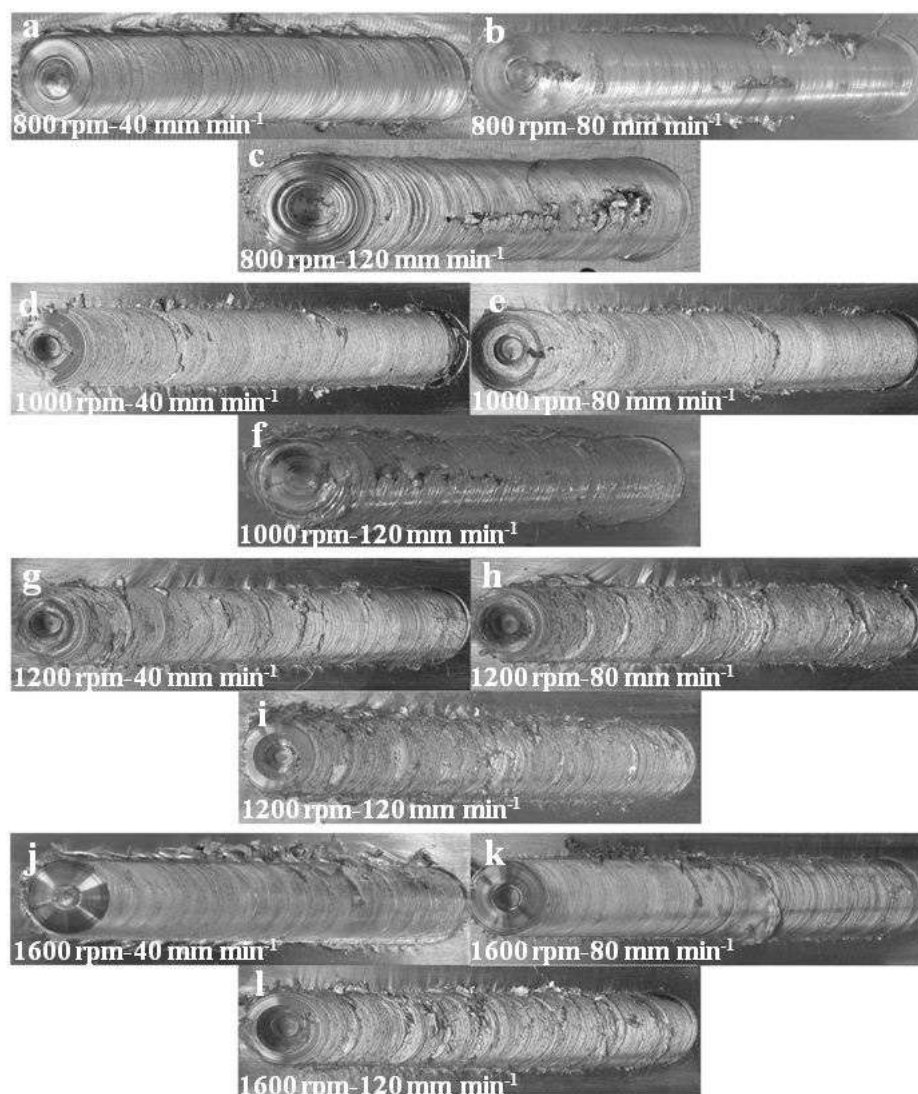


Fig. 5. Surface images of lap joints of Mg and Al using various welding conditions (a-l)

and lack of filling on the surface of magnesium (Fig. 5c, d and f). In the joints, welded under the conditions of 800 rpm-120 mm/min (Fig. 5 c) and 1000 rpm-120 mm/min (Fig. 5 f), large groove defect was formed on the surface. It seems the heat generated has been low and the heat input per unit length of the weld are insufficient, in these samples. Thus extensive plastic flow could not be achieved, and the top magnesium plate was not softened. In welds with rotation speed of 800 and 1000 rpm, when traveling speed was 40 mm/min (Fig. 5a and d), surface groove wasn't

formed, but when the traveling speed was increased to 80 mm/min (Fig. 5e), the surface of the FSW became rough, and groove defect was formed at the lower part of the weld due to the low heat input.

In this study, joints with sound appearance were achieved using tool rotation and line speeds in the ranges of 1200–1600 rpm and 40–80 mm/min, respectively. The surfaces were almost smooth, where no tearing and line defect observed. Generally, pure magnesium has low plasticity due to its HCP crystal lattice, therefore,

the surface appearance of friction stirred pure magnesium is less smooth compared to surface appearance of pure aluminum in similar conditions of FSW [22]. Because of insufficient slip systems of magnesium, its formability or processability is not high; therefore, its deformation capability is very sensitive to temperature.

3. 2. Interface Macrograph

Fig. 6 shows the transverse sections of the lap joints obtained at various rotational and traveling speeds.

It is clear that as a result of increasing rotational speed from 800 rpm to 1600 rpm the condition of joints are getting better (Fig. 6). Defects such as groove (Fig. 6b, 6c, and 6f), tunneling (Fig. 6a, 6d, and 6e), and voids (Fig. 6g, 6h, and 6i) are formed in joints cross section.

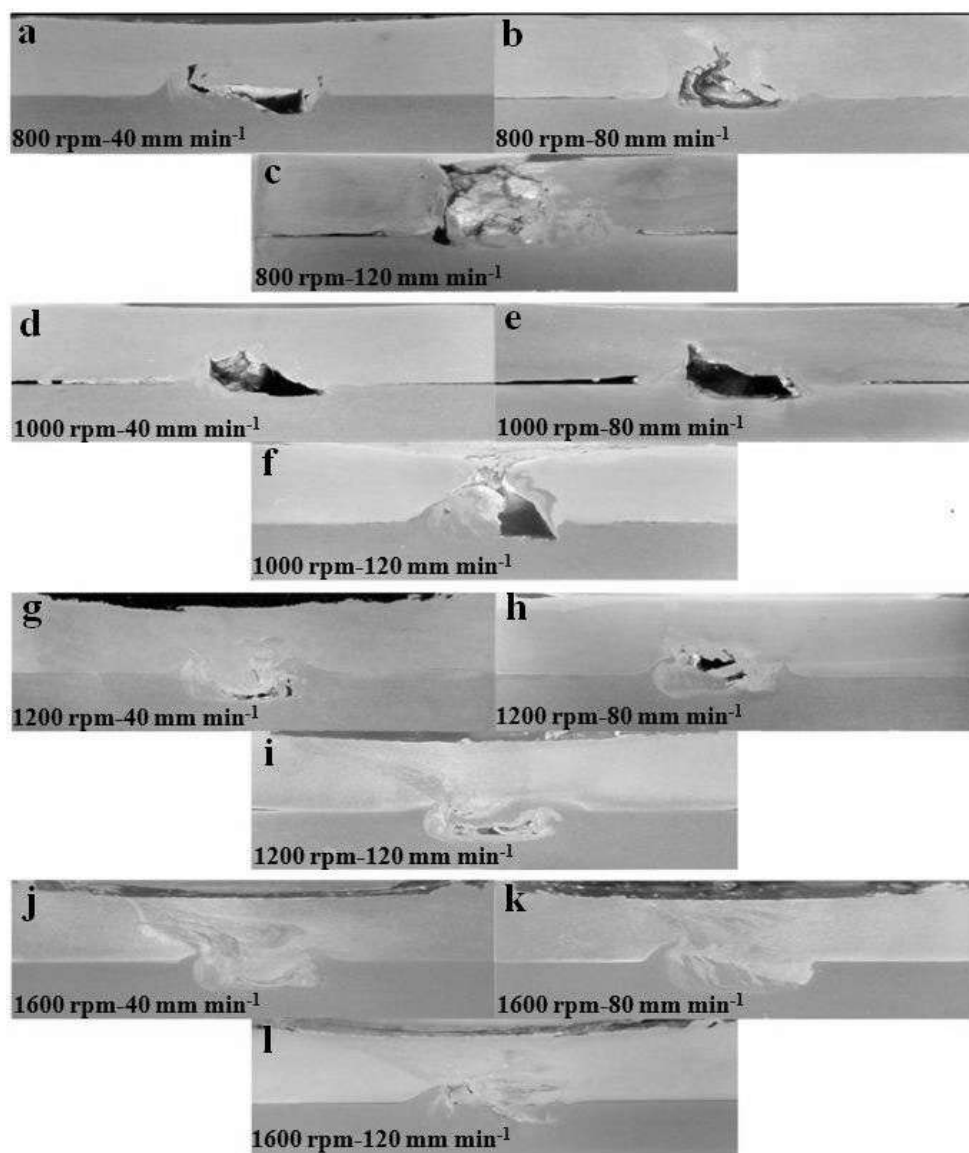


Fig. 6. Optical macrographs of lap joints cross section in various welding conditions (a-l).

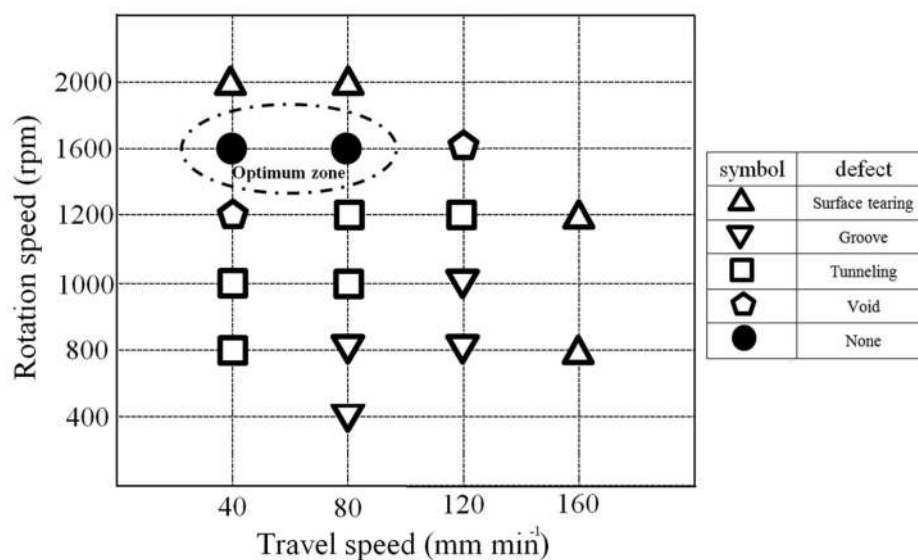


Fig. 7. Welding parameter window for producing sound dissimilar welds of Al and Mg

In lower rotational speed such as 800 and 1000 rpm, however, there are large weld flaws like groove, tunnel, and macrovoid which seems to appear due to insufficient material flow (Fig. 5, and 6). These type of defects have also been observed by Morishige [14], Yamamoto [17], Mishra [23] in other Al and Mg alloys.

According to surface appearance and cross section investigations, Fig. 7 shows the process window of various welding conditions. Defect free welds were obtained by using a process window at rotation and welding speeds of 1600 rpm and 40-80 mm/min, respectively (Fig. 7).

As shown in Fig. 6h, voids were found at the interface; however, using higher rotation speed would make acceptable weld joints (Fig. 7). Welds at the 1600 rpm had no visual surface and cross section defects. In general, joints with sound appearance and interface were achieved using tool rotation of 1600 rpm and traveling speeds of 40-80 mm/min, and no tunnels or voids were observed. In high rotation speed (1600 rpm) more heat can be generated due to friction of tool and plate [7] which soften Mg and Al enough to deform and get mixed and no voids is formed between intercalated layers.

3. 3. Microstructure of the Joints

As Fig. 8 makes clear, the interface in the central region has moved considerably into the bottom aluminum plate (below the original joint line). This part of stirring zone consists of lamellar structure of Al and Mg layers. This vertical shift of interface is attributed to the materials flow created by the tool pin. Esmaeili et al. [24] have also reported this vertical shift of interface in the dissimilar lap welding of Al and brass.

It can be observed that a less vertical shift of interface has occurred on the advancing and retreating sides. In both advancing and retreading sides, the Al come up toward the Mg top plate at lateral sides of the crater, as the result of material being forced into the top plate and toward the shoulder. This effect seen in lap welds is a thinning phenomenon of the top plate known as a “hooking defect”. Hooking have also been observed in the friction stir lap welding (FSLW) of aluminium alloys [18]. Yazdanian et al. [19] determined fracture strength values for a series of FSLW of AA6060-T5 and AZ31B-H24. They reported that increasing the rotation speed increases the hook size and observed a hook in lap joints. It was concluded that “Hook effect”

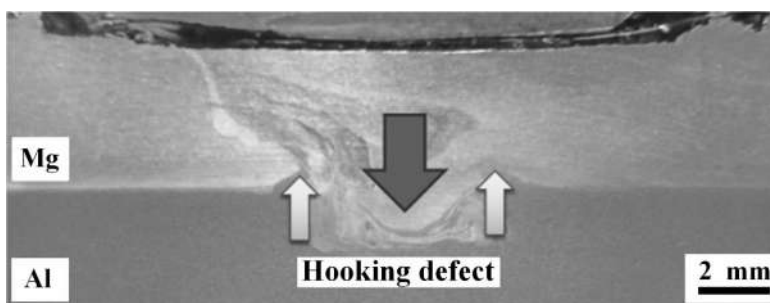


Fig. 8. Optical macrograph of lap joint produced at 1600 rpm and 80 mm/min

reduces the fracture strength significantly when its size reaches a critical value.

Fig. 9 (b) and (c) show complex embedded structure in which Mg and Al layers are swirled together. The microstructure of the lap weld has several white-etching intermetallic compounds in the interface which are mixed together. Several

studies have demonstrated the formation of intercalated layers of base materials in the stir zone of the friction stir welds of dissimilar Al and Mg alloys [11, 25]. The thickness of these intermetallic compounds was less than 10μ . This observation was in good agreement with Firouzdor et al. [15], and Mofid et al. [1] works.

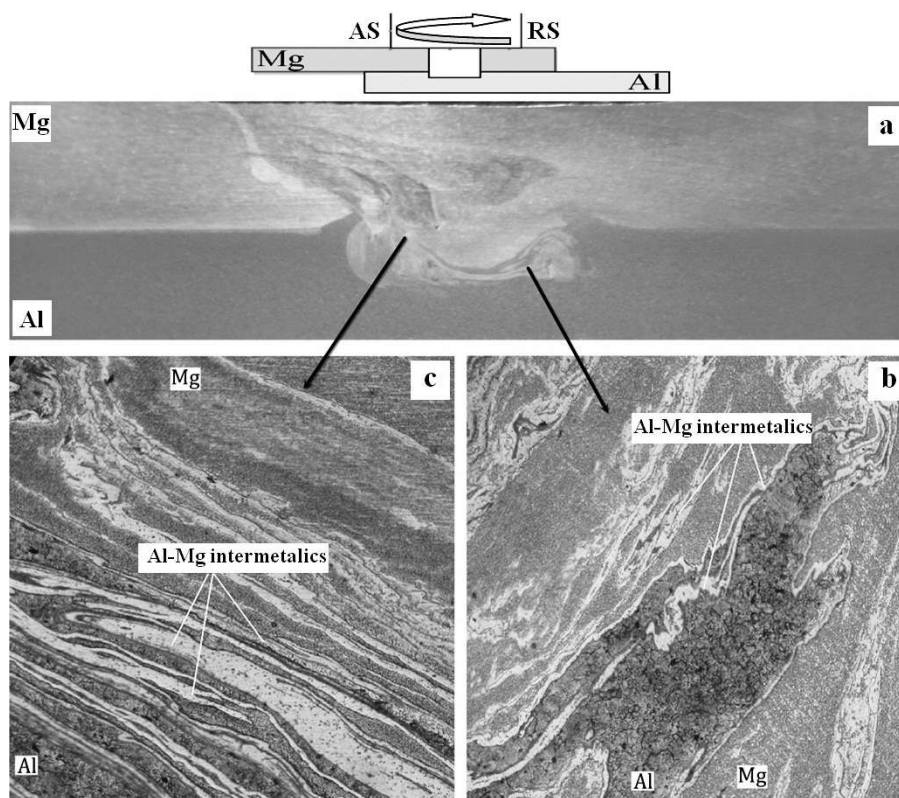


Fig. 9. Microstructure of various regions of dissimilar Al-Mg joint, under the welding condition of 1600 rpm and 40 mm/min (a-c), representing each region of the weld zone marked in macrographs.

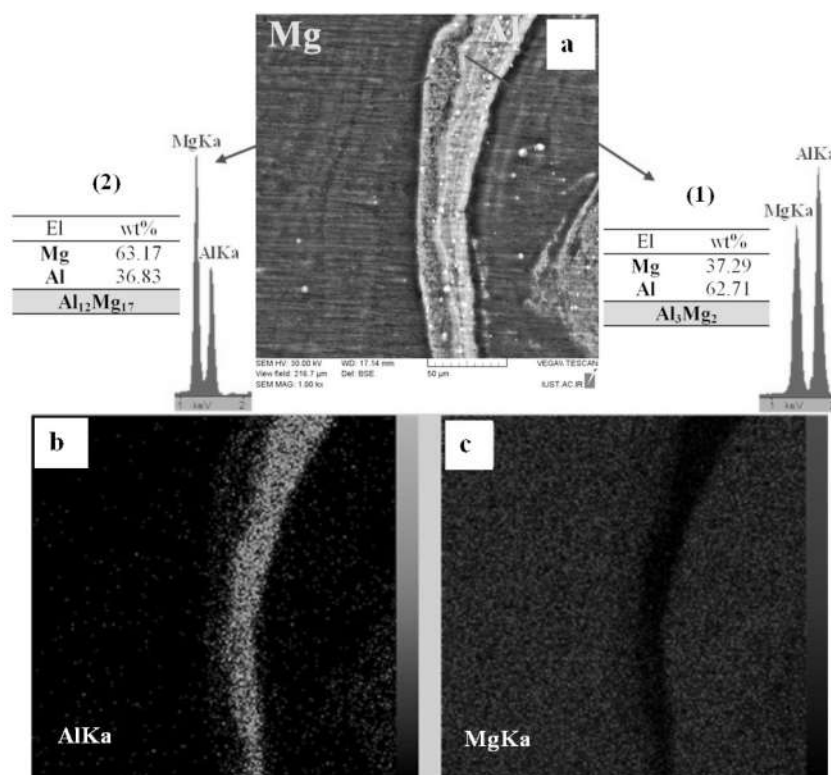


Fig. 10. EDS and map of one of white etching regions shown in figure 9

These intermetallic compounds acted as the fracture initiation sites during tensile testing, and reduced the joint strength and ductility [11].

Mg and Al elemental distributions in the regions near Mg and Al interfaces were analyzed by EDS and quantitative analysis of Mg-Al interface are shown in Fig. 10a. The EDS results demonstrated that these regions had substantially different chemical compositions in comparison to the base metals. EDX element mapping (Fig. 10 b and c) shows the two layers have different elemental composition having higher aluminum element content (63 wt %) near the Al-side and higher magnesium content (63 wt %) near the Mg-side. According to the EDS quantitative analysis and binary phase diagram of Al-Mg [26], composition of these two intermetallic layers are closely similar to Al_3Mg_2 and $Al_{12}Mg_{17}$. Both $Al_{12}Mg_{17}$ and Al_3Mg_2 phases are already reported in dissimilar joining of Al and Mg literature as products of solid state joining [27]. These two phases are brittle compounds and the main reason for the formation of

weld cracks.

In the FSW process, due to heat generation, inter-diffusion of Al and Mg atoms occurs at the interface of mixed layers [28]. Moreover, diffusion rate of atoms can be accelerated due to the intense plastic deformation of stirred layers, high density of low-angle grain boundaries, and fine grain structure. Generally, the enhanced interfacial diffusion, caused by increased interfacial area, plays an important role in enhancing the diffusion rate, and this role is more important than that of grain boundary diffusion [17, 29].

3. 4 Microhardness

Transverse cross-section hardness profiles of the joint produced in 1600 rpm and 40 mm/min are shown in Fig. 11. The hardness values in the stir zone show an inhomogeneous distribution and high values compared to the hardness of Al and Mg base metals. Moreover, the hardness values of the lower side (line 1) of the nugget

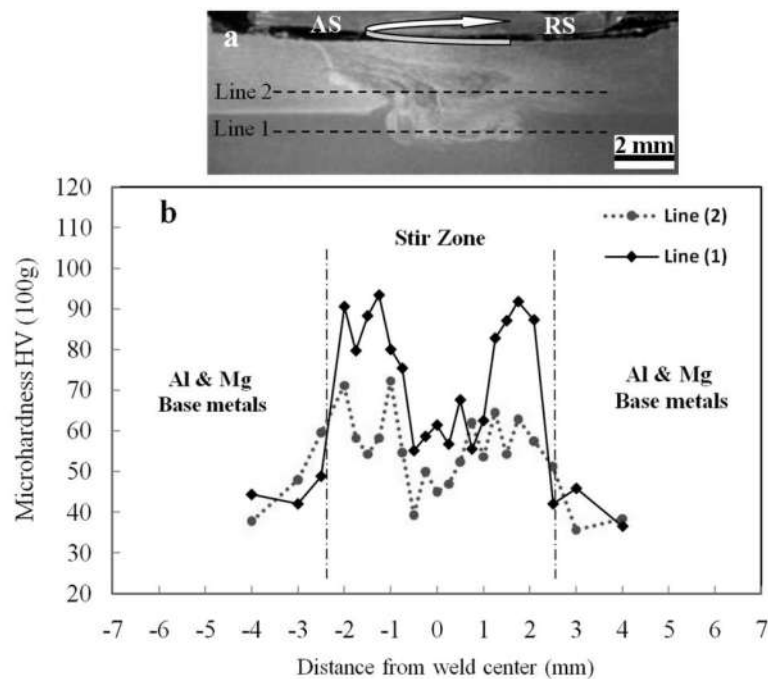


Fig. 11. Hardness distribution one mm above and below the lapping line in the sample welded at rotation speed of 1600 rpm and line speed of 40 mm/min.

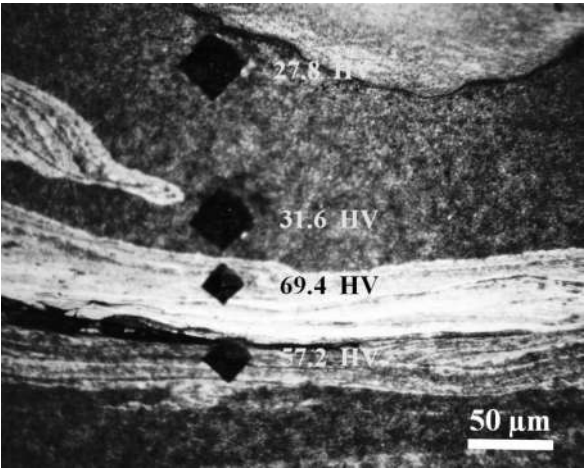


Fig. 12. Measured hardness of the intermetallic layers at the interface.

zone are higher than the upper side (line 2). The high values in the stir zone are attributed to the existence of hard intermetallic layers (Al_3Mg_2 and $\text{Al}_{12}\text{Mg}_{17}$) with complex intercalated structures [30] (Fig. 11a).

3. 5. Tensile Test Results

Experimental [31-32] and simulation studies [33-34] have shown that increase in the rotational speed leads to higher temperature in the nugget zone which could result a proper joint if other

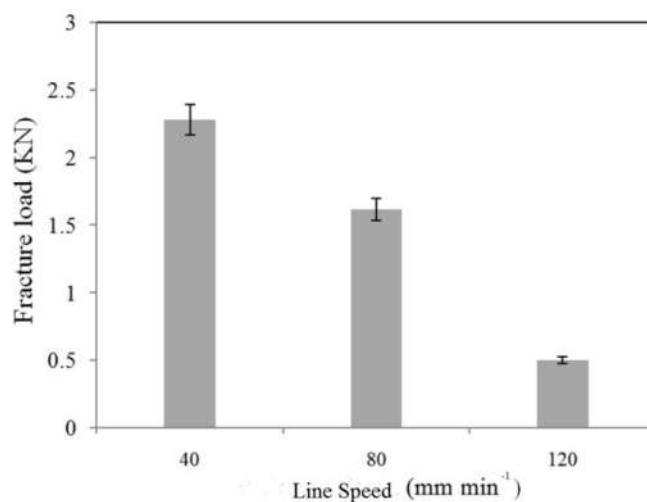


Fig. 13. Shear tensile test results of joints produced at rotational speed of 1600 rpm and different line speed

conditions are appropriate. In contrast, the line speed reduces heat generation [33-34]. The shear tensile test results of the joints are shown in Fig. 13. The results indicate that the welding line speed have a significant effect on the failure loads of the joints at the rotation speed of 1600 rpm. The maximum failure load of 2.28 kN was obtained at a welding speed of 40 mm/min. In spite of the formation of intermetallic phases (Al_3Mg_2 and $Al_{12}Mg_{17}$) the size, shape and distribution of these two intermetallic are such that overall strength is in the range mentioned above. The joint strength in the present study is comparable to the study by Chen et al. [16] in which the joint prepared at 50 mm/min and 1500 rpm, showed 1.8 kN strength. It is important to note that in their study Al plates were on top which possibly produce more heat and create thicker intermetallic compounds at the interface.

The joints failing did not occur at the interface and failure has always occurred on the advancing side in Mg plates possibly due to hooking effect and thinning of top mg plate. It seems the hook acts like a crack in the lap joints produced by FSW and strongly influences the load-bearing ability of the joints and the failure location [35]. At higher welding speeds, failure loads of the joints showed lower values (Fig. 13). This can be related to microvoids and mismatch of mixed

layers of Al and Mg, which cause stress concentration during tensile testing.

From the macrostructural point of view, local thinning of the top sheet caused by both hooking defect from the bottom and shoulder depth plunging from the top surface seems to be the main reason of this failure. Also, the formation of brittle intermetallic compounds are due to the vertical flow of the bottom aluminum plate toward the top magnesium plate which most likely occur at the AS side of joint. These compounds have been widely illustrated as the crack initiation and growth areas [11]. Because of the tensile load direction in lap joint, the load has weak influence on the RS and stress on RS is very low.

The magnified image of a typical fracture surface is shown in Fig. 14. The fracture surface consisted of protuberances and cleavage cracks, which are considered as a proof of brittle fracture mode, signifying that the cracks may have originated from the intermetallic compounds in reaction layer [36-37]. Quantitative analysis of the chemical compositions by EDS showed that the fracture surface consisted of cleavage cracks of intermetallic compounds, and Mg dimples. This result indicates that a local plastic deformation in magnesium base metal can be observed in fracture locations before fracture.

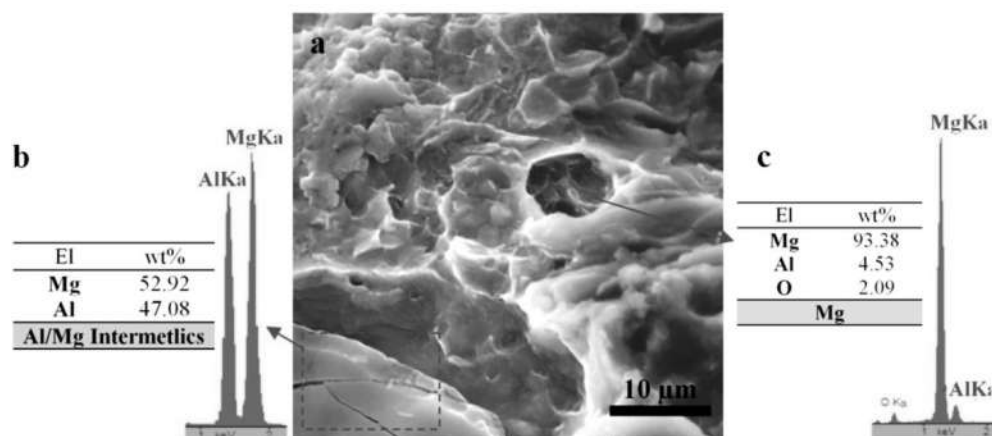


Fig. 14. Quantitative analysis of the chemical compositions by EDS, and the fracture surface consisting cleavage cracks of intermetallic compounds, and Mg dimples

4. CONCLUSIONS

1. Joints with sound appearance were achieved using tool rotation of 1600rpm and welding line speeds in the range and 40–120 mm/min. The joints had smooth surfaces and no porosity and defect lines were observed
2. In low rotational speeds, such as 800 and 1000 rpm, there were large weld defects like groove, tunnel, and macrovoid.
3. Microstructure of stir zone had a complex flow pattern. Microhardness measurements of the dissimilar Al and Mg welds presented an uneven distribution due to the complicated microstructure of the welded zone. The maximum value of microhardness in the stir zone was twice higher than the base materials.
4. The joint strength in the present study was higher compared to similar works where Al plate was positioned on the top. This seems to be the result of the lower heat generation and thinner intermetallic layer formation in the stirred zone.

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