Bimetal Friction Stir Welding of Aluminum to Magnesium

P. Pourahmad, M. Abbasi[1]★, H.A. Mehrabi
Department of materials science and engineering, Karaj Branch, Islamic Azad University, Iran

ARTICLE INFO

ABSTRACT

FSW material flow and phase transformation were studied at the interface of dissimilar welding of Al 6013 to Mg. Defect free butt weld was obtained when aluminum and magnesium test plates were placed in the advancing side and retreating side respectively, and the tool was placed 1 mm off the weld centerline into the aluminum side. In order to understand how the materials flow during FSW, steel shots were implanted as indexes into the test plate's intimate face and welding was performed with determined optimum parameters. X-ray images were used to evaluate secondary positions of the steel shots at weld zone. It was revealed that steel shots implanted in the advancing side test plate were penetrated from advancing side into the retreating side with a relatively large rotational displacement of α. But shots implanted in retreating side test plate remained only in retreating side, without penetrating into the advancing side, and displaced by a low angle of β. It could be concluded that to reach defect free welds by FSW between two dissimilar metals, the tool should be inserted in harder metal and harder metal should be placed in the advancing side too. EDS analysis was performed in order to study formation and distribution of intermetallic phases in the welds interface. Two intermetallic compounds formed sequentially at Al6013/Mg interface were Al_3Mg_2 and $Al_{12}Mg_{17}$ in weld condition. Welded specimens were heat treated and their effects on mechanical properties of welds and formation of new intermetallic layers were investigated.

Introduction

Aluminum and its alloys are widely used in aerospace, automotive and other industries, where the combination of high strength and weight reduction is the main concern. On the other hand, magnesium and magnesium alloys are also used in the aforementioned industries because of their lower density and high strength.

Thus, the need for obtaining sound weld by good mechanical properties for aluminum and magnesium joints is often needed. As Chen and Nakata, 2008, reported, a variety of attempts have been made to weld these alloys using fusion welding technology. It has been shown that this technique was not suitable due to the intermetallic compounds formed in the weld, being deleterious to the

---

♣ Corresponding author: M. Abbasi, mehrdad600@gmail.com, 09121750803

mechanical properties. Friction stir welding is a solid-state welding technique invented by The Welding Institute (TWI) in 1991 [1]. Attallah et al. [2] and Sauvage et al. [3] showed that defect free welds with good mechanical properties can be made in a wide variety of aluminum alloys. Also, Abbasi et al. [4], Afrin et al. [5] and Cao and Jahazi [6], have achieved successful FSWed joints for different magnesium alloys. FSW dissimilar welding between aluminum and magnesium has recently received much attention. Yan et al. [7] investigated friction stir weldability of Mg alloy AZ31 to Al alloy 1060. As they reported, visually, sound welds could be produced. However, the formation of a thin intermetallic layer at the interface resulted in welds that exhibited virtually no ductility. The intermetallic layers were identified as Al_3Mg_2 and $Al_{12}Mg_{17}$. Also, Kostka et al. [8] have found that during friction stir welding of AZ31 to AA6040, two intermetallic phases have been formed in the intermediate layer. Further studies show that these intermetallic compounds consist of Al_3Mg_2 and $Al_{12}Mg_{17}$. Also, Firouzdorand Kou [9] have studied the FSW of 6061 aluminum to AZ3. Their study showed that placing materials in different sides of the weld can lead to different consequences. Also, they reported that macroscopic intermetallic could be formed during FSW, which is a direct result of melting in the interface of the weld.

In this study, the metallurgical parameters of friction stir welding of 6013 aluminum and pure magnesium were studied in order to provide more information for the practical friction stir welding of Al-Mg joints. The influence of heat treatment on intermetallic layers and mechanical properties of friction stir welded joints was also investigated.

Experimental procedure

Plates of 10 mm thickness of 6013 aluminum and pure magnesium with specifications summarized in **Table 1** were welded by friction stir welding. The weld has two sides relative to the centerline; One side is referred to as the advancing side (AS), where the rotational motion and linear motion of the pin are in the same direction. The other is the retreating side (RS), where the rotational motion and linear motion of the pin are in the opposite directions. Kostka et al. [8], Yan et al. [7], and kwon et al. [10], have reported that the best metallurgical quality for Al to Mg FSWed joints could be achieved if aluminum and magnesium were placed in the advancing side and retreating side respectively. Considering these results, in this study, magnesium plate was located on the retreating side and aluminum plate was located on the advancing side. Dimensions of the plates were rectangular, 100×100×10 mm, and FSW tool was made of H13 tool steel heat treated at 900 °C, 1h and quenched in oil .The shoulder diameter of the tool was 20 mm. The pin of the tool had a conic shape (with max diameter of 6 and min diameter of 4 mm) and a height of 6mm.In order to optimize the welding parameters, various tool rotation speeds from 800 to 2000 rpm, traverse speed from 31 to 75 mm/min and offset tool angle of 2 and 3 degree were applied. Experiments were performed first when the stirring pin was placed off the centerline for 1mm to the aluminum advancing side, and second, when the stirring pin was exactly placed at centerline. Finally, it was placed off the centerline for 1mm into the magnesium retreating side. Also, a copper block, used as the heat sink, was placed under joint assembly to prevent excessive heating in all tests.

To investigate the material flow around the FSW tool, steel shots with diameter of 1mm were embedded firstly 1 mm into the advancing side and secondly, 1 mm into the retreating side. In both tests, welding was performed using the optimized parameter. Then, X-ray images were taken from the welded joints to detect the secondary position of the steel shots. Distribution of the steel shots in different heights from the faying surface clarified the material flow from the face to the root of the weld.

In order to study the effects of heat treatment on the formation of intermetallic phases and mechanical properties of the FSWed joints,

Table 1. Chemical and mechanical properties of the Al and Mg.

Metal	Chemical composition (Wt %)	UTS (MPa)
Al 6013	Al: 96.26, Si:0.497, Fe:0.622, Cu:1.201, Mn:0.115, Mg:1.183	201
Magnesium	Mg:99.7±0.2, Si:0.06	90

Table 2. Chemical composition of tool steel.

Metal	% C	% P	% S	% Cr	% Mo	% V
H13 (DIN 1.2344)	0.44	0.018	0.009	4.960	1.464	0.983

specimens were heated to 320 °C for 1, 2 and 4 h. Then, they were cooled in still air in room temperature. The mechanical properties of the joint were measured using tensile tests. FSWed joints were cross-sectioned perpendicular to the welding direction and then machined into the rectangular specimen with dimensions of 200×20×10 mm for the tensile tests, whereas the weld zone was placed in the middle of the specimens. The metallurgical microstructures of dissimilar weld interface were analyzed by scanning electron microscopy, which was equipped with an energy-dispersive X-ray spectroscopy (EDS) analysis system.

Results and Discussion

Optimizing the welding parameters

In this study, welding of 6013 aluminum and pure magnesium was possible only when the rotating pin was placed 1mm off the centerline into the aluminum advancing side (**Fig. 1**). Inserting the pin into the centerline caused a process more like a milling process in which no welding could be reached. Also, inserting the pin off the centerline for 1mm into magnesium resulted in a defected weld due to the melting of magnesium. Line defects were also observed along the weld line. Reaching the good welding quality was possible when no melting occurred throughout weld line and a high viscose mash or semi-solid state volume of material was formed. Inserting pin into aluminum caused a frictional heat concentrated on aluminum side and less heat reached to magnesium. When pin was inserted into Al, more heat would be wasted through higher heat conductive aluminum. Because of the higher heat conductivity of Al,

250 W/m·°C, relative to Mg,156 W/m.°C, and near the same heat capacity of aluminum, 0.91kJ/Kg ·°C, and magnesium, 1.05kJ/Kg·°C, aluminum needs more heat input to melt done and remain in viscose mash state.

Mishra and Ma [11] have presented a series of equations for the FSW of aluminum alloys.

Similarly, **Eq. 1** determines the principle correlation between welding parameters and heat generation in FSW based on which, rotational speed (w) has a direct effect on heat input and linear speed (v) has a reverse effect on heat input.

$$\frac{w}{v} \propto \text{Heat Input} \qquad (1)$$

It can be concluded that to reach a sound weld by FSW between two dissimilar metals, it is better to insert the tool pin in the material
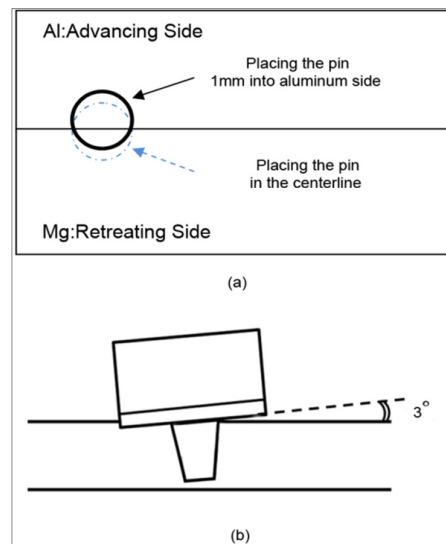

Fig.1. a) Placing the pin 1mm off the centerline into the aluminum advancing side. b) Tilt angle between the surface of the weld and the FSW tool.

which has a higher heat capacity and a higher plasticity. The appearance of the FSW joints with different parameters of welding can be seen in **Fig.2**. Using rotation speed of 1250 rpm, welding speed of 50 mm/min and tilt angle of 2 degrees caused a void throughout the weld line (a) .This defect is likely to occur due to the poor stirring action and the low heat. Raising the rotation and welding speed up to 1600 rpm and 70 mm/min, increased the size of the void.On the contrary, surface morphology of the weld became smoother, (b). For the sample(c), heat generation was elevated due to a decrease in the linear welding speed with respect to **Eq.1**. Consequently, the void became much smaller. Sound weld was obtained when the tilt angle of the weld was changed to 3 degrees and accompanied by rotation and welding speed of 1600 rpm and 35 mm/min.This suggests that using 3 degrees of tilt angle of the pin hasimproved the stirring action of the pin and

caused more penetration force for extrusion of Al into Mg.Changing the tilt angle helps the shoulder of the tool push the stirred material from front to the rear of the pin. It is also due to the rise of the aluminum extrusion pressure into magnesium by increasing the tilt angle. Further reductions of the welding speed and increase of the rotation speed lead to excessive heat generation which, in turn, caused the weld metal to melt.

Material flow patterns

In order to evaluate material flow pattern in FSW welds, steel shots with diameter of 1 mm were planted in the test plate's intimate face, parallel to the weld line. These steel shots were moved with material flow during FSW. To study flow pattern, welding was accomplished using optimized parameters in two different cases. First when the steel shots were planted 1 mm into the advancing side and second, when
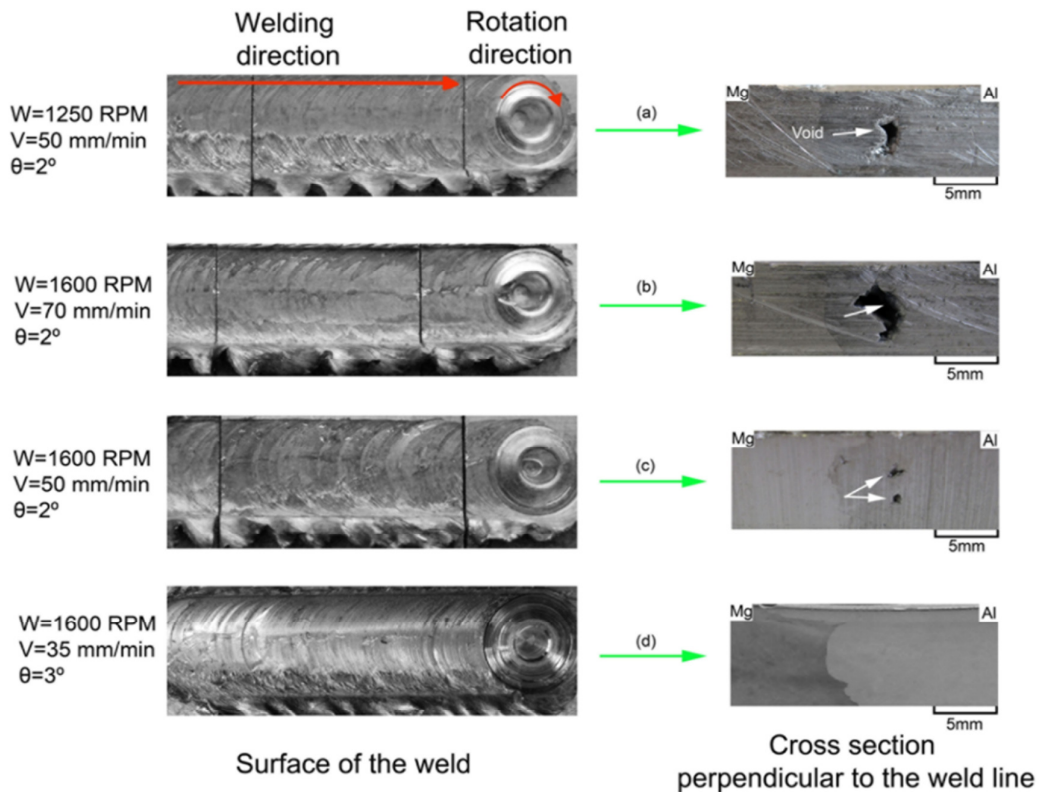

Fig.2. Surface appearances of the weld and cross section perpendicular to the weld line.

they were planted 1 mm into the retreating side. New positions of the shots were detected in X-ray images taken from FSWed joints. The original position of the steel shots planted in aluminum advancing side is presented in **Fig. 3a**. X-ray image in **Fig. 3b** was taken after FSW of the same plate, indicating the secondary position of the shots. The secondary position of the shots reveals that the flow of the material causes the steel shots to be displaced from the advancing side to the retaining side and then, extruded about 1.5 to2 mm into the retreating side with total displacement of 2.5 to 3 mm. Also, shots arestored in the back of the pin by the displacement of about one diameter of tool pin. This movement is shown by the black arrow in **Fig. 3**. Secondary positions of the steel shots also illustrated the correlation between original position of the shots in the plate and the secondary position of them after FSW. For example, steel shot No.1 did not move during FSW process. Since the pin height was 6mm, and position of steel shot was 7mm from the faying surface of weld, no material flow could take place in this depth.

The original position of the steel shots in magnesium retreating side is shown in **Fig. 4a**. The X-ray image taken after FSW of the test plates is shown in **Fig. 4b**. In contrast to **Fig. 3**, steel shots have remained in the retreating side. In this test, plate steel shots were moved for about 1.5 to 2 mm into retreating with the total displacement of 0.5 to 1 mm. Also, shots are stored in the back of the pin by displacement of about one diameter of pin. The amount of this movement depends on the original places of the shots.

The difference between movements of the steel shots in the advancing and retreating sides is illustrated in **Fig. 5**, separately. Steel shots in the advancing side have moved through semi solid materials, turning α degree into the retreating side and storing it behind the pin. On the contrary, the steel shots in the retreating side tend to remain in the retreating side. They are just pushed back with the movement of β degrees and stored behind the pin. **Fig. 6** is a cross section of FSWed joint. Interface macrograph of the welded specimens showed that three different regions can be recognized in the interface regarding the depth of the region from the surface of the weld. The first region is near the surface of the weld, where plastic deformation and material flow were large due to the shoulder effect. It can be seen that aluminum has been extensively extruded into magnesium and a rough and zigzag interface has been formed.
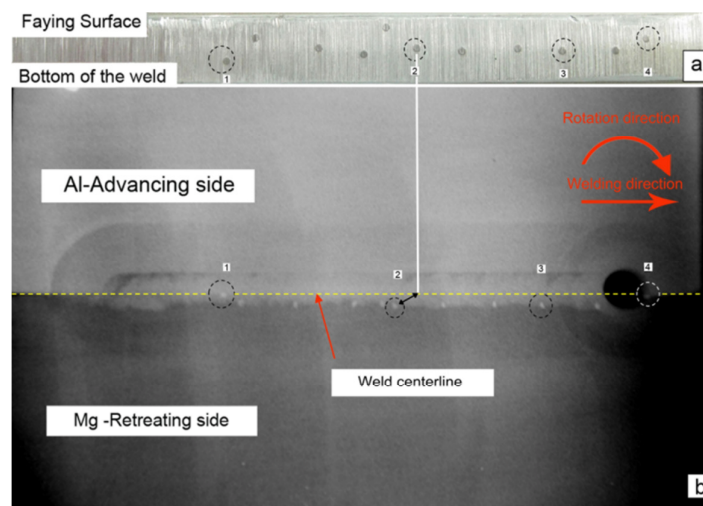

Fig.3. a) Initial place of the steel shots planted into aluminum advancing side. b) X-ray Image after FSW showing the secondary position of the steel shots.
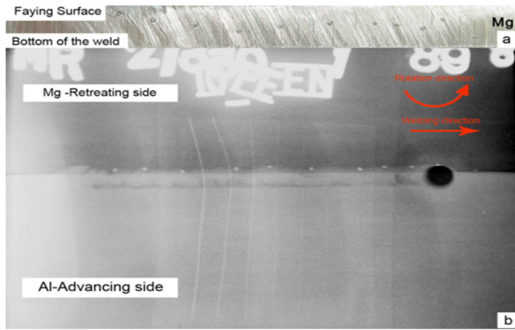
Fig. 4. a) Initial place of the steel shots planted into magnesium retreating side. b) X-ray Image after FSW showing the secondary position of the steel shots.
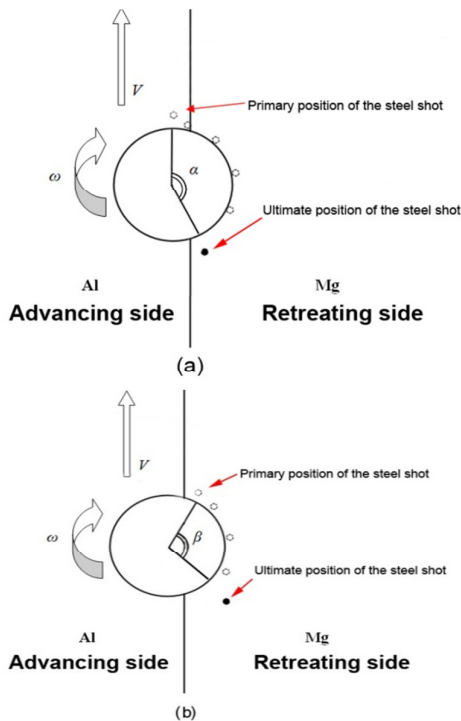

Fig. 5. Movementof a steel shot during FSW, planted in a) advancing side b) retreating side.

Fig.6 b area No. 1 indicates that the separation of aluminum island takes place in the magnesium side, and area No. 2 shows magnesium island takes place in the aluminum side. Interlocking was also evident in the upper part of the weld, which is the direct effect of the intensive plastic
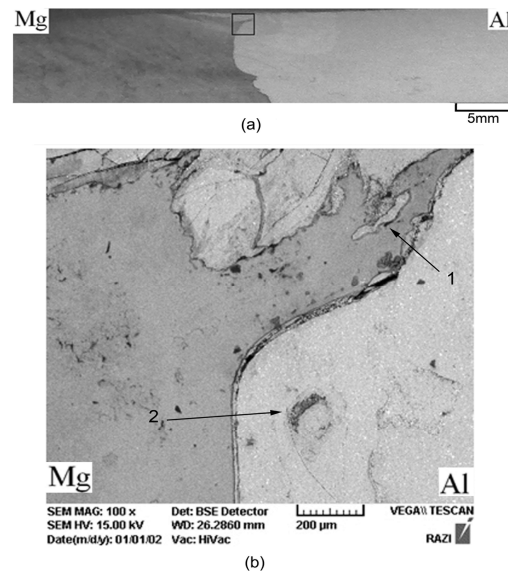

Fig. 6. a) Cross section of weld showing different regions of the interface b) islanding and interlocking in the upper part of the weld.

deformation and extrusion at the top of the weld. Islanding and interlocking were observed only in the first region of the weld. On the contrary, in the middle of the weld or the second region, the interface becames moother and the extrusion of aluminum into magnesium was much less than the first region. The third region is near the end of the pin in which extrusion of aluminum into magnesium was the least. The difference in the mixture pattern of the materials in different regions is the consequence of diverse material flows and extrusion and penetration forces.

Microstructure observation of Al/Mg interface

Formation of the intermetallic phases in the as-weld and heat treated specimens was studied in the FSWed joints that have been weldedbytheoptimizedparameters.SEMand EDS analysis were done in order to study if the intermetallic compounds would be formed in the Al/Mg interface during friction stir welding process. EDS analysis from the upper region and central region of the Al/Mg interface is illustrated in **Fig.7**. From EDS line analysis and SEM image, it is evident that in
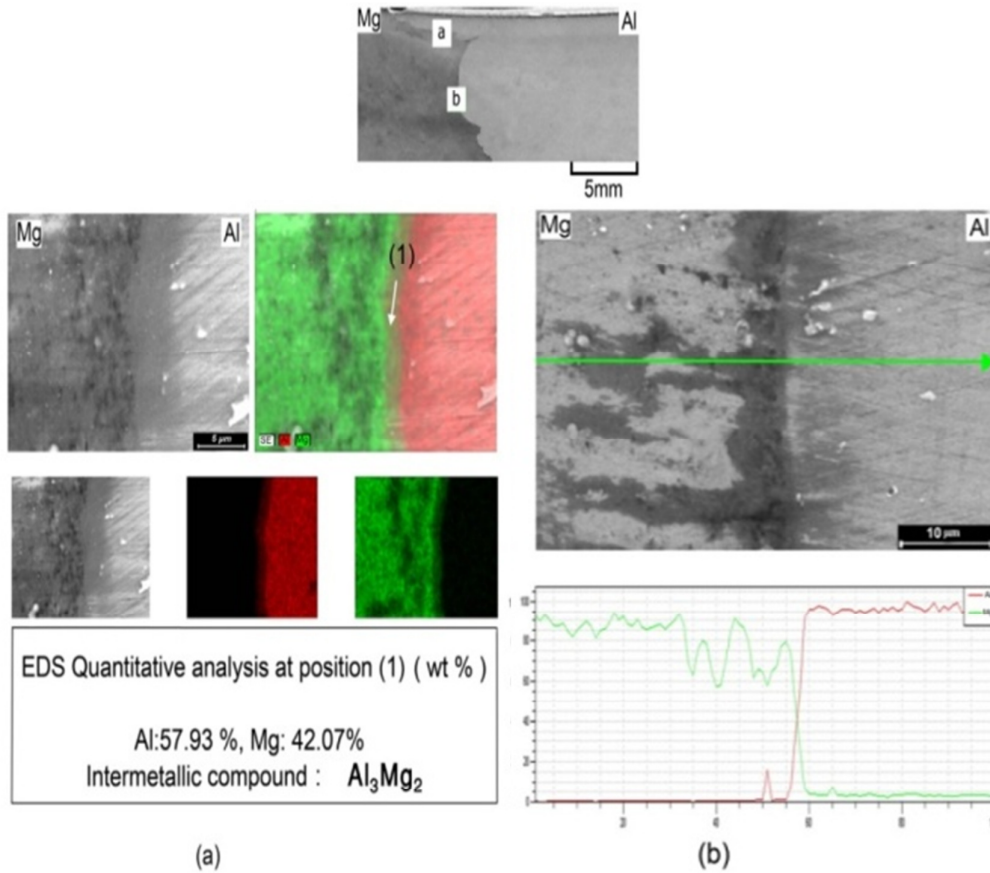
Fig. 7. SEM and EDS analysis of as-weld FSWed joints. a) EDS mapping data and quantitative analysis from top of Al/Mg interface b) EDS line analysis from the middle of the Al/Mg interface.
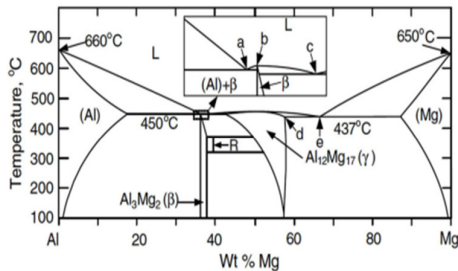

Fig. 8. Al-Mg Phase Diagram. The eutectic points (e) at 437 and 450°C [12].

the middle of the interface, no intermetallic layer was formed. On the contrary, it is revealed that in the upper parts of the Al/Mg interface, a continuous layer of intermetallic component has been formed at the weld interface.

According to the EDS quantitative analysis and binary phase diagram of Al-Mg (**Fig. 8**),

composition of the intermetallic layer is defined to be Al_3Mg_2 or β (Al=57.93, Mg= 42.07). The appearance of the intermetallic layer with thickness of 2μm in the upper part of the interface can be attributed to the more heat input in the surface of the weld, which was generated by friction effect of the shoulder.

Effects of heat treatment on the intermetallic layer in the Al/Mg interface

Mishra and Ma [11] showed that a huge amount of residual stress would remain in the weld zone as a result of stirring action and plastic deformation during the FSW process. This residual stress has a deleterious effect on mechanical properties of the weld. In order to enhance the metallurgical properties and release the residual stress, post weld heat

treatment was performed on the welded plates. 1, 2 and 4 h of heat treatment was applied on the FSW joints. In order to prevent melting in the interface, heat treatment temperature was chosen to be 320°C due to the eutectic reactions at 437 and 450 °C in the binary phase diagram of Al-Mg. SEM image, accompanied by EDS line and quantitative analysis of Al/Mg interface for 1 h of heat treatment, is illustrated in **Fig. 9**. EDS line scan of the Al/Mg interface suggests that after 1 h of heat treatment, thickness of the intermetallic layer was slightly developed to about 4μm. Quantitative analysis also revealed that the intermetallic layer composition would be Al_3Mg_2 or β(Al=58.51,Mg=41.49).

In **Fig. 10a**, it seems that after 2 h of heat treatment, the intermetallic layer has been more thickened to about 12μm. Quantitative analysis showed that the composition of the intermetallic layer is β phase with the composition ofAl=63.92 and Mg=36.08. Also, in the EDS mapping analysis of the interface, the intermetallic layer is evident by the white arrow and yellow color.Firouzdor and kou [13] reported the presence of this thick intermetallic layer in weld specimen.

They stated that in the limited time of the FSW process, solid state diffusion is very low; therefore, the presence of thick intermetallic layers is attributed to the solidification of the liquated material in the interface. Also, Chen and Nakata [14] reported that the layers of intermetallic compounds can be formed in the middle of the FSW lap joints as a result of melting during the welding. They stated that these intermetallics had a solidified micro–structure. However, in this study, the growth of intermetallic layer was due to the heat treatment and there was no sign of the solidified microstructure in the interface.

Fig. 11 shows that after 4 h of heat treatment, intermetallic layer in Al/Mg interface has been developed even more. Unlike other samples, intermetallic layer in the interface would consist of two different compositions which can be detected by the contrast in the image. These two compositions were defined to be mostly Al_3Mg_2 or β(Al=63.93,Mg=36.07) and slightly $Al_{12}Mg_{17}$or γ (Al=43.24, Mg=56.76). It can be expressed that heat treatment of the FSW joints of aluminum and magnesium caused the growthof the intermetallic component in the Al/Mg
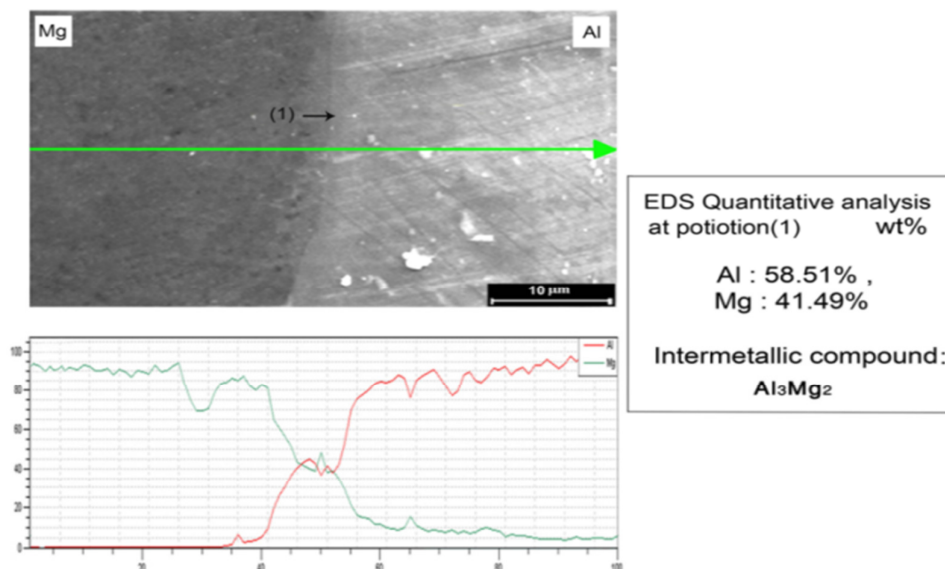

Fig. 9. EDS line and quantitative analysis of the Al/Mg interface for the FSW joint, heat treated, 1h, at 320°C.
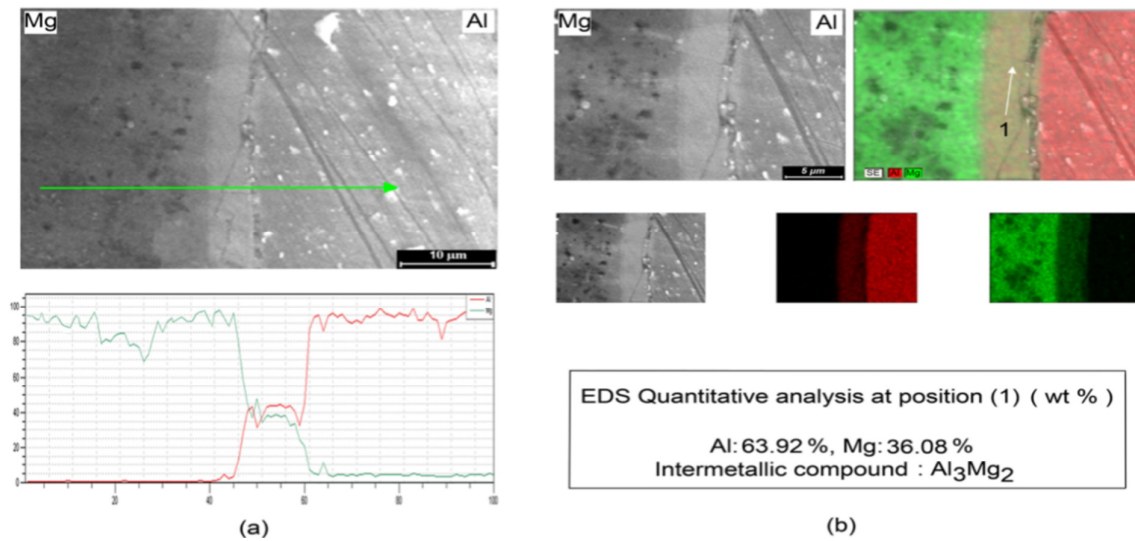
Fig. 10. SEM and EDS analysis of FSW joints, heat treated 2h, at 320°C. a) EDS line analysis, b) EDS mapping data and quantitative analysis from the Al/Mg interface.
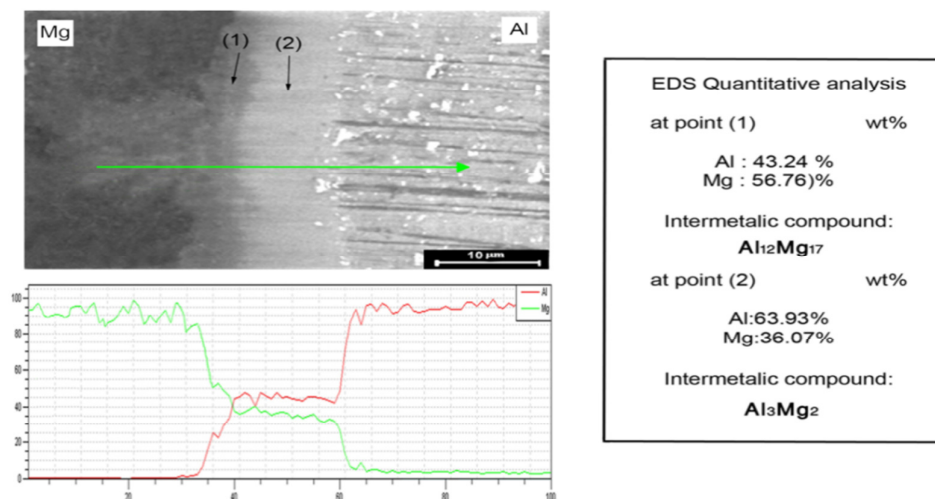

Fig. 11. EDS line and quantitative analysis of the Al/Mg interface for the FSW joint after 4h of heat treatment at 320°C

interface and the overall thickness of the intemetallic layers is about 23 μm.

Fig 12 is also a SEM image taken from the heat treated specimen after 4 h. It can be seen that β and γ intermetallic layers are formed together. Al_3Mg_2 was always formed near aluminum and $Al_{12}Mg_{17}$ was formed near magnesium. In this image, $Al_{12}Mg_{17}$ is the light etched layer and the dark pits show Mg rich area that has been more susceptible to corrosion.

Effects of Heat treatment on the mechanical properties

The frictional heat of FSW process increases the temperature and accelerates the chemical reaction between the two active metals, resulting in formation of intermetallic compounds layers at Al/Mg weld interface.
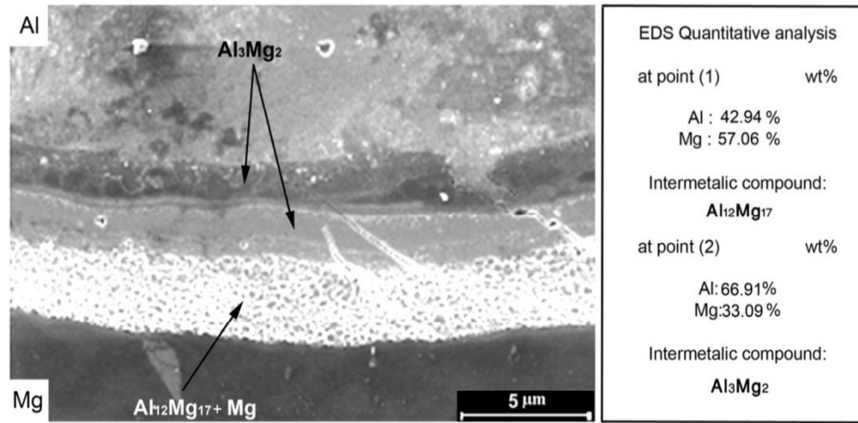
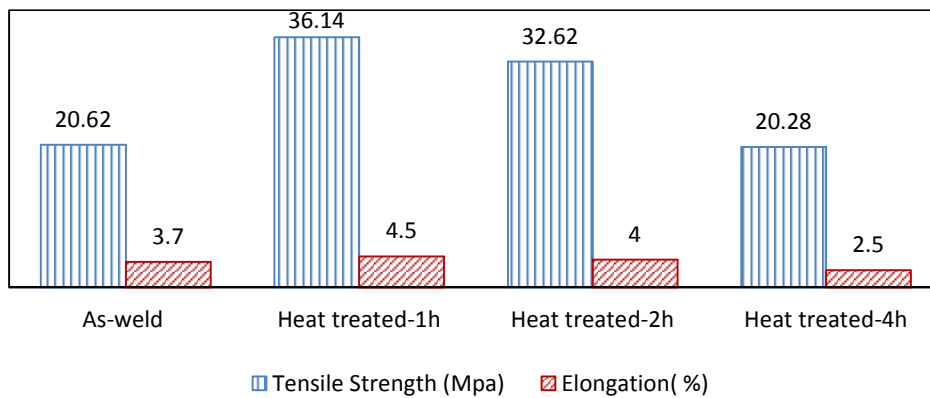**Fig. 12.** EDS point analysis in Al/Mg interface in FSWed joint after 4 h of heat treatment at 320 °C

Fig. 13. Tensile strength and elongation percentage of as-weld and heat treated specimens.

The results of the tensile tests for as-weld and heat treated conditions are shown in **Fig. 13**. The tensile strength of As-weld specimen was about 20.62 MPa and elongation was 3.7 %. The low tensile strength in this specimen was due to the formation of a brittle layer of β phase at the interface. Heat treatment at 320 °C for 1h improved tensile strength and elongation up to 36.14 MPA and 4.5%,respectively. This result was double checked and confirmed. Although β phase has been thickened up to 4μm, this improvement of mechanical properties can be attributed to the tempering of β phase brittleness and the increase of coherency at the interface of β phase and matrix. 2 h of heat treatment leads to a decrease in tensile strength and elongation to

32.62 MPa and 4%, respectively. This reduction of mechanical properties can be due to the growth of β phase to about 12μm. 4 h of heat treatment causes a decrease in tensile strength and elongation to 20.28 MPa and 2.5%. This is due to the excessive growth of the β phase and the formation of γ phase between Mg and β phase. Overall thickness of these layers reached up to 23μm. This growth of intermetallic layers would cause join strength to be decreased.

In comparison with the tensile strength of gas tungsten arc welded joints of 1060/AZ31 without filler metal that is nearly zero [14],in this study, the maximum tensile strength for FSW of Al6013 to pure magnesium was 36.14MPa.

Conclusions

In this study, dissimilar FSW between Al6013 and pure magnesium plates was carried out and the following results were obtained:

1) Defect-free welds were successfully achieved when tool rotation speed was 1600 rpm, traverse speed was 35 mm/min, and tilt angel was 3°. Welds were made only when the stirring pin was 1mm off the centerline towards aluminum. By placing FSW tool 1mm into aluminum advancing side, material flow was improved, extrusion of Al in to Mg was enhanced and voids formation wasprevented behind the pin. In general, to reach a defect free weld by FSW between two dissimilar metals, it is better to insert the pin tool in a higher heat capacity metal with a higher melting point.

2) Material flow pattern was studied in two cases by means of implanting steel shots in the advancing and retreating side respectively. It was revealed that steel shots implanted in the advancing side penetrate from the advancing side into the retreating side with a relatively large rotation path of α. Displacement of steel shots implanted in the retreating side revealed that shots and material in the retreating side remained only in the retreating side, without penetrating into the advancing side and moving by a low angle of β. Displacement of the materials in the advancing side was bigger than the retreating side $\alpha > \beta$.

3) Material and steel shots which were planted near the surface were exposed to the rotating effect of shoulder and pin and displaced more than steel shots planted in the deeper location. It practically demonstrates that the material flow near the weld face is more than the weld root.

4) Three regions were defined for studying the micrographs of welds cross section. The upper region that was placed under the tool shoulder was the first region where extrusion and stirring action have been extensive. In the first region, aluminum was extruded into magnesium and zigzag interface, interlocking, and islanding were observed. The second region was placed in the middle of the weld in which the extrusion of aluminum into magnesium was less than the upper portion and weld interface was smoother. The third region is around the weld root that was near the end of the pin, where the extrusion of aluminum into magnesium was the least.

5) The frictional heat of FSW process increases the temperature and accelerates the chemical reaction, resulting in the formation of intermetallic compounds layers at Al/Mg weld interface. In as-weld specimen, a 2μm layer of intermetallic was formed in the upper region of the weld due to the higher temperature and extrusion effect imposed by the shoulder. According to EDS analysis, thin layer would consist of Al_3Mg_2 or β phase.

6) The heat treatment showed that the intermetallic layers became thicker with time. 1 and 2 h of heat treatment increased intermetallic layer thickness to about 4 and 12μm respectively. After 4 h of heat treatment, a new intermetallic layer was added in between Mg and β phase. The composition of the new layer was detected to be $Al_{12}Mg_{17}$ and the total thickness of γ and β intermetallic layers was about 23μm.

7) The tensile test showed that the as-weld specimen has a fairly low tensile strength and elongation. This may be due to the formation of brittle intermetallic layer of β phase. 1 h of heat treatment at 320 °C improved the tensile strength and elongation. Mechanical properties improvement in this specimen was likely due to the tempering of brittle intermetallic. After 2 h of heat treatment, the tensile strength and elongation of weld were decreased. This may be due to the increasing thickness and amount of intermetallic compounds. The lowest tensile strength was observed when the γ phase was formed after 4 h of heat treatment.

References

[1] M.W. Thomas, J. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, "Friction Stir Butt welding", GB Patent Application No.9125978.8 Dec 1991. US Patent No.5460317, (Oct. 1995).

[2] M.M. Attallah, H.G. Salem, "Friction stir welding parameters: a tool for controlling abnormal grain growth during subsequent heat treatment", J.Mater. Sci. Eng. A, Vol. 391, 2005, pp. 51–59.

[3] X. Sauvage, A. Dede, A. Cabello Munoz, B. Huneau, "Precipitate stability and recrystallization in the weld nuggets of friction stirwelded Al–Mg–Si and Al–Mg–Sc alloys", J. Mater. Sci. Eng. A, Vol. 491, 2008, pp. 364–371.

[4] M. AbbasiGharacheh, A.H. Kokabi, G.H. Daneshi, B. Shalehi, R. Sarrafi, "The influence of the ratio of rotational speed/traverse speed on mechanical properties of AZ31 friction stir welds",J. Machine Tools and Manufacture, Vol. 46,2006, pp. 1983–1987.

[5] N. Afrin, D.L. Chen, X. Cao, M. Jahazi, "Microstructure and tensile properties of friction stir welded AZ31B magnesium alloy", J.Mater. Sci. Eng. A, Vol. 472, 2008, pp. 179–186.

[6] X. Cao, M. Jahazi, "Effect of welding speed on the quality of friction stir welded butt joints of a magnesium alloy", J. Mater. Design, 2009, Vol. 30, pp. 2033–2042.

[7] J. Yan, Z. Xu, Z. Li, L. Li, Sh. Yang, "Microstructure characteristics and performance of dissimilarwelds between magnesium alloy and aluminum formed by friction stirring", Scr. Mater.,Vol. 53, 2005, pp. 585–589.

[8] A. Kostka, R.S. Coelho, J. dos Santos, A.R. Pyzallac, "Microstructure of friction stir welding of aluminum alloy to magnesium alloy", Scr.Mater., Vol. 60, 2009, pp. 953–956.

[9] V. Firouzdor, A. Kou, "Al-to-Mg Friction Stir Welding: Effect of Material Position, Travel Speed, and Rotation Speed", Metall. Mater. Trans. A, Vol. 41, 2010, pp. 2914-2935.

[10] Y.J. Kwon, I. Shigematsu, N. Saito, "Dissimilar friction stir welding between magnesium and aluminum alloys", J.Mater. Letters, Vol. 62, 2008, pp. 3827–3829.

[11] R.S.Mishra, Z.Y.Ma, "Friction stir welding and processing", J. Mater. Sci. Eng. R, Vol. 50, 2005, pp. 1–78.

[12] ASM Handbook, "Binary alloy phase diagram", Vol. 3, First edition, 1992, p.48.

[13] V. Firouzdor, A. Kou, "Formation of liquid and intermetallics in Al-to-Mg Friction Stir Welding", Metall. Mater. Trans. A, Vol. 41, 2010, pp.3238.

[14] Y.C. Chen, K. Nakata, "Friction stir lap joining aluminum and magnesium alloys", Scr. Mater., Vol. 58, 2008, pp. 433–436.