Materials Science and Engineering B 161 (2009) 46–49

Contents lists available at ScienceDirect

Materials Science and Engineering B

journal homepage: www.elsevier.com/locate/mseb

Effect of alloying elements on interface microstructure of Mg–Al–Zn magnesium alloys and titanium joint by friction stir welding

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ARTICLE INFO

Article history:
Received 30 May 2008
Received in revised form 21 January 2009
Accepted 20 February 2009

Keywords:
Magnesium
Titanium
Aluminum
Joint interface

ABSTRACT

An effect of alloying element on interfacial microstructure of Mg–Al–Zn alloys and Ti dissimilar butt joints by friction stir welding (FSW) was studied. Mg–Al–Zn alloy and Ti plates of 2 mm in thickness were successfully butt joined by inserting a probe into the Mg alloy plate and slightly offsetting it by 0.5 mm into the Ti plate side. Al-rich thin layers and Ti–Al intermetallic compound layers formed at the interface of these joints. The thickness of the intermetallic compound layer increased with increasing aluminum content of the Mg–Al–Zn alloy. The tensile strength of the joint decreased with increasing aluminum content. A fracture occurred near the joint interface in a tensile test. This suggests that the thickness of the Ti–Al intermetallic compound layer affected the tensile strength of the joints.

1. Introduction

Titanium (Ti) and magnesium (Mg), which belong to the group of lightweight metals, have a hexagonal close-packed structure and do not form a solid solution. Hence, it is difficult to join these metals by fusion welding. Aluminum (Al) is usually added as an alloying element for a magnesium alloy to improve the mechanical properties. These Mg alloys containing Al are used in the automotive and aerospace industries where lightweight metals are needed to minimize the weight of products. Some research on solid state joining of Mg alloys has been performed [1–4]. Friction stir welding (FSW) is a solid state joining process and there are high expectations that it will be a suitable technique for joining dissimilar metals. The combination of frictional heat and intense deformation caused by the tool produces a local forging and stirring effect which results in a high-quality metallurgical bond. Ti has a high strength, a high corrosion resistance and high heat resistance. Therefore, there are hopes for creating a new type of lightweight part by combining Mg alloys and Ti. However, not many studies have been made on the interfacial microstructure of Mg alloys and Ti [5–7]. This study has focused on reactions of Al as an alloying element of Mg–Al–Zn alloys with Ti at the joint interface during FSW.

2. Experimental procedures

A dissimilar metal joint was made between Mg–Al–Zn alloy plates of AZ31B, AZ61A and AZ91D, and a Ti plate. Table 1 shows the chemical compositions of these plates, which had a thickness of 2.0 mm. Square butt joints with 50 mm × 150 mm rectangular plates were used and groove surfaces were machined and degreased with acetone. The FSW tool used was made of SKD61 alloy tool steel. The FSW tool size was 15 mm in shoulder diameter, 1.9 mm in length, 5.0 mm in diameter and was a screw-type probe. The joining conditions are presented in Table 2 and a schematic of the plates in FSW is shown in Fig. 1, in which the probe's insertion position was offset on the joint interface by 0.5 mm. The probe was inserted in the Mg alloy side and the probe edge was slightly offset into the Ti. This joining method was suggested by some research [8–11]. The Ti was positioned on the retreating side and the Mg alloy was positioned on the advancing side in this study. After joining, these joints were heat-treated to investigate the reaction of alloying elements on the interface under high temperature conditions. Heat treatments were at 673 K for 72ks in an Ar atmosphere.

Metallurgical examinations were done on a cross-section of the joint after polishing and etching. The distribution of alloying elements on the cross-section was examined using a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscope (EDS). A tensile test was done, a micro Vickers hardness measurement was taken, and the distribution of alloying elements on the fractured surface was examined by SEM and EDS.

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0921-5107/$ – see front matter
doi:10.1016/j.mseb.2009.02.020

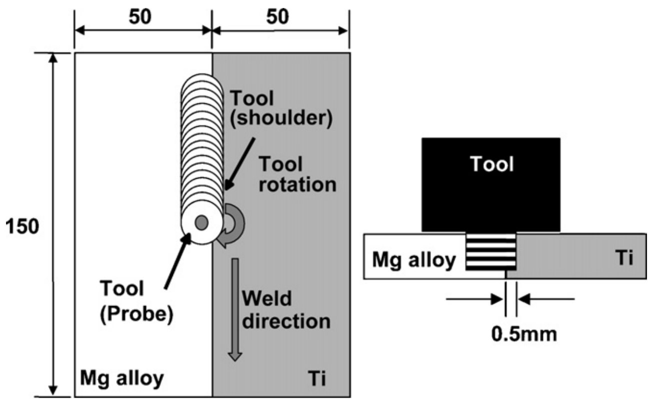

Fig. 1. Schematic of illustration of joint arrangement in FSW.

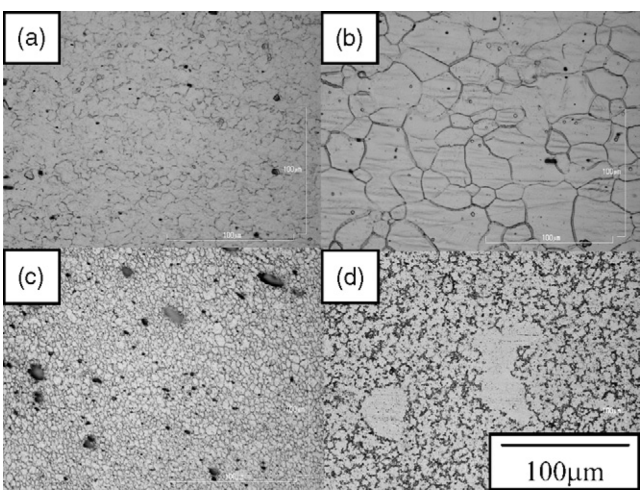

Fig. 2. Cross-sectional microstructure on stir zone of joint and base metal in Mg–Al–Zn alloy, (a) stir zone of AZ61A, (b) base metal of AZ61A, (c) stir zone of AZ91D, (d) base metal of AZ91D.

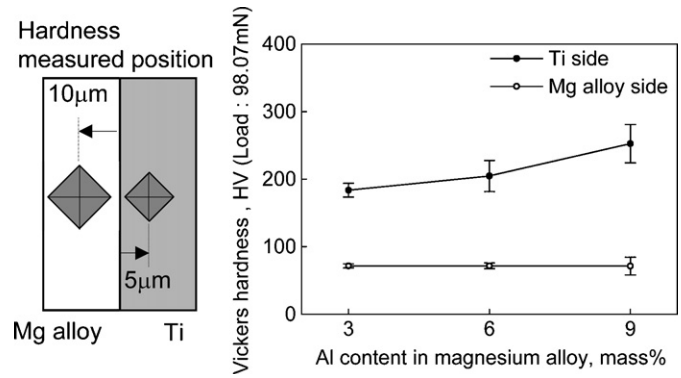

Fig. 3. Micro Vickers hardness on cross-sections near joint interface.

Table 1
Chemical compositions of alloy plates.

Alloy	Chemical composition (mass%)					
	Al	Zn	Mn	Fe	Si	Mg
AZ31B	3.00	0.88	0.58	0.018	0.015	Bal.
AZ61A	6.40	0.70	0.24	0.003	0.030	Bal.
AZ91D	9.17	0.65	0.28	0.002	0.020	Bal.

Alloy	C	H	O	N	Fe	Ti
Ti	0.003	0.0022	0.079	0.004	0.070	Bal.

Table 2
Joining conditions.

Machine type	Load control type
Material of tool	SKD61 alloy tool steel
Tool size	
Shoulder diameter (mm)	15
Probe diameter (mm)	5
Probe length (mm)	1.9
Tool rotation speed (rpm)	850
Travel speed (mm/min)	50
Axial tool force (kN)	7.8
Weld length (mm)	130
Tilt angle (degree)	3

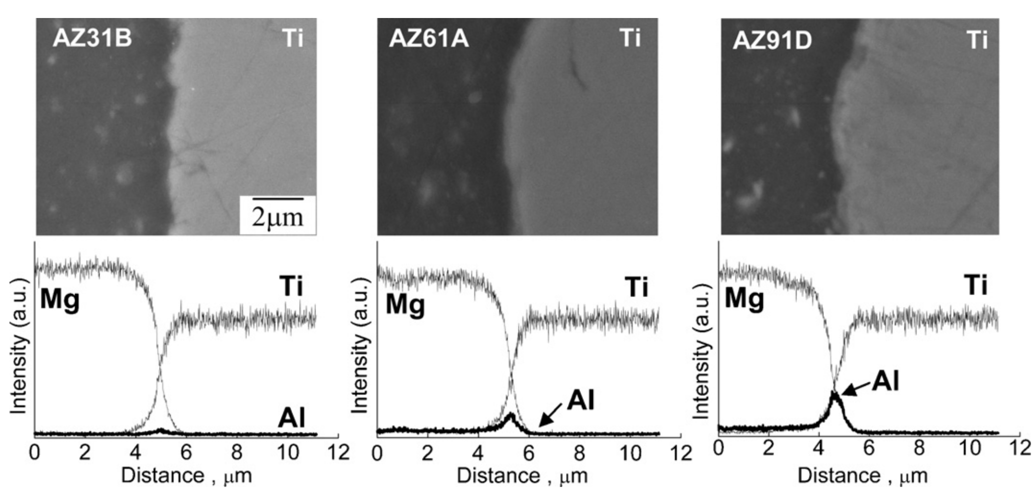

Fig. 4. Cross-sectional SEM images and result of line analysis near the joint interfaces by EDS.

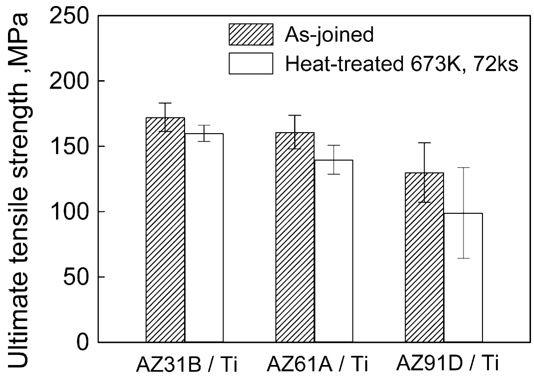

Fig. 5. The comparison of the tensile strengths of joints.

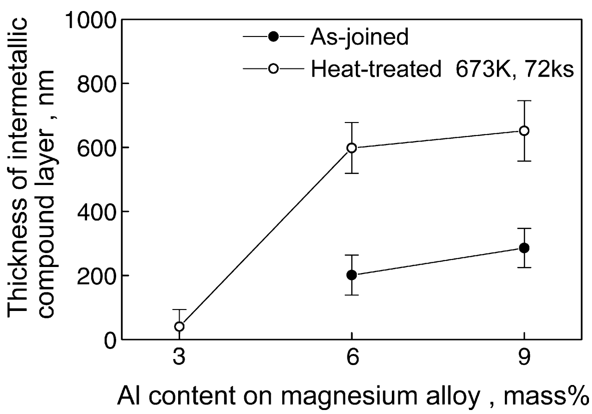

Fig. 6. Thickness of the intermetallic compound layer at the joint interface.

3. Results and discussion

3.1. Microstructure in stir zone of Mg–Al–Zn alloy

The cross-sectional microstructures in the stir zone of the joint and base metal of Mg alloys AZ61A and AZ91D are shown in Fig. 2. The grains of AZ61A in the stir zone were refined to under 10 μm as shown in Fig. 2a. Dynamic recrystallization was observed in comparison with the base metal in Fig. 2b over 20 μm. Cast AZ91D is a dual-phase alloy with an $Mg_{17}Al_{12}$ intermetallic compound and α-Mg as shown in Fig. 2d. In the stir zone of AZ91D the intermetallic compound was disappeared and the Al contained in the $Mg_{17}Al_{12}$ intermetallic compounds diffused into a solid solution of Mg in the stir zone as shown in Fig. 2c.

The micro Vickers hardness measurement near the interface is shown in Fig. 3. On the Ti side, the hardness near the interface increased with increasing Al content in the Mg alloy. It is considered that the increased hardness in the Ti side that was observed near the joint interface is due to the formation of an intermetallic compound and the diffusion of Al to the Ti side.

Fig. 4 shows SEM images and the result of line analysis near the joint interfaces by EDS. A thin Al-rich layer was partly detected on the joint interface by EDS. In the AZ61A/Ti and AZ91D/Ti interfaces, a Ti–Al intermetallic compound layer was observed clearly on the joint interface by SEM-EDS. This layer was observed partly at the as-joined interface. This suggests that the Ti–Al intermetallic compound layer was formed in the interface.

3.2. Effect of aluminum on joint interfacial microstructure and tensile strength

Fig. 5 shows the effect of Al content on the tensile strengths of joints under as-joined and heat-treated conditions. The tensile strengths decreased with increasing Al content of the Mg alloy under both conditions, but samples under heat-treated conditions showed lower values than those under as-joined conditions.

Fig. 6 shows the thickness of the intermetallic compound layer at the joint interface. These thicknesses were measured using a SEM. The thickness of the intermetallic compound layer increased with increasing Al content of the Mg alloy, and with heat treatment. This difference in the tensile strength of the joints is considered to depend on the Al content in the Mg alloy and the formation of an intermetallic compound at the interface. This tendency was especially clear in the heat-treated joint. This suggests that the thickness of the Ti–Al intermetallic compound layer affected the tensile strength of the joints.

Fig. 7 shows SEM images and characteristic X-ray images on the fractured surface of the Ti side under as-joined conditions for each Mg alloy/Ti joint. The fracture occurred in the joint interface or in the stir zone of Mg near the interface. Aluminum at the fractured surface of the Ti side was detected intensely by increasing the aluminum content in Mg alloys compared with AZ31B, AZ61A and AZ91D. The fractured surface of the Ti side on heat-treated AZ91D/Ti joint was examined by using X-ray diffraction. The phase on the fractured surface was identified as $TiAl_3$. It is considered that the diffusion of the Al contained in the Mg alloy into the Ti was accelerated at the joint interface and made the intermetallic compound layer at the joint interface, which was necessary to improve the tensile strength of the dissimilar joint of Ti and Mg alloy. It was concluded that Ti–Al intermetallic compounds is formed at the interface during solid state joining (FSW) by rapid heat cycles at low temperature and the intermetallic compound plays an important role in making a Mg alloy/Ti joint.

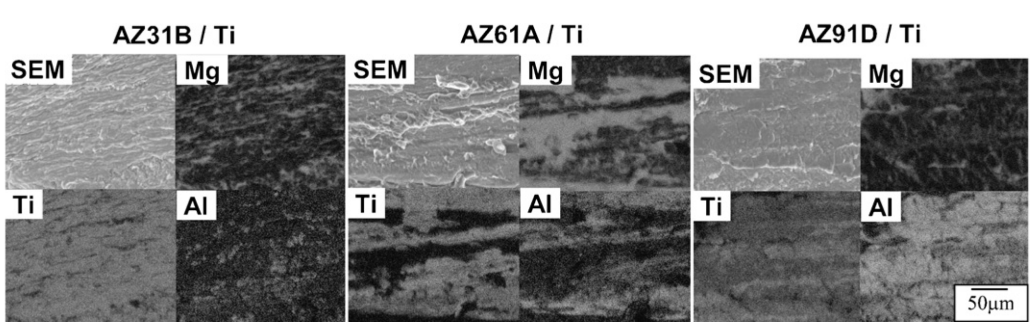

Fig. 7. SEM images and characteristic X-ray images on fractured surface of Ti side as weld joint.

4. Conclusion

The effect of Al as an alloying element of Mg–Al–Zn alloy was studied on the interfacial microstructure of a dissimilar joint with titanium by friction stir welding. The following conclusions can be summarized.

(1) An Al-rich layer was formed at the joint interface. Increasing the aluminum content of the Mg–Al–Zn alloy, Ti–Al intermetallic compound layer was observed clearly on the joint interface.
(2) The joint fractured in the intermetallic compound layer in the tensile test. The intermetallic compound plays an important role in making a Ti/Mg joint, but the increased thickness of this compound tends to reduce the tensile strength.

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