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Interfacial Microstructure of CP-Ti and AZ31 Joint by Friction Stir Welding*

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Friction stir welding (FSW) is a suitable solid-state joining process for dissimilar metal joining. We have performed metallographic characterizations to investigate the effects that an alloying element has on the interfacial microstructure between a dissimilar joint of AZ31 magnesium alloy and commercial pure titanium, produced by FSW. At the joint interface, an interfacial layer was observed with a thickness of less than 100 nm in a STEM-HAADF image produced with a transmission electron microscope (TEM) and an energy dispersive X-ray spectroscope (EDS). In this layer, TiAl intermetallic compound was observed with nano-beam diffraction (NBD).

Key Words: Dissimilar Metal Joining, Friction Stir Welding, Titanium, Magnesium Alloy

1. Introduction

Friction stir welding (FSW) has attracted a great deal of attention in the welding industry because it can produce high performance joints between light metals. In FSW, base metals are joined by means of frictional heating and plastic deformation at the temperature below the melting temperature of alloys joined1). Therefore, the joining temperature used in FSW is lower than that used in the fusion welding method. In dissimilar metal joint by fusion welding, the joint is brittle because of forming an intermetallic compound at the joint interface. FSW is suitable solid-state joining process to prevent forming the intermetallic compound in the dissimilar metal joining. The intermetallic compound formation has to be controlled as less as possible at the joint interface. Therefore, dissimilar metal joining of lightweight alloys by FSW is of considerable practical interest. Magnesium has the highest strength-to-weight ratio of any commercially available metals. Magnesium alloy is attractive in automotive, aerospace products application for improving energy efficiency. Dissimilar joining between magnesium and other alloys can be applied to reduce the weight of various products. Recently, the degree to which FSW can join dissimilar metals had been investigated in the combinations of Mg/Al 2-5), Al/Ti 6) and Mg/Ti 7-9). Among them, Mg/Ti dissimilar joining by FSW was investigated between Mg-Al-Zn alloy and commercial pure titanium. In a previous paper, we pointed out that a content of aluminum in Mg-Al-Zn alloy affected tensile strength of Mg-Al-Zn alloy and commercial pure titanium joints. In comparison of the joint between AZ31, AZ61, AZ91 and commercial pure titanium, the tensile strength of the joint depended on the Al content in the Mg alloy and the formation of an interfacial layer. The tensile strength of AZ31 and titanium joint showed a high value in these joints 8). However, detailed the interfacial microstructure of titanium and AZ31 high strength joint has not been reported in nano level by a transmission electron microscope (TEM). In this study, the interfacial microstructure has been examined through metallographic characterizations by using TEM equipped with an energy dispersive X-ray spectroscope (EDS).

2. Experimental procedure

Commercially available Mg-3.0 mass% Al-0.88 mass% Zn (AZ31) was joined to commercially available 99.5 mass% titanium (CP-Ti) by FSW. The chemical compositions of the base metals employed during this investigation are summarized in Table 1. The plates used had dimensions of 50 mm × 150 mm × 2.0 mm. The grooved surfaces of square butt joint were produced by machining them. The plates were cleaned with a surface-conditioning abrasive to remove surface oxides, and degreased with acetone before joining.

The joining conditions are shown in Table 2 and schematic illustrations of the joint arrangement in FSW are shown in Fig. 1 (a). The same joining conditions were used as in the previous paper 8). The FSW tool size was 15.0 mm in shoulder diameter, 1.9mm in probe length, and 5.0 mm in probe diameter and was a screw-type probe. The FSW tool used was made of SKD61 alloy steel. CP-Ti was positioned on the advancing side. AZ31 was

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Table 1 Chemical compositions of base metals.

Alloy	Chemical composition, mass%					
	Al	Zn	Mn	Fe	Si	Mg
AZ31	3.00	0.88	0.58	0.018	0.015	Bal.
Alloy	**C**	**H**	**O**	**N**	**Fe**	**Ti**
CP-Ti	0.003	0.0022	0.079	0.004	0.070	Bal.

Table 2 Friction stir welding conditions.

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
Probe position (mm)		0.5

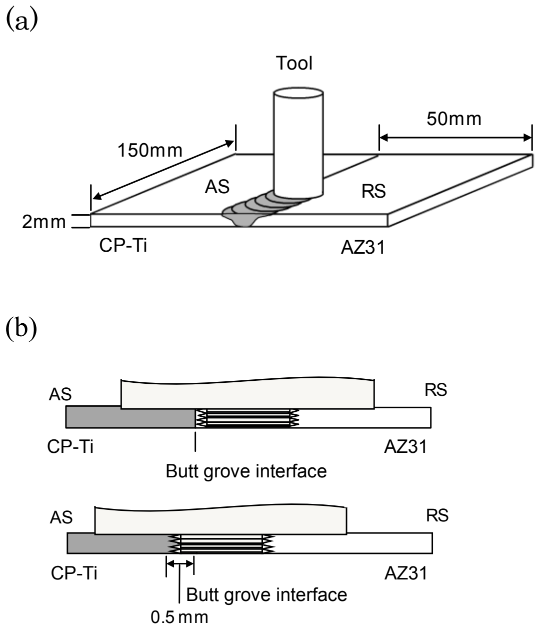

Fig. 1 Schematic illustrations of dissimilar joint arrangement in FSW (a) showing a probe offset into CP-Ti side (b).

positioned on the retreating side in this study as following reason; in the offset method, the probe was inserted mainly into the softer material, and a harder material was set at the advancing side to clean the surface of the interface by scrubbing it with the probe edge. Therefore, the probe was inserted in the AZ31 side and the probe edge was slightly offset into the CP-Ti side at a distance of 0.5 mm from the butt joint interface as shown in Fig.1 (b). The cross-sectional microstructures of the stir zone and the base metal were observed using an optical microscope. The distribution of alloying elements on the cross-section was examined using a scanning electron microscope (SEM) and TEM equipped with EDS.

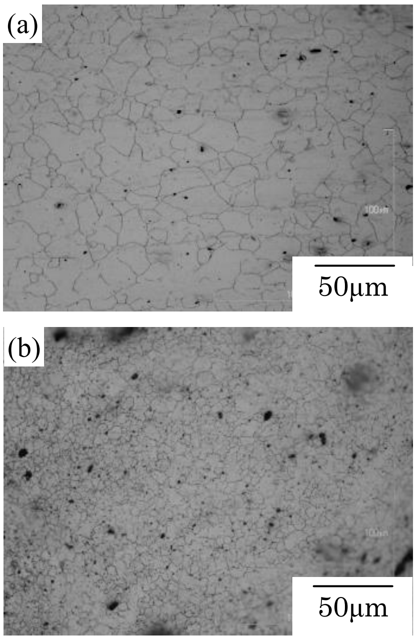

Fig. 2 Cross-sectional microstructures of the joint in AZ31 side; (a) AZ31 base metal, (b) stir zone.

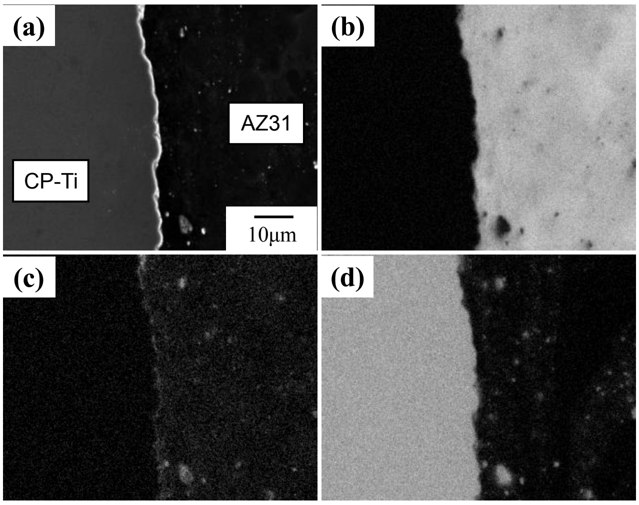

Fig. 3 SEM image (a) and characteristic X-ray images of Mg (b), Al (c) and Ti (d) near CP-Ti and AZ31 joint interface by FSW.

3. Result and discussion

The cross-sectional microstructures in the stir zone and base metal of AZ31 are shown in Fig. 2(a) and (b) respectively. AZ31 base metal is a single-phase alloy composed of α-Mg. In the stir zone of AZ31, dynamic recrystallization was observed, and the α-Mg grain became small to less than 10 μm in diameter in comparison with that of the base metal. Grains of α-Mg in the stir zone were refined.

The SEM image and characteristic X-ray images of the CP-Ti /AZ31 joint interface are shown in Fig. 3. The observed area was

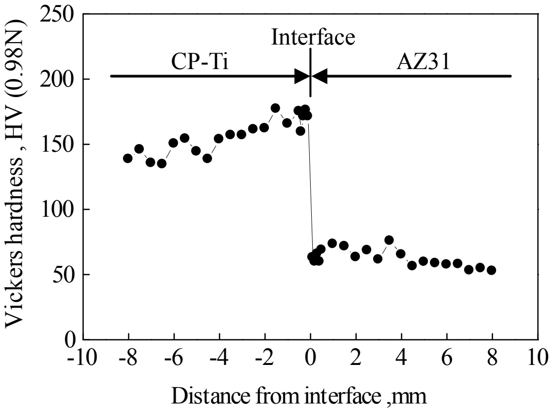

Fig. 4 Micro Vickers hardness distribution near the joint interface of CP-Ti and AZ31.

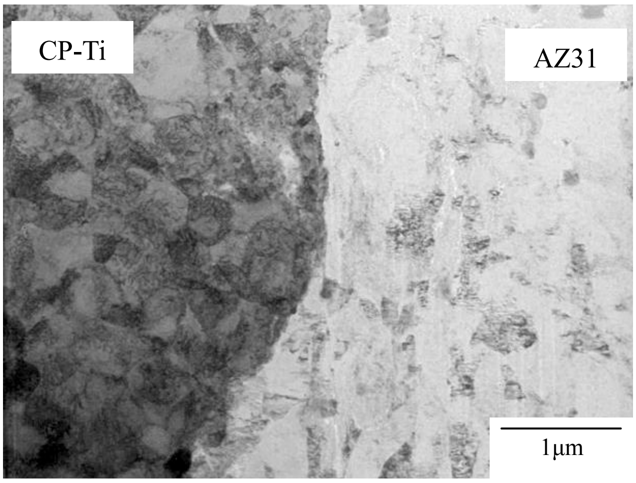

Fig. 5 Bright field image by TEM at the joint interface of CP-Ti and AZ31.

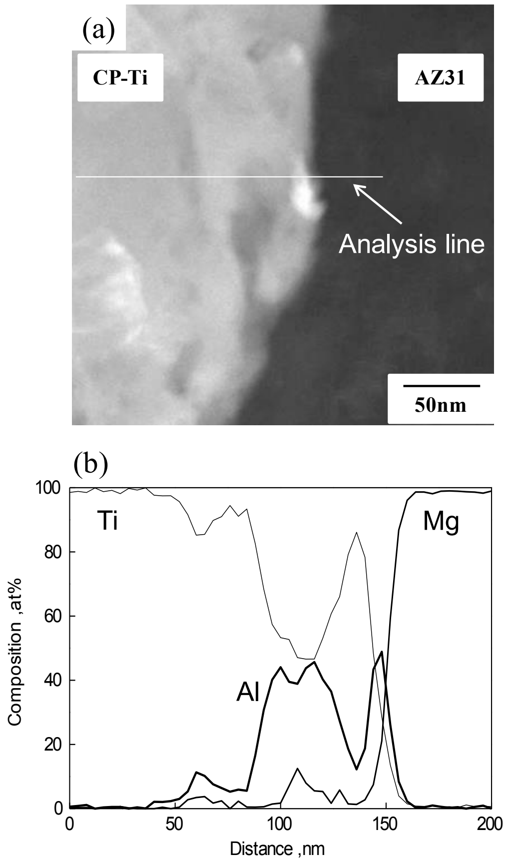

Fig. 6 STEM observation result of the joint interface of CP-Ti and AZ31; (a) A STEM-HAADF image, (b) result of line analysis by TEM-EDS.

the interface at a depth of 0.7 mm from the surface of the joint. CP-Ti chips cut by the probe were dispersed in the stir zone of AZ31 near the interface, and a very thin Al-rich layer was observed at the joint interface. According to the binary phase diagram, titanium and magnesium do not form a solid solution and any compounds. However, titanium and aluminum form Ti_3Al, TiAl and $TiAl_3$ intermetallic compounds [10]. It was probable that aluminum reacted with titanium and formed the interfacial layer containing intermetallic compound at the CP-Ti side of the CP-Ti /AZ31 joint [8].

The micro Vickers hardness distribution near the joint interface is shown in Fig. 4. The hardness of AZ31 near the interface was higher than in the base metal. In the AZ31 stir zone, CP-Ti chips were dispersed and the grain size was smaller than in the AZ31 base metal. These caused the increase of the hardness in the AZ31 stir zone.

In a previous paper, CP-Ti and Mg-Al-Zn alloy joints by FSW were fractured at the joint interface or in the stir zone of Mg-Al-Zn alloy near the interface by the tensile test. The average tensile strength of Ti/AZ31 joint was 165 MPa, which is lower than 239 MPa of AZ31 base metals. The tensile strength of CP-Ti/AZ31 joint was higher than those of CP-Ti/AZ61 and CP-Ti/AZ91. The tensile strength of CP-Ti/AZ91 was 116 MPa. The Al-rich interfacial layer was observed in CP-Ti/AZ91 joint interface, and the thickness of the interfacial layer was more than 280 nm. At the fracture surface on the CP-Ti side of CP-Ti/AZ91 joint, $TiAl_3$ intermetallic compound was detected by X-ray diffraction [8].

Fig. 5 shows a bright field image by a TEM at the joint interface at about 0.7 mm depth from a surface of the CP-Ti/AZ31 joint. Both matrixes of the CP-Ti and AZ31 near the interface were a single phase, and the grains of CP-Ti near the joint interface were refined to less than 1 μm by the dynamic recrystallization.

Fig. 6(a) shows a STEM-HAADF image of the joint interface, in which a thin reaction layer was observed. Fig. 6(b) shows the result of line analysis by TEM-EDS from the line indicated by the

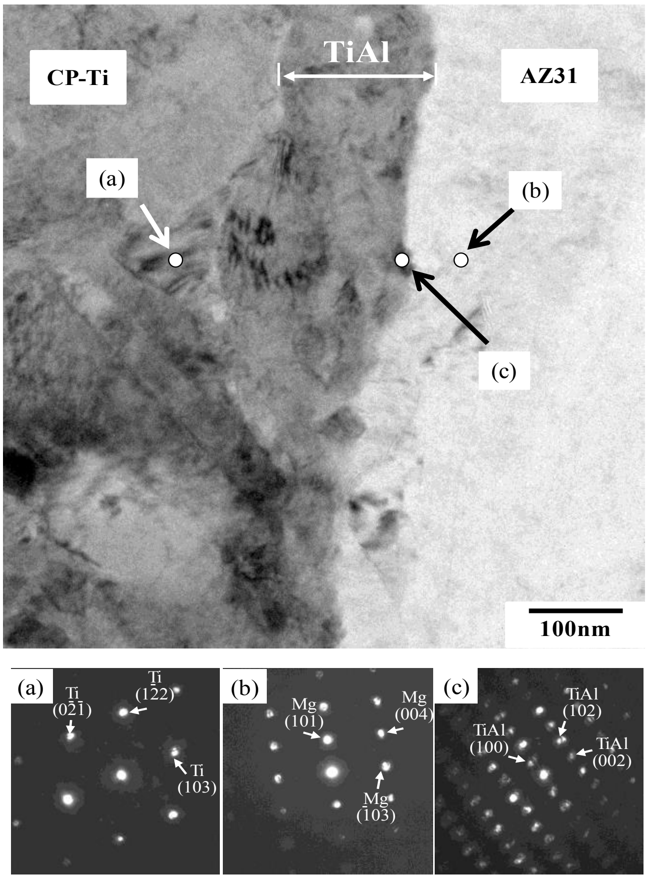

Fig. 7 Bright field image and nano beam diffraction pattern at AZ31 and CP-Ti dissimilar joint interface by FSW.

arrow in Fig. 6(a), which indicates that the reaction layer consists of aluminum and titanium with a thickness of 100 nm, and the aluminum content in the Al-rich region was about 50 at%. The aluminum element in AZ31 is in a solid-solution condition in α-Mg phase and can easily react with titanium at an elevated temperature. Hence, it is considered that the intermetallic compound was formed at the interfacial layer.

Fig. 7 shows a bright field image and results of nano-beam diffraction (NBD) by TEM at the joint interface. TiAl intermetallic compound was observed at near the interface of the CP-Ti side by NBD. In Fig. 6, the interfacial layer was observed in thickness of 100 nm, and the Al-rich region was observed in thickness of about 70 nm near the joint interface. These results suggest the interfacial layer consisted of TiAl intermetallic compound and an aluminum layer that had diffused into titanium.

These results would indicate that the aluminum content in Mg-Al-Zn alloy affect the thickness of the interfacial layer and the composition of the intermetallic compound in the layer.

4. Conclusions

The interfacial microstructure between CP-Ti and AZ31 dissimilar joint by friction stir welding has been examined through metallographic characterizations by TEM-EDS. The aluminum in the alloying elements of AZ31 formed the interfacial layer with titanium at the joint interface. The interfacial layer consists of TiAl intermetallic compound and an aluminum layer that had diffused into titanium. The thickness of the layer was 100 nm in analysis by TEM-EDS. It can be predicted that the aluminum in the alloying elements of AZ31 affects the thickness of the interfacial layer and the composition of intermetallic compound in the layer.

Acknowledgements

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