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Dissimilar metal joining of ZK60 magnesium alloy and titanium by friction stir welding

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ABSTRACT

Friction stir welding (FSW) is a solid-state joining process, and the joining temperature is lower than that in the fusion welding process. The effect of alloying elements on the microstructure of dissimilar joints of a Mg–Zn–Zr alloy (ZK60) and titanium by using FSW, was examined. A commercial ZK60 and a titanium plates with 2 mm in thickness was butt-joined by inserting the probe into the ZK60 plate, and slightly offset into the titanium plate side to ensure the direct contact between them. The average tensile strength of the joint was 237 MPa, which was about 69% of that of ZK60 and a fracture occurred mainly in the stir zone of ZK60 and partly at the joint interface. A thin Zn and Zr-rich layer with about 1 m in thickness was formed at the joint interface, which affected the tensile strength of the dissimilar joint of ZK60 and titanium.

1. Introduction

Magnesium alloys have the lowest density among the commercially available alloys, but their corrosion resistance is poor [1,2]. Titanium alloys also have low density, but its corrosion resistance is very high [3]. Hence, there are urgent needs to achieve dissimilar joining between magnesium and titanium so that these alloys can be applied to reduce the weight of various products. Most of the works about dissimilar joining of magnesium alloys and other metals have been performed on magnesium and aluminum joint [4–6]. However, titanium and magnesium do not form a solid solution and any compounds [7]. This means that it is difficult to join pure titanium and pure magnesium. In previous work, we have reported that AZ-type magnesium alloy (Mg–Al–Zn alloy) and AMCa-type magnesium alloy (Mg–Al–Ca alloy), which contain aluminum as an alloying element, can be successfully joined to pure titanium, because an aluminum-rich thin layer formed at the joint interface by reaction with titanium, and the tensile strength of the joint interface was improved by this aluminum-rich layer [8,9]. Thus, the content of aluminum of the magnesium alloy affected the interfacial microstructure and the tensile strength of the dissimilar joint.

Among magnesium alloys, Mg–Zn–Zr alloy has a higher tensile strength than Mg–Al–Zn alloys. Therefore, Mg–Zn–Zr alloy such as ZK60 has been used in airplane and automobile products. However, it was difficult to fusion weld this alloy because of high susceptibility to the solidification cracking at the weld metal, which were caused relatively high Zn content in Mg–Zn–Zr alloy [10]. Hence, friction stir welding (FSW) is a solid state joining process and a joining temperature is lower than that in the fusion welding process. Therefore, FSW is suitable joining process for a Mg–Zn–Zr alloy [11]. In addition, Zn and Zr have a strong affinity with titanium and are expected to act as the similar effect of aluminum to form the reaction layer at the joint interface. However, no study has been reported on the characteristics of the dissimilar metal joint interface between titanium and Mg–Zn–Zr alloy. This study has been conducted by focusing on the effect of Zn and Zr of alloying elements on the microstructure and the tensile strength of the dissimilar metal joint of ZK60 Mg–Zn–Zr alloy and titanium by FSW in composition with pure magnesium and titanium joint.

2. Experimental procedures

Chemical compositions of titanium and Mg–Zn–Zr alloy were shown in Table 1. Commercially used Mg–5.5 mass% Zn–0.57 mass% Zr alloy (ZK60) and 99.5 mass% magnesium (Mg) were joined to commercially used 99.5 mass% titanium (Ti) by FSW. In ZK60 alloy, Zn is soluble in magnesium, and Zr partly forms the compound with Zn [12]. The joining conditions are presented in Table 2

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Table 1
Chemical composition of base metals.

Alloy	Chemical composition (mass%)					
	C	H	O	N	Fe	Ti
Titanium	0.003	0.0022	0.079	0.004	0.070	Bal.

Alloy	Chemical composition (mass%)		
	Zn	Zr	Mg
ZK60	5.5	0.57	Bal.

Table 2
Joining conditions.

Tool dimensions (mm)			Joining parameters				
Shoulder diameter	Probe diameter	Probe length	Rotation speed (rpm)	Travel speed (mm/min)	Loading force (kN)	Tool tilt (degree)	Weld length (mm)
15	6	1.9	850	50, 100	7.8	3 forward	125

and a schematic of the plates used in FSW is shown in Fig. 1. The probe was inserted in the ZK60 side and the probe edge was slightly offset into the Ti plate with 1.0 or 1.5 mm from the joint interface. More probe offset caused the severe wear or break of the probe, and thus, the probe offset was limited up to 1.5 mm. This probe offset method for dissimilar metal joining was already applied in some researches on Al alloy and steel joint [13–16]. Butt joint with 50 mm × 150 mm rectangular plate with thickness of 2.0 mm was used. The root surface of each plate was machined and degreased with acetone before joining. A FSW tool used was made of SKD61 alloy steel, with a shoulder diameter of 15 mm, probe length of 1.9 mm and probe diameter of 6.0 mm, and was a screw-type probe. In the offset method, the probe was inserted mainly into the softer material, and a harder material was set at the advancing side to make the clean surface of the interface by scrubbing it with the probe edge [16]. Therefore, the Ti plate was positioned on the advancing side and the ZK60 plate was positioned on the retreating side in this study [9,10].

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). The joint was cut into a piece with a width of 10 mm, and a transverse tensile test to the FSW joint line was performed to evaluate the joint strength.

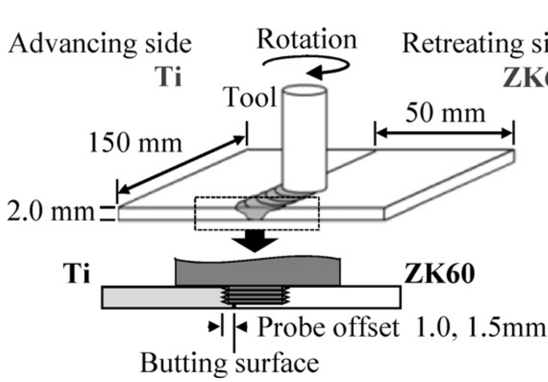

Fig. 1. Schematic illustration of joint arrangement in FSW.

3. Results and discussion

Fig. 2 shows the tensile strength of Ti and ZK60 joints at different probe offsets of 1.0 and 1.5 mm in comparison with those of the Ti and Mg joints for comparison. The tensile strengths of the Ti and ZK60 joints increased with increasing the probe offset and reached to 237 MPa, at 1.5 mm offset, which was 69% of that of ZK60 base metal, and much higher than that of Ti and Mg joint, 135 MPa the probe offset 1.5 mm, though, in the Ti and Mg joint, little change was observed in the tensile strength with increasing the travel speed. Increasing the probe position increases a contact area of the probe and Ti plate, which corresponds to the cleaned interface between them and in addition, this will raise the interface temperature by increasing the friction increased heat input. Therefore, it is considered that these combined effects improved the tensile strength of Ti and ZK60 joints.

Fig. 3(a) shows the cross-sectional macrostructure of the joints at a travel speed of 50 mm/min in probe offset 1.5 mm. The joint interface in the upper half of the plates on Ti side was deformed from Ti side to ZK60 side. In the stir zone of ZK60, light gray regions are observed at the ZK60 stir zone shown in Fig. 3(a).

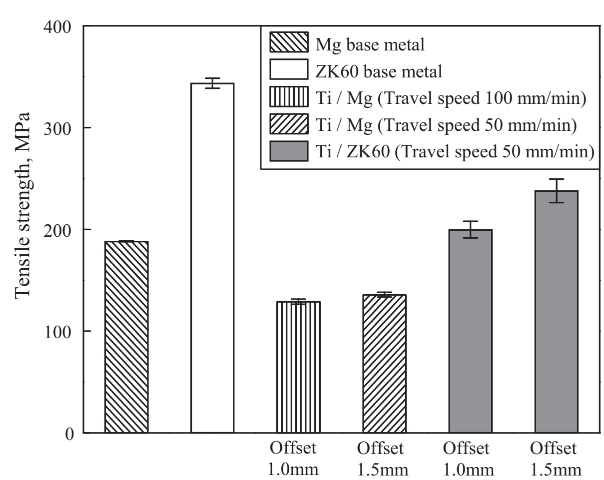

Fig. 2. Tensile strengths of ZK60 base metal and FSW joints.

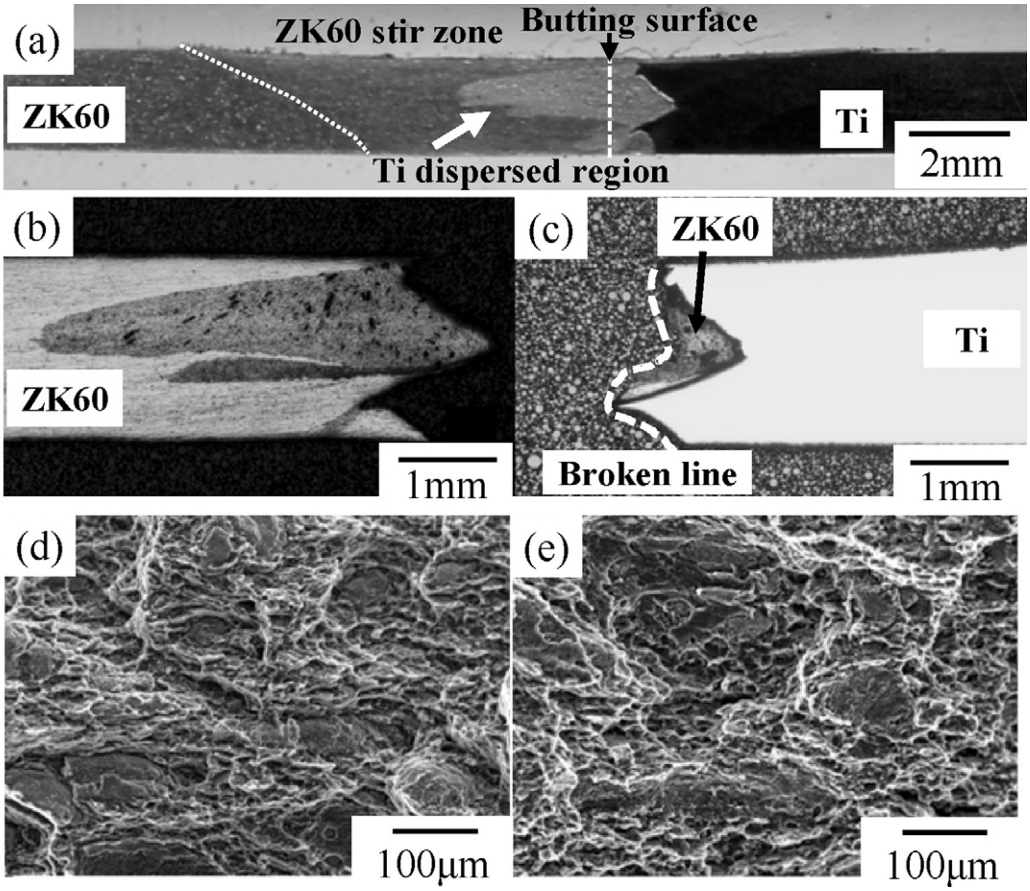

Fig. 3. Appearances of the Ti and ZK60 joint at travel speed 50 mm/min in probe offset 1.5 mm: (a) cross-sectional macrostructure, cross-sectional macrostructure after tensile test (b) ZK60 side and (c) Ti side, (d) fractured surface of ZK60 side, (e) fractured surface of Ti side.

In this region, Ti chips cut by the probe were dispersed as indicated by white arrow in Fig. 3 (a). Fig. 3(b) and (c) shows the cross sections of the joint of ZK60 side and Ti side after tensile test, respectively. The fractured position of the Ti and ZK60 joint of ZK60 and Ti sides, respectively. The fracture of the joint occurred mainly in the stir zone of ZK60 near the joint interface of Ti as shown by a broken line in Fig. 3(c). Each fractured surface at a mid-thick of the joint is shown in Fig. 3(d) and (e), respectively. In ZK60 side, dimple pattern of ZK60 was mainly observed, which are indicated that the joint had the ductility and Ti chips cut by the probe were partly observed in the fractured surface. Ti base metal was not observed at the fractured surface which suggested that ZK60 was tightly joined to the surface of Ti.

Fig. 4 shows SEM images on the fracture surface of the Ti and Mg joint at a travel speed of 100 mm/min in the probe offset 1.0 mm. The Ti and Mg joint was fractured at the interface of Ti and the stir zone of Mg. Both fracture surfaces of the Ti side and the Mg side were smooth, expecting that some Mg fragments were partly observed on the fracture surface of Ti side, but their region was

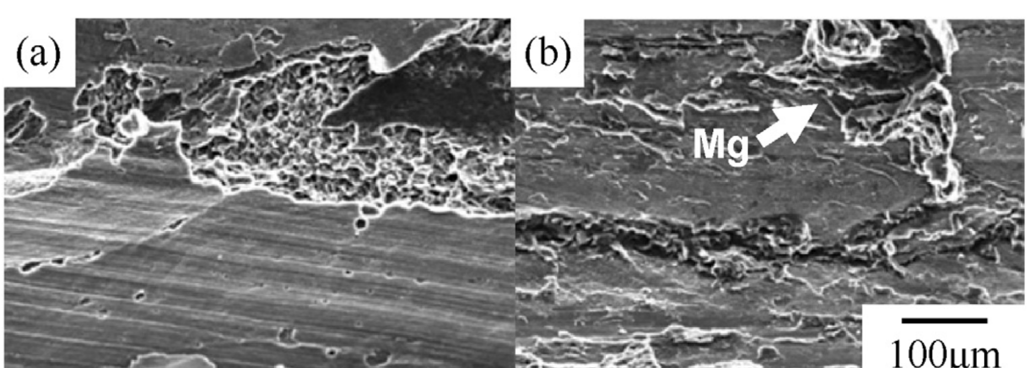

Fig. 4. Fractured surface of Mg and Ti joint at travel speed 100 mm/min in probe offset 1.0 mm; (a) Mg side and (b) Ti side.

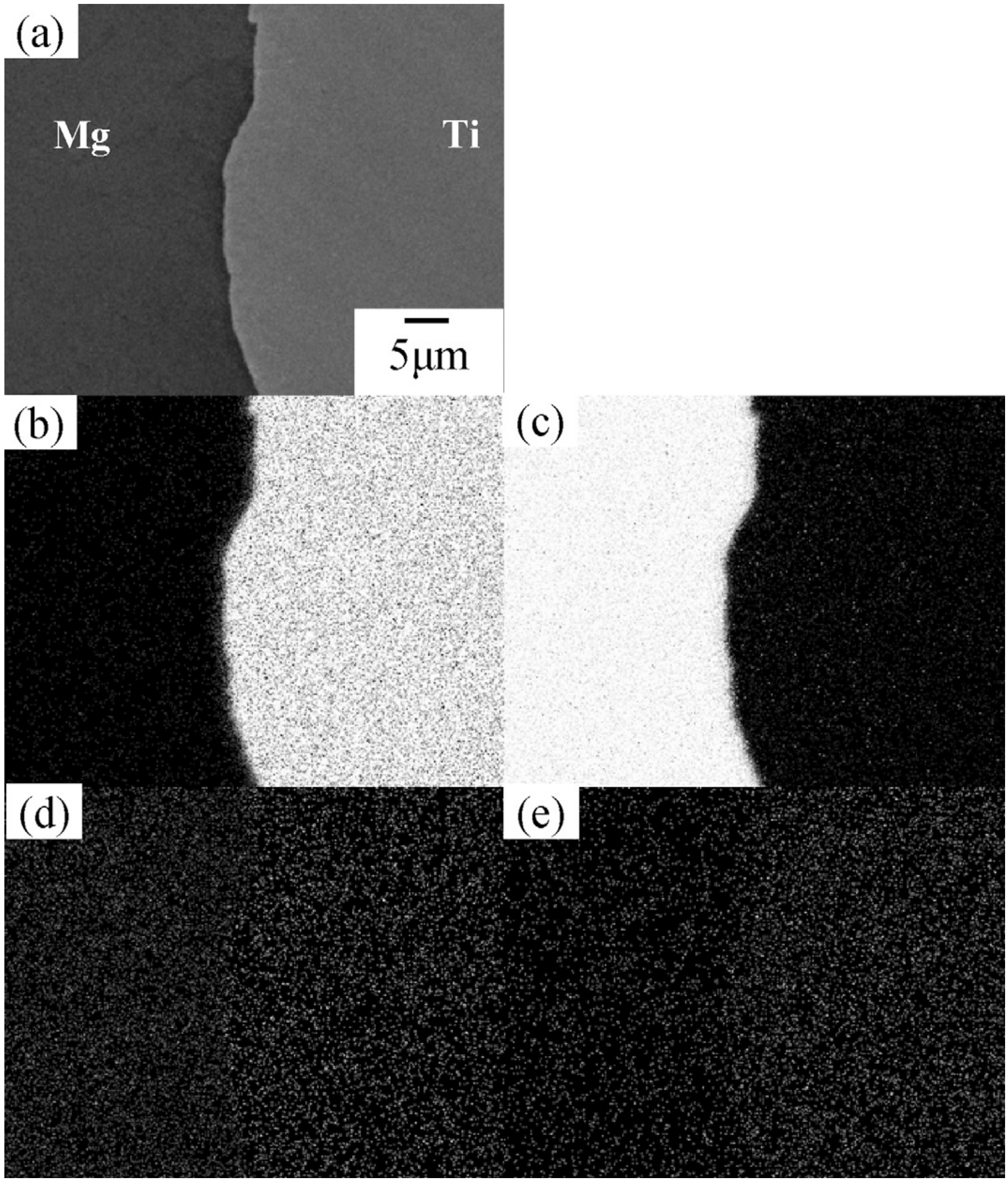

Fig. 5. SEM image (a) and characteristic X-ray images of Ti (b), Mg (c), Zn(d), and Zr (e) near Ti and Mg joint interface at the travel speed 100 mm/min in probe offset 1.0 mm.

small area in the fractured surface at the all the joining conditions. In addition, at the Ti and Mg joint interface, the reaction layer was not observed by SEM-EDS analysis in the cross section and the fractured surface. Therefore, in comparison with Figs. 3 and 4, it is considered that the joint interface of Ti and ZK60 is superior to that of the Ti and Mg joint interface.

The SEM image and characteristic X-ray images of the Ti and Mg joint interface at a travel speed of 100 mm/min in probe offset 1.0 mm are shown in Fig. 5. At the interface, a reaction layer consisted of Ti, Mg, and the other elements was not observed by SEM-EDS. The SEM image and characteristic X-ray images of the Ti and ZK60 joint interface at a travel speed of 50 mm/min in probe offset 1.5 mm are shown in Fig. 6. Zn and Zr-rich layer was observed at the joint interface. This layer was mainly detected on the Ti side in upper half of the joint. As already mentioned Ti plate was cut by the rotating probe at the butt joint interface, and a fresh clean surface of Ti appeared during FSW. Hence, it is probable that Zn and Zr in ZK60 easily reacted with Ti and formed the reaction layer on the interface at the Ti side, because Ti and Zn can form an intermetallic compound, and also Ti and Zr forms a solid solution according to the phase diagrams [7]. Therefore, it is considered that this layer consisted mainly of Ti, Zn and Zr. Variations in the thickness of the layer appear at the interface, and the maximum thickness observed by SEM-EDS was about 1 m. At Ti/Mg joint interface, Ti and Mg was joined without the reaction layer, which was not observed by SEM-EDS. On the contrary, in Ti/ZK60 joint interface, Zn and Zr reacted with Ti and formed the reaction layer at the interface, which caused the higher tensile strength of Ti and ZK60 joint than that of Ti/Mg joint.

These results suggest that Zn and Zr as the alloying elements of ZK60 reacted with Ti at the interface, and the tensile strength of the joint was improved by the reaction layer formed.

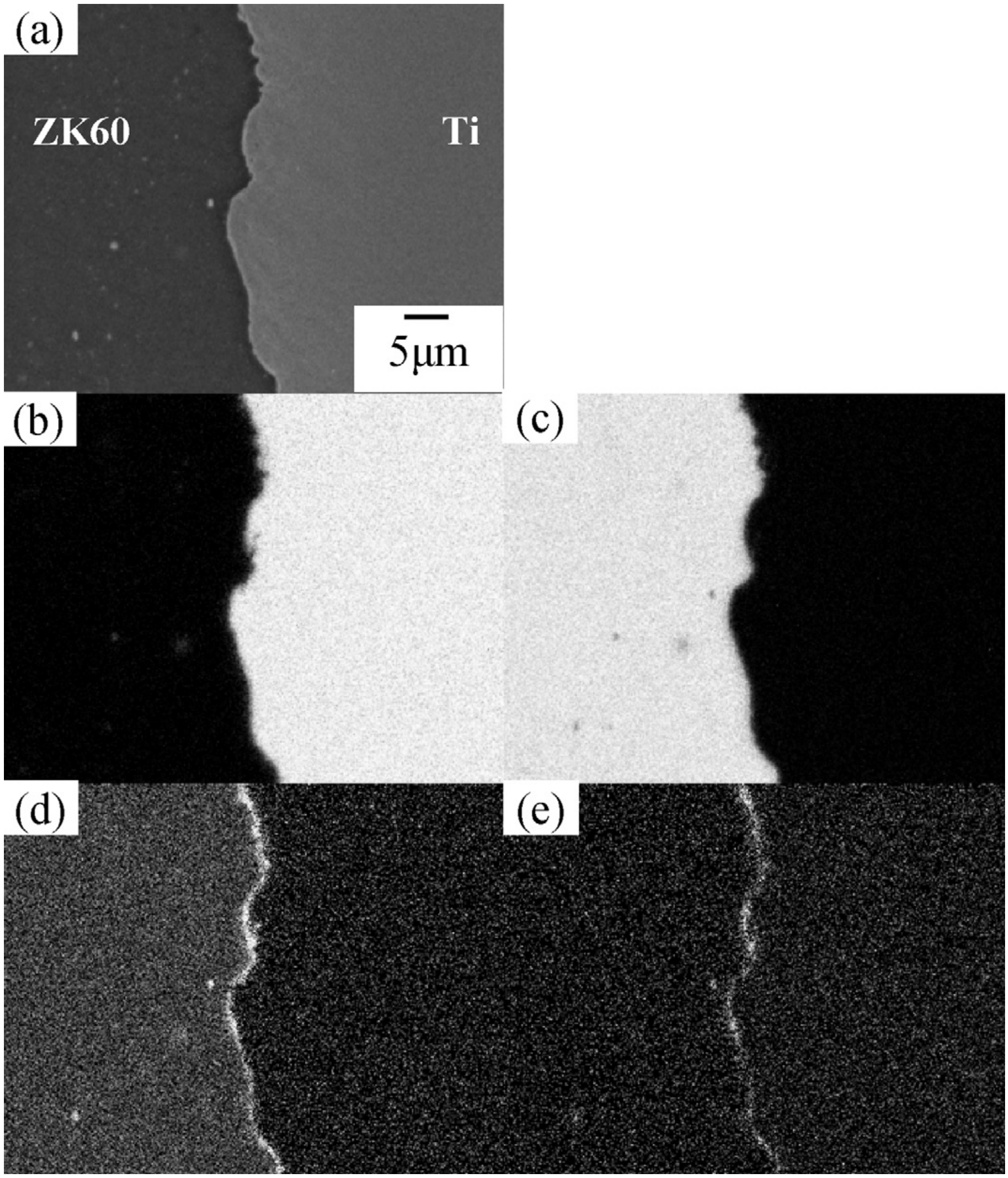

Fig. 6. SEM image (a) and characteristic X-ray images of Ti (b), Mg (c), Zn(d), and Zr (e) near Ti and ZK60 joint interface at the travel speed 50 mm/min in probe offset 1.5 mm.

4. Conclusion

The effect of alloying elements of ZK60 Mg–Zn–Zr alloy on the microstructure of the dissimilar joint interface with titanium and the joint strength in comparison with pure magnesium and titanium has been investigated. Zn and Zr of alloying elements formed a thin reaction layer with titanium at the joint interface by friction stir welding. The fracture of the joint by tensile test occurred mainly in the stir zone of Mg–Zn–Zr alloy and partly at the joint interface. The tensile strength of the Mg–Zn–Zr alloy and titanium joint was higher than that of the pure magnesium and titanium joint, in which the reaction layer was not formed and fractured at the joint interface. Hence, it can be understood that Zn and Zr of alloying elements of Mg–Zn–Zr alloy improved the tensile strength of titanium and magnesium joints by forming the thin reaction layer at the joint interface during friction stir welding.

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