Materials Science and Engineering B 173 (2010) 135–138

Contents lists available at ScienceDirect

Materials Science and Engineering B

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

Effect of calcium on intermetallic compound layer at interface of calcium added magnesium–aluminum alloy and titanium joint by friction stir welding

Masayuki Aonuma[a,*], Kazuhiro Nakata[b]

[a] Tokyo Metropolitan Industrial Technology Research Institute, 3-13-10 Nishigaoka, Kita-ku, Tokyo 115-8586, Japan
[b] Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

ARTICLE INFO

Article history:
Received 29 June 2009
Received in revised form
24 November 2009
Accepted 6 December 2009

Keywords:
Intermetallic compound
Magnesium
Titanium
Aluminum
Calcium
Joint interface

ABSTRACT

Commercial AMCa602 alloy (Mg–6% Al–2% Ca) and AM60 alloy (Mg–6% Al) were joined to titanium plates by friction stir welding to evaluate the effect of a calcium on the reaction layer at the dissimilar joint interface and the joint tensile strength. At the titanium and AM60 joint interface, a $TiAl_3$ intermetallic compound layer was formed. The thickness of this layer was about 2 μm. A layer containing calcium and a layer containing aluminum and titanium were observed at the titanium and AMCa602 joint interface. The aluminum and titanium layer in the titanium and AMCa602 joint interface was very thin. The content of aluminum in solid-solution in the matrix of AMCa602 was lower than that of AM60 due to the formation of a Ca–Al compound, and this suppressed the formation of $TiAl_3$ at the titanium and AMCa602 joint interface.

1. Introduction

Mg–Al alloy is a high strength-to-weight ratio material and has excellent mechanical properties. However, when the temperature rises in the atmosphere, Mg–Al alloys burn easily. On the contrary, Mg–Al–Ca alloy, which was made by adding calcium to a Mg–Al alloy, does not burn easily because its igniting temperature is much higher than that of conventional Mg–Al alloy [1]. Therefore, it becomes possible to use it as a construction material for trains, cars, and aircraft.

Aluminum alloys and titanium alloys have been widely used as high strength-to-weight ratio materials. Thus, dissimilar joining of magnesium alloys to aluminum alloys and titanium alloys is expected to widen the industrial application of these alloys for weight-saving of the products.

In the previous work, joining of titanium and Mg–Al–Zn alloys (AZ31, AZ61 and AZ91) was examined by friction stir welding (FSW) [2]. As a result, it was shown that an intermetallic compound of titanium and aluminum formed at the joint interface, and the tensile strength of the joint was affected by the intermetallic compound layer.

In the Mg–Al–Ca alloy, a Ca–Al compound, namely Al_2Ca is already formed and scattered in the matrix due to the strong affinity between calcium and aluminum as alloying elements of magnesium alloy [3,4]. Therefore, when Mg–Al–Ca alloy and titanium are joined, it is surmised that these strong affinities between calcium and aluminum will affect the microstructure of the joint interface. However, no study has been reported on the microstructure of the dissimilar metal joint interface between titanium and Mg–Al–Ca alloy. This study has focused on the effects of calcium and aluminum as alloying element on the intermetallic compound layer at the joint interface of Mg–Al–Ca alloy and titanium by friction stir welding.

2. Experimental procedures

AM60 alloy was used as the Mg–Al alloy, and AMCa602 alloy was used as the Mg–Al–Ca alloy, which was made by adding calcium to AM60 alloy as an additive alloying element. So, the contents of other alloying elements in each alloy are almost the same value as shown in Table 1. As a counter material, commercially pure titanium was used. Butt joints with 50 mm × 150 mm rectangular plates in a thickness of 2.0 mm were used and groove surfaces were machined. The FSW tool used was made of SKD61 alloy steel. The tool size was 15 mm in shoulder diameter, 1.9 mm in length, 6.0 mm in diameter and was a screw-type probe. The schematic of the plates in friction stir welding is shown in Fig. 1, in which the insertion position of the probe was offset on the joint interface by 1.5 mm. The probe was inserted in magnesium alloy side and the probe edge was slightly offset into titanium plate. This joining

* Corresponding author. Tel.: +81 3 3909 2151; fax: +81 3 3909 2590.
E-mail address: aonuma.masayuki@iri-tokyo.jp (M. Aonuma).

0921-5107/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.mseb.2009.12.015

Table 1
Chemical compositions of alloy plates.

Alloy	Chemical composition (mass%)					
	C	H	O	N	Fe	Ti
Titanium	0.080	0.013	0.200	0.030	0.250	Bal.

Alloy	Chemical composition (mass%)					
	Al	Zn	Mn	Fe	Si	Ca	Mg
AM60	5.9	0.20	0.27	0.006	0.01	–	Bal.
AMCa602	5.9	0.04	0.28	0.003	0.04	2.03	Bal.

method was suggested by some researches [5–8]. Titanium plate was positioned on the retreating side and magnesium alloy plate was positioned on the advancing side in this study.

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 (EDX) and a transmission electron microscope (TEM). The joint was cut into a piece with a width of 10 mm, and a transverse tensile test to FSW direction was performed.

3. Results and discussion

To examine the effect of calcium contained in AMCa602 alloy, the joint interface of AM60 alloy and titanium was observed. Fig. 2 shows the SEM image and characteristic X-ray images of the joint interface of AM60 and titanium (AM60/Ti) joint. The reaction layer was clearly observed in the joint interface. The thickness of the layer was different depending on the observed position. The layer near the surface of the plate was thicker than that near the bottom of the plate, because the peak temperature of the joint during FSW is higher near the plate surface than near the bottom of the plate as well known [9]. The maximum thickness of the layer was about 2 μm. Quantitative analysis of this layer was done using EDX. The average composition of the layer was 23.65% Ti and 76.35% Al (by atomic percentage). This result suggested that the layer is a $TiAl_3$ intermetallic compound.

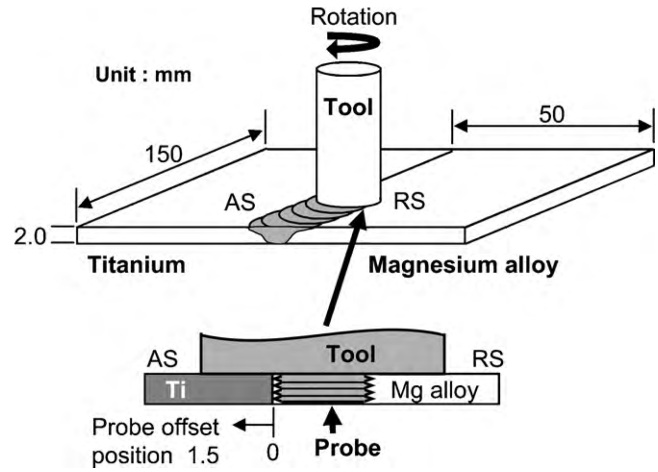

Fig. 1. Schematic illustration of joint arrangement in FSW.

The SEM image and characteristic X-ray images of AMCa602 and titanium (AMCa602/Ti) joint interface are shown in Fig. 3. The reaction layer was observed partly and did not cover all the joint interfaces. In the joint interface, two kinds of layers were observed by SEM. One was a layer containing magnesium, calcium, and aluminum; and the other was a layer containing only magnesium and aluminum. The thick intermetallic compound layer, which had been observed in the AM60/Ti joint interface as shown in Fig. 2, was not observed in the AMCa602/Ti joint interface. The

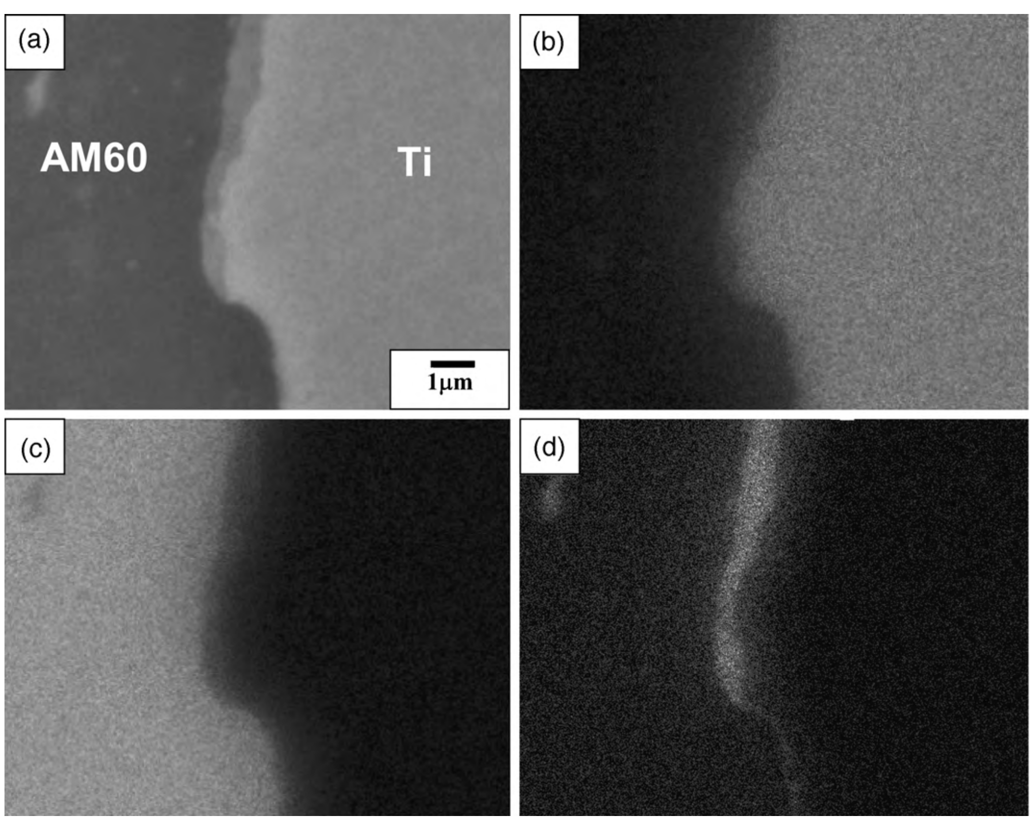

Fig. 2. SEM image (a) and characteristic X-ray images of Ti (b), Mg (c) and Al (d) near joint interfaces of titanium and AM60.

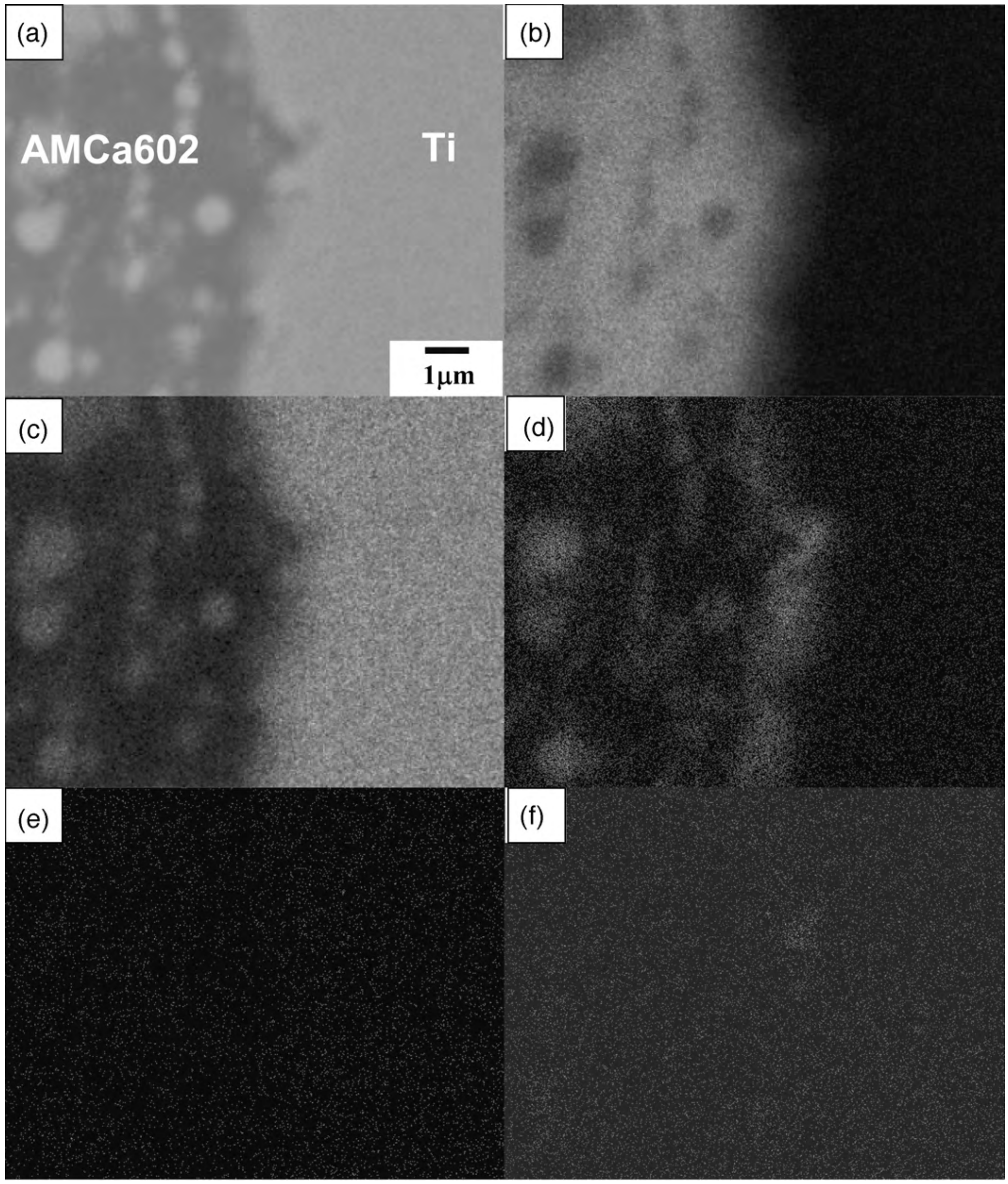

Fig. 3. SEM image (a) and characteristic X-ray images of Mg (b), Ti (c), Al (d), Mn (e) and Ca (f) near joint interfaces of titanium and AMCa602.

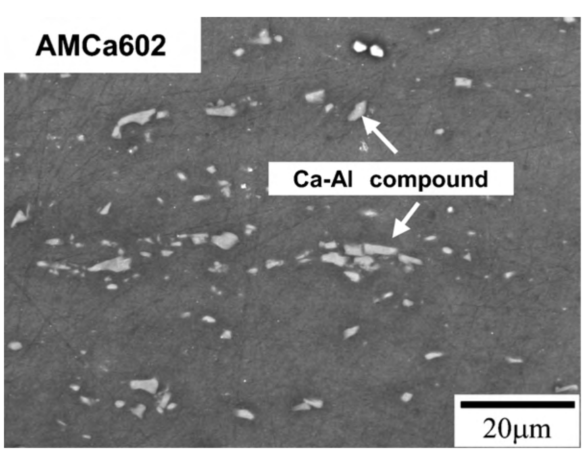

Fig. 4. SEM image of AMCa602 base metal.

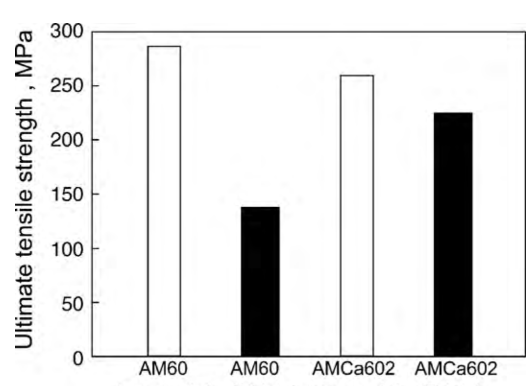

Fig. 5. Tensile strengths of FSW joints of titanium and magnesium alloys.

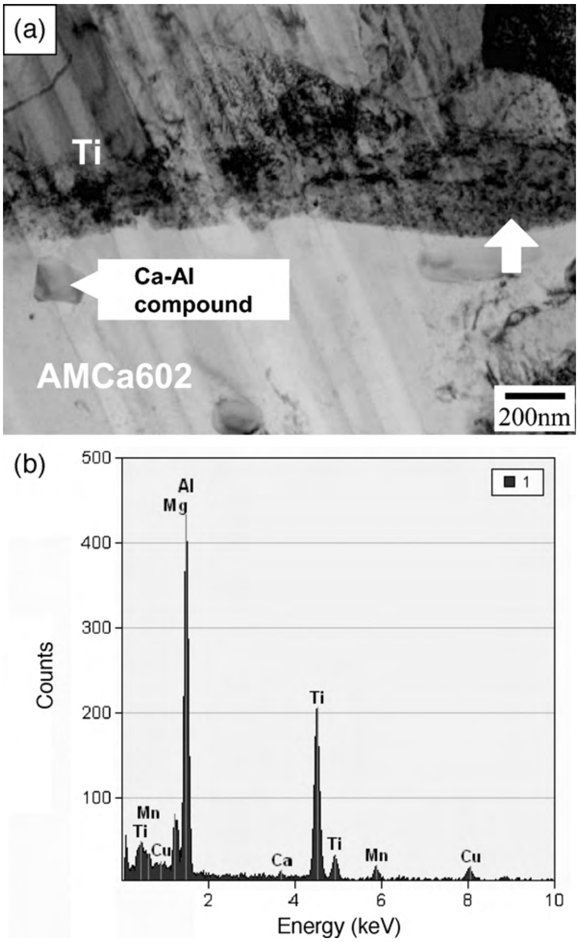

Fig. 6. TEM observation result of the joint interface of titanium and AMCa602 joint: (a) bright field image and (b) EDX spectrum from the spot indicated by the arrow (a).

reason why the formation of the intermetallic compound layer at the joint interface was different in AM60 and AMCa602 is surmised as follows.

Al_2Ca compounds were observed in the AMCa602 base metal by SEM and EDX, as shown in Fig. 4. The quantitative analysis by EDX revealed that the aluminum content in the matrix of the AMCa602 base metal was 3.45 mass%, which was less than that in the matrix of the AM60 base metal, 5.05 mass%. Calcium has strong affinity with aluminum, and thus reacts with aluminum and makes Al_2Ca compound in AMCa602 [10]. Therefore, the aluminum content in the matrix of AMCa602 is less than that in AM60. Aluminum element in the matrix is in solid-solution condition and easy to diffuse at elevated temperature. Hence, it is considered that a thick $TiAl_3$ intermetallic compound was formed at AM60/Ti joint interface compared with AMCa602/Ti interface due to larger content of diffusible aluminum element in AM60.

Fig. 5 shows the tensile test results of these joints. All the joints fractured at the joint interface. The tensile strength of the AMCa602/Ti joint was 225 MPa and the tensile strength of AM60/Ti joint was 138 MPa. The tensile strength of the AM60/Ti joint was lower than that of the AMCa602/Ti joint at each offset position and friction stir welding condition. It is surmised that the formation of intermetallic compound layer at the AMCa602/Ti joint interface was suppressed to be a thin layer.

Fig. 6(a) shows a bright field image by TEM at the AMCa602/Ti joint interface. The grains of titanium near the joint interface were refined to under 1 μm by the plastic deformation in the friction stir welding. In AMCa602 near the joint interface, grainy phases consisted of calcium and aluminum were observed. It is considered that these phases were Al_2Ca compound crushed by friction stir welding on the titanium side adjacent to the joint interface, the very thin layer with gray color up to 200 nm in the thickness was observed along the interface. Fig. 6(b) shows the EDX spectrum from the spot indicated by the arrow in Fig. 6(a), which indicates that the layer consists of aluminum and titanium without calcium, suggesting the formation of $TiAl_3$ intermetallic compound layer.

4. Conclusion

We studied the effect of aluminum and calcium as alloying element on the intermetallic compound layer at the joint interface between calcium added Mg–Al alloy and titanium dissimilar joint by friction stir welding.

Calcium added in Mg–Al alloy reacted with aluminum to make Al_2Ca compound and decreased the solid-solution aluminum in the matrix of Mg–Al–Ca alloy. This suppressed the formation of Ti–Al intermetallic compound layer at the joint interface and resulted in the higher tensile strength of the dissimilar joint with titanium plate in comparison with Mg–Al alloy containing same aluminum contained.

References

[1] M. Sakamoto, S. Akiyama, T. Hagio, K. Ogi, J. JFS 69 (1997) 227–233.
[2] M. Aonuma, K. Nakata, Mater. Sci. Eng. B 161 (2009) 46–49.
[3] A. Yamamoto, M. Terashita, H. Tsubakino, J. Jpn. Inst. Light Met. 57 (2007) 99–104.
[4] Y. Nakaura, A. Watanabe, K. Ohori, Mater. Trans. 47 (2006) 1031–1039.
[5] S. Hirano, K. Okamoto, M. Doi, H. Okamura, M. Inagaki, Y. Aono, Q. J. Jpn. Weld. Soc. 21 (2003) 539–545.
[6] T. Watanabe, A. Yanagisawa, H. Takayama, Q. J. Jpn. Weld. Soc. 22 (2004) 141–148.
[7] T. Watanabe, A. Yanagisawa, H. Takayama, S. Konuma, Q. J. Jpn. Weld. Soc. 23 (2005) 603–607.
[8] M. Fukumoto, M. Tsubaki, Y. Shimoda, T. Yasui, Q. J. Jpn. Weld. Soc. 22 (2004) 309–314.
[9] M. Kokubo, Y. Takayama, S. Kazui, T. Kaneuchi, H. Kato, S. Hirano, J. Jpn. Inst. Light Met. 57 (2007) 511–517.
[10] B. Tang, X.-S. Wang, S.-S. Li, D.-B. Zeng, R. Wu, Mater. Sci. Technol. 21 (2005) 574–578.