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Continuous drive friction welding of 5A33 Al alloy to AZ31B Mg alloy

Zhida Liang, Guoliang Qin*, Peihao Geng, Fan Yang, Xiangmeng Meng

Key Laboratory for Liquid-Solid Structural Evolution & Processing of Materials, Ministry of Education, Shandong University, Jinan 250061, China

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ABSTRACT

5A33 aluminum alloy bar was joined with AZ31B magnesium alloy bar by continuous drive friction welding. The friction weldability of Al alloy to Mg alloy was investigated. The microstructure of the friction interface in joints was analyzed by optical microscopy, scanning electron microscopy, and X-ray diffraction analysis. The chemical compositions of newly formed phase on the interface were tested by energy dispersive spectroscopy. The results show that the sound joints of Al alloy to Mg alloy can be obtained by continuous drive friction welding process. The tensile strength of the joints increased with increasing friction time, and on average the highest strength could reach up to 101 MPa when friction time was 5 s. All the friction welded samples failed at the friction interface during tensile test. The fracture appearances showed almost flat surface, so the fracture of the as-welded Al/Mg joints in this experiment was brittle mode. A new reaction layer formed on the friction interface consisted of intermetallic compounds (IMCs) layer and Mg solid solution layer, and the IMCs were mainly $Mg_{17}Al_{12}$ and Al_3Mg_2. The type of IMCs was variable with increasing friction time. Due to high microhardness of reaction layer, the microhardness value on the interface was dramatically larger than that of the Mg base material. The thickness of hardened layer in the Mg side and softened layer in the Al side increased with increasing friction time.

1. Introduction

Aluminum (Al) and magnesium (Mg) alloy have been extensively used in automotive, electronics and aerospace industries [1]. Composite structure of Al and Mg alloy catches researchers' eyes because it can improve the flexibility and reduce the weight of structures through partial substitution of Mg alloy for Al alloy. Welding process is the key technology to manufacture the Al/Mg composite structures, while the weldability of Al to Mg is very poor, which makes the joining between Al and Mg very difficult.

In the past decades, Al and Mg were joined by many welding methods, such as friction stir welding (FSW) [2–5], vacuum diffusion bonding [6–8], laser welding [9], resistance spot welding [10], brazing [11], explosion welding [12], cold metal transfer (CMT) welding [13], tungsten inert gas (TIG) welding [14], and laser-TIG hybrid welding [15]. Borrisutthekul et al. [9] found that a large amount of brittle intermetallic compounds (IMCs) formed in joints of Al to Mg alloy by laser welding, which deteriorated the properties of the joints. Cao et al. [13] studied CMT welding of Mg AZ31B to Al A6061-T6. The results presented that although many efforts had been exercised to control the heat input, harmful IMCs still formed in the joints. Generally, the fusion welding processes are not suitable for joining of Mg alloy to Al alloy because of the formation of a large amount of IMCs in the joints.

Continuous drive friction welding is a solid state welding technique. Compared with fusion welding, the good joints can be achieved by continuous drive friction welding because welding temperatures are lower than the melting points of base metals. Therefore, the continuous drive friction welding is suitable candidate for producing composite structure of Al bar to Mg bar. The continuous drive friction welding of pure Mg/pure Al and Mg alloy/pure Al have been studied [16,17]. Kimura et al. [17] studied the continuous drive friction welding of pure Mg to pure Al with post-weld heat treatment, and the joints being obtained had the same mechanical properties with the base metal. However, the friction welding of Al alloy to Mg alloy is very difficult, so the relevant research results are very less in the retrieved literature. The welding of Mg alloy to Al alloy has significant application in manufacturing industry, so the friction welding of Al alloy to Mg alloy need to be studied.

In this paper, the continuous drive friction welding of 5A33 Al alloy to AZ31B Mg alloy was investigated. We studied the friction weldability and the microstructure of the joints and we also tested

* Corresponding author at: Qianfoshan Campus of Shandong University, 17923 Jingshi Road, Jinan 250061, China. Fax: +86 0531 88369277.
E-mail addresses: liangzdchina@gmail.com (Z. Liang), glqin@sdu.edu.cn (G. Qin).

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Table 1
Chemical compositions (in wt.%) of base metals were determined by optical emission spectrometer.

Material	Al	Mg	Si	Fe	Cu	Mn	Zn	Cr	Ti	Ni
5A33	Bal.	7.55	0.41	1.40	0.07	0.25	1.85	0.49	0.05	0.02
AZ31B	2.25	Bal.	0.016	0.005	–	0.44	1.10	–	–	0.009

Table 2
Physical properties.

Material	Density (g/cm^3)	Melting temperature (°C)	Hv	Tensile strength (MPa)	Yield strength (MPa)	Young's modulus (E)
5A33	2.71	655	90	352	298	69
AZ31B	1.78	615	55	271	206	45

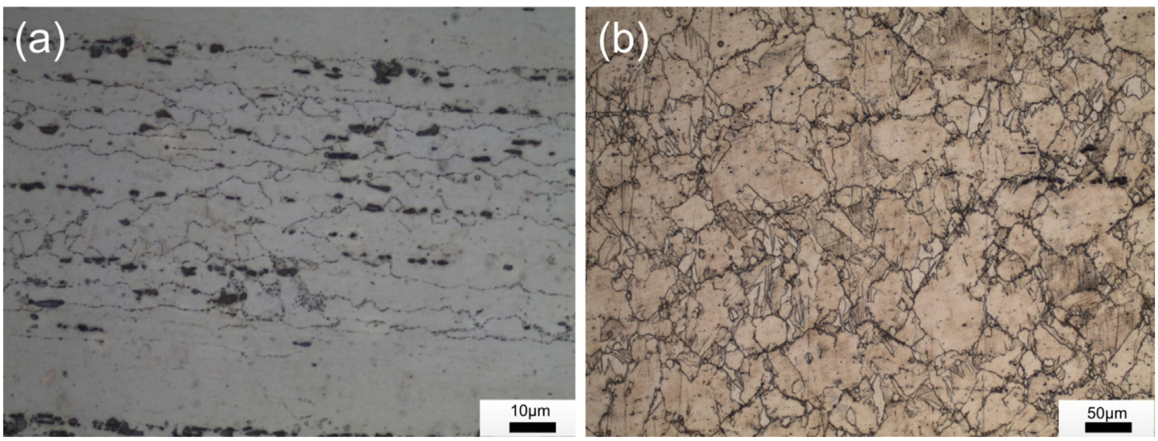

Fig. 1. Microstructures of base materials: (a) 5A33 Al alloy; (b) AZ31B Mg alloy.

the mechanical properties of the joints and the fracture appearances. The relationship among welding conditions, microstructure, and the strength of joints was discussed in details.

2. Experimental details

2.1. Materials

The 5A33 Al alloy bars and AZ31B Mg alloy bars of 12 mm in diameter were used in the experiments. Their chemical compositions were determined by optical emission spectrometer and shown in Table 1. The physical properties of 5A33 Al alloy and AZ31B Mg alloy were shown in Table 2. The microstructures of 5A33 Al alloy and AZ31B Mg alloy were shown in Fig. 1.

2.2. Friction welding parameters

A continuous drive friction welding machine was used for joining in this experiment. For all friction welding experiments of Al alloy to Mg alloy, the friction welding parameters such as rotation speed (n), upsetting pressure (P_2), friction pressure (P_1) and upsetting time (t_2) were kept constant, which were 2200 rpm, 180 MPa, 60 MPa and more than 10 s, respectively, while friction time (t_1) were varied from 1 to 20 s. During welding experiment, the 5A33 Al alloy bar rotated with the spindle and the AZ31B Mg alloy bar moved axially under the axial pressure.

2.3. Microstructure observation

The metallographic cross-sections of the specimens were machined from the welded joints. Then the samples were etched with a mixture solution of 10 mL acetic acid, 10 mL distilled water, and 6.5 g picric acid in 100 mL ethanol for 18 s and 20 g NaOH in 100 mL distilled water for 55 s to reveal Al and Mg structures, respectively. The microstructure of the friction interface was analyzed using optical microscope (OM) and field emission scanning electron microscopy (FSEM), and its chemical compositions were determined by energy dispersive X-ray spectrometer (EDS). Phases in both matching fracture surfaces (the one on the Al alloy side and the other on the Mg alloy side) after tensile test were analyzed with X-ray diffraction (XRD) analysis conducted with Co-Kα radiation at 30 kV and 40 mA. Diffraction angle (2θ) varied from 30° to 90° with a step size of 0.026° and 0.08 s in each step.

2.4. Tests of mechanical properties

Vickers microhardness was measured on both sides of the welded samples by means of Vickers indenter with a load of 0.5 N dwelled for 10 s. Tensile strength of the joints was tested using tensile testing machine at a constant displacement rate of 1 mm/min at room temperature. All tensile test specimens were machined to 12 mm diameters. Three specimens were tested at least for each group of welding parameters to ensure the representativeness and reproducibility of the fracture.

3. Results and discussion

3.1. Joints appearance and the burn-off length

Fig. 2 shows the appearance of the as-welded joints with different friction time. It is evident that the upset metal of the as-welded Al/Mg joints increases gradually with friction time being increased. During friction welding process, the accumulated friction heat is sufficient to soften the base metal. When the base metal reaches the plastic state, the upset metal subsequently forms under the squeezing action of friction pressure and upsetting pressure. Thus, the burn-off length increases rapidly with the increase of friction time, as shown in Table 3.