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Microstructural characterizations and mechanical properties in underwater friction stir welding of aluminum and magnesium dissimilar alloys

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ABSTRACT

Formation of intermetallic compounds in the stir zone of dissimilar welds affects the mechanical properties of the joints significantly. In order to reduce heat input and control the amount and morphological characteristics of brittle intermetallic compounds underwater friction stir welding of 6013 Al alloy and AZ31 Mg alloy was carried out. Microstructures, mechanical properties, elements distribution, and the fracture surface of the joints were analyzed by optical microscopy, scanning electron microscopy and energy dispersive X-ray spectroscopy, etc. The result shows that sound dissimilar joint with good mechanical properties can be obtained by underwater friction stir welding. Al and Mg alloys were stirred together and undergone the process of recrystallization, forming complex intercalated flow patterns in the stir zone. Tensile strength of the dissimilar joint was up to 152.3 MPa. Maximum hardness (142HV) appeared in the middle of the centerline of the specimen. Intermetallic compounds layer consisting of Al_3Mg_2 and $Mg_{17}Al_{12}$ formed in the Al/Mg interface and resulted in the fracture of the joint.

1. Introduction

As light alloys with low density, high special strength and good anti-corrosion properties aluminum and magnesium are widely used in transportation and electronic communications industries. In certain applications, the successful welding of dissimilar metals of aluminum and magnesium is advantage for producing lightweight structures, pushing forward the lightweighting technology and the project of energy-saving and emission-reduction [1]. Researchers had tried various fusion welding methods such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW) [2], laser welding [3] and solid state welding technology such as vacuum diffusion bonding [4] to join Al–Mg. However, these welding methods are not widely used because of the poor weld joint strength caused by pores, cracks and Al–Mg intermetallic compounds with high hardness and low ductility. In addition, some specific process requirements which are difficult to carry out cause these methods limited.

Being different from fusion welding, friction stir welding (FSW) is a solid-state welding process. In the process of FSW, shouldered tool with a pin rotates and moves between sheets of the pieces to be welded and friction heat which is not sufficient to melt the materials generates. In consequence, materials to be welded reach the plastic state and are joined together under the action of stirring and pressure [5,6]. Naturally, the obvious lower temperature helps FSW to avoid many defects appearing in fusion welding and the nature features FSW owns make it get higher joint strength. All these make FSW be a potential welding technique in dissimilar materials joining. More details about the process of FSW were described in many earlier publications [7–11].

Recent years, many efforts had been focused on the application of FSW in dissimilar materials such as dissimilar Al alloys [12–14], dissimilar Mg alloys [15], Al to steel [16,17], and Al–Mg [18–21]. Some researchers had tried to weld Al and Mg alloys under water using the method of FSW and got better mechanical properties than in air [22]. While joints of Al alloys and Mg alloys obtained by FSW under water were sound with good mechanical properties, the details of microstructural evolution of dissimilar joints of Al and Mg alloys have not been fully understood. In this paper, 6013 Al alloy and AZ31 Mg alloy were welded by FSW under water. The microstructure, distribution of elements, hardness, tensile strength and fracture feature of the joints were investigated to make a comprehensive analysis of the microstructures and mechanical properties of the FSW joints of 6013 Al alloy and AZ31 Mg alloy.

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2. Material and experimental procedures

Commercial available base materials (BM) AA6013 aluminum alloy and AZ31 magnesium alloy sheets (100 × 90 × 2.5 mm) were welded in the study. Their chemical compositions and mechanical properties are listed in Table 1. The weld process was done under water at a FSW-3LM-002 machine produced by China Friction Stir Welding Center in this experiment. The shouldered tool which was made of H13 steel was 16 mm in diameter and concave, with a 2.5 mm long and 5 mm in diameter threaded cylindrical probe. During the welding process AA6013 was placed at the advancing side (AS) and AZ31 Mg was placed at the retreating side (RS). The two alloys were welded at a rotation speed of 1200 rpm and travel speed of 80 mm/min. The welding tool rotated counterclockwise and the tilt angle was 2.5° from the normal surface of the workbench. Oxide film was removed with steel brush and greasy was cleaned by ethanol before welding.

Following FSW, transverse cross section was observed by optical microscopy (OM). The specimens for OM were cut perpendicular to the welding direction by using an electrical discharge machine. After the sample was ground and polished, the Al and Mg side of the joint were swabbed multiple times with different etching solutions (1 mL HNO_3 + 1 mL CH_3COOH + 1 g $H_2C_2O_4$ + 150 mL distilled water for the Mg alloy; 2 mL HF + 5 mL HNO_3 + 95 mL distilled water for the Al alloy) by using a cotton ball until visible etching was obtained. Additionally, the samples were cleaned with ethanol after a few seconds of the swabbing. Microstructures of the weld were observed with an optical microscope and the fracture surface of the FSW joints after tensile tests (according to ASME BPVC IX-2010) were examined by a JSM-6460 scanning electron microscope (SEM) equipped with an Oxford energy dispersive X-ray spectroscope system (EDS).

The phase analysis was carried out by using a multi-functional D/max 2550VL/PC X-ray diffractometer (XRD) to identify the intermetallic compounds in the dissimilar joints from the fracture surface (both AZ31 side and AA6013 side). The XRD process used Cu Kα radiation at 45 kV and 40 mA. The diffraction angle (2θ) at which the X-rays hit the sample varied from 20° to 110° with a speed of 6° per minute.

Vickers microhardness was measured with a MH-5D digit hardness tester across the sectioned weld and a load of 100 g and dwell time of 15 s was applied.

3. Results and discussions

3.1. Appearances and microstructures

Fig. 1 shows the surface appearance of the friction-stir joint of Al 6013 and Mg AZ31 performed under water. It can be seen that sound weld without obvious defects such as cracks or tunnel type defects was obtained when rotation speed was 1200 rpm and travel speed was 80 mm/min with the pin moving along the center. This is contrary to some other researcher's result. Yan et al. [23] reported that if rotating pin traveled along the butt line between the two base materials cracks developed.

A cross-sectional macrograph of the dissimilar joint is presented in Fig. 2. In the macrograph the left side is AA6013 and the right side is AZ31 Mg alloy. The delineation which means the boundary between nugget zone (NZ) and the thermo-mechanical affected zone (TMAZ) on the Al side is sharper and clearer than that on the Mg side. This is related to the difference in the state of plastic flow during welding process. In the stir zone, with the cavity effect produced by the rotating tool, the material on the advancing side was squeezed to the back of the pin. In this case, the plastic deformation direction of base metal is consistent with the welding direction and a relative deformation difference formed between base metal and the plastic deformed metal. So the boundary between the nugget zone and the thermal mechanically affected zone is obvious on the Al side. Plasticity deformed metal on the retreating side flow to the back of the pin and the deformation direction of base metal is contrary to the welding direction. Almost base metal on the retreating side deform together with the plasticity deformed metal. This make no obvious boundary between NZ and TMAZ form on the retreating side.

Table 1
Chemical compositions and mechanical properties of experimental materials.

Metal	Chemical composition (wt.%)						UTS/MPa
	Al	Mg	Mn	Cu	Si	Zn	
Al 6013	Bal.	0.90	0.21	0.90	0.73	–	385
Mg AZ31	3.74	Bal.	0.29	–	0.02	0.75	241

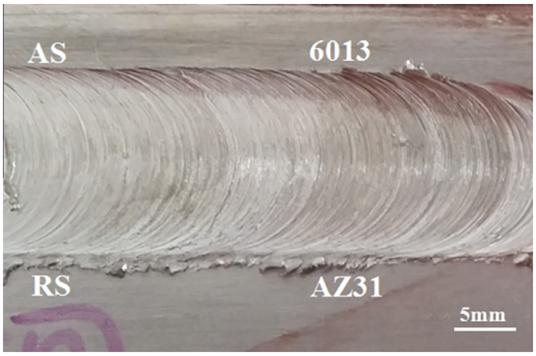

Fig. 1. Appearance of the plates friction-stir-welded under water.

The joint of 6013 Al alloy and AZ31 Mg alloy got underwater in this experiment is much smoother and less intermixed than that got in air with the same welding parameter in our earlier experiment. This is because the heat input acting on the water welded specimen is lower than that acting on the air welded specimen, making plastic flow be more difficult to achieve.

Fig. 2a and b shows the microstructures of 6013 Al alloy and AZ31 Mg alloy respectively. Obviously, the microstructures of base materials of AA6013 and AZ31 consist grains of unequal sizes and distributions. Fig. 2b shows a grain size of about 25 μm for the AZ31 Mg alloy base metal. Fig. 2f shows a typical optical image of the interface of a dissimilar Al/Mg weld and the right side near the interface is recrystallized Mg. In the process of FSW, the stirring movement and friction thermal cycle cause intense plastic deformation and high temperature and induce dynamic recrystallization. This makes the recrystallized Mg grains (about 2 μm) be much finer than grains in Fig. 2b. Mofid et al. [22] reported that, as a result of lower heat input and lower peak of temperature of water submerged weld, the recrystallized Mg grain size in the interface and stir zone of water welded specimen was considerably finer than that of air welded specimen.

The electron probe micro analysis (EPMA) image and distribution maps of major elements Mg and Al in mixture structure of the stir zone corresponding to Fig. 2f are presented in Fig. 3. It can be seen clearly in the image that elements of Al and Mg are stirred together in the weld zone. During FSW the alloys in the two sides of the welding center undergo a high temperature action and continuous deformation. In the process of plastic deformation, two different alloys are stirred up together and mixture structure forms. In the high temperature action recrystallization occurs, causing the original extrude slender Al grains and coarse primary Mg grains transform to fine equiaxed grains.