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Improving tensile properties of Al/Mg joint by smashing intermetallic compounds via ultrasonic-assisted stationary shoulder friction stir welding

Zhenlei Liu[a], Xiangchen Meng[a,b,*], Shude Ji[a,*], Zhengwei Li[b], Lin Wang[c]

[a] *Faculty of Aerospace Engineering, Shenyang Aerospace University, Shenyang 110136, PR China*
[b] *State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, PR China*
[c] *Department Advanced Molding Process, Shenyang Aerospace Xinguang Group Co., Ltd., Shenyang 110136, PR China*

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ABSTRACT

Continuous intermetallic compounds (IMCs) at the nugget zone (NZ) of dissimilar friction stir welded Al/Mg joint easily become crack initiation and propagation path, deteriorating mechanical properties. To reduce or eliminate the disadvantages induced by the continuous IMCs, ultrasonic-assisted friction stir welding (UaFSW) based on stationary shoulder system was employed to join 6061-T6 aluminum alloy and AZ31B magnesium alloy. Defect-free joint without the shoulder marks was obtained under the synergistic effect of the stationary shoulder and the ultrasonic. Vibration and acoustic streaming induced by the ultrasonic broke the continuous IMCs layer near the thermo-mechanically affected zone (TMAZ) of advancing side (AS) into pieces or particles. Facture path from the short Al/Mg interface near the TMAZ at the AS of the conventional joint was changed to the long Al/Mg interface at the retreating side (RS) of the UaFSW joint, improving tensile properties. Maximum values of tensile strength and elongation of the UaFSW joint were 152.4 MPa and 1.9%, which were 17 MPa and 0.8% higher than those of the conventional joint, respectively.
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1. Introduction

Al alloys are widely applied to transportation and electronic industries due to the high specific strength [1,2]. Meanwhile, as the structural metals with the lowest density, Mg alloys have been becoming more and more important in aerospace, automotive and shipbuilding industries [3,4]. In the backgrounds of energy-saving and emission-reduction, optimizing structure configuration and decreasing weight are very essential. Therefore, the welding of dissimilar Al/Mg alloys has become research hotspot. However, owing to the disadvantages of coarse grains, hot cracks, pores and especially amounts of brittle intermetallic compounds (IMCs), conventional fusion welding techniques are difficult to obtain high-quality Al/Mg joint [5,6].

Friction stir welding (FSW), involving temperature, mechanics, metallurgy and interactions, is a highly complex solid state joining process, which has been validated to potentially join Al/Mg alloys [7]. Furthermore, morphologies of the IMCs and mixing degree of Al/Mg alloys in nugget zone (NZ) significantly influence joint quality. On one hand, Mofid et al. [8–10] reported that tensile fracture easily occurred at a location with the continuous IMCs layer. Zhao et al. [11] elaborated that the Al/Mg joint failed at the NZ where hardness gradient was the sharpest induced by the brittle IMCs. Yan et al. [12] also indicated that the IMCs resulted in the uneven hardness distribution during FSW of 5052 Al and AZ31Mg alloys, causing joint fracture. Yamamoto et al. [13] stated that the tensile strength of the Al/Mg joint was mainly governed by the thickness of the IMCs layer and the mechanical interlocking of Al/Mg alloys. On the other hand, Rao et al. [14] expounded that the strong bonding in the NZ was obtained due to the partial mechanical interlocking between Mg alloy and the IMCs layer. Firouzdor et al. [15] stated that the joint strength was improved by a long interface length and an interpenetrating feature thickness. Therefore, how to regulate and control the distribution characteristic of the IMCs at the Al/Mg interface improving mechanical properties has been becoming a research hotspot. Ultrasonic, a new assisted energy, has been widely applied to FSW, which provides many benefits, such as vibration and acoustic streaming [16–20]. Liu et al. [16] and Shi et al. [17] reported material flow behavior during ultrasonic-assisted FSW (UaFSW)

* Corresponding authors at: Faculty of Aerospace Engineering, Shenyang Aerospace University, Shenyang 110136, PR China.
E-mail addresses: mengxch2013@163.com (X. Meng), superjsd@163.com (S. Ji).

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and expounded that material flow was distinctly improved owing to the reduction of material flow stress induced by the vibration. Ji et al. [18] indicated that fracture propagation path was changed from along the IMCs at the Al/Mg interface of conventional joint to across the Mg alloy during ultrasonic assisted friction stir spot welding of Al/Mg alloys. Lv et al. [19] also pointed out that the ultrasonic exerted a little preheating effect on the welded workpieces, and hardly influenced the peak temperature during UaFSW of Al/Mg alloys. Therefore, it can be concluded from the published papers [16–20] that UaFSW owns the advantages of improving material flow and changing the form of the IMCs as well as without obvious temperature variation, which has the feasible and huge potential to join Al/Mg alloys.

In this study, UaFSW was mainly employed to join 6061-T6 aluminum alloy and AZ31B magnesium alloy to change the distribution of the IMCs at the Al/Mg interface and the mixing degree of Al/Mg alloys in the NZ. Meanwhile, effects of the ultrasonic on joint formation, evolution of the IMCs and mechanical properties of joint were investigated in detail.

2. Experimental procedure

The base materials (BMs) were respectively 6061-T6 aluminum alloy and AZ31B magnesium alloy, whose dimensions were 200 mm × 100 mm × 3 mm. Chemical compositions and mechanical properties of the two BMs are listed in Tables 1–3. A self-designed stationary shoulder with an 11 mm inside diameter and a 16 mm outside diameter was applied to enhance joint formation, as indicated in Fig. 1a [20]. In order to improve material flow behavior, a rotational tool containing a concentric circles shoulder and a right screwed thread pin is employed. The diameters of the shoulder, the pin bottom and top of the inside rotational tool are 10 mm, 5 mm and 3 mm, respectively. The length of the rotational pin is 2.8 mm. For the displacement-controlled machine used in this study, a plunge depth was 0.1 mm. The inside rotational tool rotated anticlockwise and a tilting angle with respect to Z-axis was 2.5°. A rotational velocity of 1000 rpm and a welding speed of 60 mm/min kept constant. The inside rotational tool offset 0.3 mm to Mg sheet. Additionally, the Al sheet located at the retreating side (RS) and the Mg sheet laid at the advancing side (AS). Schematic diagram during the UaFSW of Al/Mg alloys is displayed in Fig. 1b. Ultrasonic generator was exerted on the Mg sheet in order to improve material flow of the Mg side due to the limitation of numbers of slip systems of hexagonal close packed (HCP) crystal lattice [21]. A power of 1400 W and a frequency of 20 kHz for the ultrasonic generator were used. Meanwhile, the vibration amplitude of the Mg sheet at the welding interface was about 42 μm. The edge of ultrasonic generator was 20 mm distance away from the welding centerline, which has been validated to be the optimum position [25]. During the process, the outer stationary shoulder is not rotating and the inner rotational tool with rotational shoulder and pin is rotating. The action point of the ultrasonic generator is shown in Fig. 1c. Before welding, the workpieces to be welded were burnished using abrasive paper and cleaned by acetone in order to wipe off oxide layer.

After welding, microstructural and mechanical specimens were cut perpendicular to the welding line by an electrical discharge cutting machine. Microstructural specimen was etched for 6061 alloy using a reagent (2 ml HF, 3 ml HCl, 5 ml HNO_3 and 190 ml H_2O) and for AZ31 alloy by a reagent (5 ml CH_3COOH + 5 g $C_6H_2OH(NO_2)_3$ + 10 ml H_2O + 100 ml C2H5OH), and observed with an optical microscopy (OLYMPUS, GX71). Element distribution of the Al/Mg interface was observed using a scanning electron microscopy (SEM) equipped with an energy dispersive X-ray spectroscopy (EDS). Tensile specimen was prepared for each joint with reference to GB/T 2651-2008 (equivalent to ISO 9016: 2001) to evaluate tensile properties of joint [22]. Tensile test was carried out at room temperature under a constant crosshead speed of 3 mm/min. Fracture surface of the tensile specimen was characterized using SEM. Microhardness distribution was measured by a micro-hardness tester at a load of 200 g for a dwell time of 10 s. Two tested layers on the joint through the thickness direction across the cross-section were measured, which were 1 mm and 2 mm distances away from the top surface of joint, respectively. The interval between the two adjacent points was 0.5 mm.

Table 1
Chemical composition of 6061-T6 aluminum alloy (mass, %).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.4–0.8	0.7	0.15–0.4	0.15	0.8–1.2	0.1	0.25	0.15	Bal.

Table 2
Chemical composition of AZ31B magnesium alloy (mass, %).

Al	Mn	Zn	Si	Fe	Cu	Ni	Mg
3.1	0.48	0.88	0.11	0.0027	0.0015	0.0005	Bal.

Table 3
Mechanical properties of 6061-T6 alloy and AZ31B alloy.

Metal	Tensile strength (MPa)	Elongation (%)	Hardness (Hv)
6061-T6 alloy	284	9.5	98
AZ31B alloy	256	10	79

3. Results and discussion

3.1. Surface appearance

Fig. 2 shows the surface appearances of the joints using different welding processes. According to the references reported by Ji et al. [4] and Yang et al. [23], the stationary shoulder is beneficial to improve joint formation and broaden process parameter windows, which is effective to eliminate the shoulder marks and reduce the size of flashes during FSW of similar Al alloys. Fig. 2a displays the surface formation of the conventional joint using the stationary shoulder without the ultrasonic. The shoulder marks still appear on the surface of the Al/Mg joint. During FSW, some liquid materials above the eutectic temperatures occur and overflow out of the NZ, adhering to the shoulder of the rotational tool. Meanwhile, a small scratch forms at the top surface rather than a groove defect due to the scraping induced by the minor adhesion materials on the stationary shoulder. As reported by Yan et al. [12], the adhesion phenomenon on a rotational tool was induced by the IMCs and further the formation of IMCs was validated by XRD. The adhesion materials on the rotational shoulder cause that the surface of the inside rotational shoulder is convex with respect to the outside stationary shoulder, resulting in the formation of the shoulder marks. However, with the addition of ultrasonic, the shoulder marks disappear at the surface of the joint, obtaining a smooth surface similar to FSW of similar Al alloys based on the stationary shoulder. The improvement of surface quality by UaFSW may be attributed to the following reasons. On one hand, the ultrasonic can provide vibration between workpieces to be welded and the stationary shoulder, producing second contact. On the other hand, acoustic streaming of the ultrasonic can break the adhesion materials into pieces or particles, reducing the adhesion phenomenon. Under the combined effect of two actions, the shoulder marks can be eliminated.

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