Research Article

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Investigation on ultrasonic assisted friction stir welding of aluminum/steel dissimilar alloys

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Abstract: The extensive use of light metal material such as aluminum has brought about problems in its joining with steel. However, the weak metallurgical bonding between the dissimilar materials and the formation of hard and brittle intermetallic compounds (IMCs) lead to unsatisfactory joint strength. Aiming at achieving high-quality joining of aluminum and steel, 6061-T6 aluminum and 301L steel alloys were lap joined by ultrasonic assisted friction stir lap welding (UaFSLW) in this study. The UaFSLW joints were well formed with uniform flashes and even arc lines. The strong plastic flow of the aluminum material driven by the dual effects of mechanical stirring and ultrasonic vibration inhibited the excessive growth of the Al–Fe IMCs at the lap interface. Thanks to the enhanced metallurgical bonding and the effective control of the layer thickness of IMCs, the tensile load of the UaFSLW joint under 1,800 rpm reached 16.5 kN, which was an increase of 27.9% compared to that of the conventional FSLW joint.

Keywords: ultrasonic vibration, friction stir lap welding, dissimilar materials, tensile property

1 Introduction

With the increasingly prominent problems of energy crisis and environmental pollution, the energy conservation and emission reduction have become the consensus in the manufacturing industries [1,2]. Choosing light alloy materials such as aluminum and magnesium alloys to realize the product lightweight is an effective approach to achieve the above aims. Because of the wide applications of aluminum and steel alloy materials, the aluminum/steel hybrid welding is an inevitable topic in automobile, rail transit, and other equipment manufacturing industries. At present, the welding of aluminum/steel dissimilar materials can be realized by brazing [3] and fusion welding methods such as arc welding [4], laser welding [5], and electron beam welding [6]. In recent years, a relatively new solid-state welding technique of friction stir welding (FSW) has been proved to be successfully applied in the welding of aluminum/steel dissimilar alloys [7,8].

The FSW technique has advantages such as low welding temperature and small welding distortion because of its process characteristics [9,10]. During FSW, large plastic deformation and severe material flow occur in the weld, and the welded joint is obtained with extremely fine grains and dense texture [11,12]. The FSW process is proved to be suitable in the welding of dissimilar materials [13]. In the friction stir lap welding (FSLW) of aluminum/steel dissimilar materials without penetrating the upper plate, the interfacial metallurgical bonding is the main joining mode [14]. Because of the low solid solubility of iron element in aluminum matrix, the bonding of aluminum/steel lap joint mainly depends on the layer of Al–Fe intermetallic compounds (IMCs) formed at the interface [14]. In general, the thin layer of IMCs is beneficial to obtain the high strength of the hybrid joint, but the excessively growing thick layer of IMCs becomes an obstacle to further enhance the interface bonding [15]. When the joint is loaded, the crack is easy to initiate and expand along with the thick brittle layer of IMCs, which leads to the decrease in joint strength [16].

The process parameter optimization is the accessible method to control the thickness of the layer of Al–Fe

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Table 1: Elemental compositions of alloy materials in weight (wt%)

Alloys	Al	Mg	Si	Cu	Mn	Cr	Ni	C	Fe
6061-T6	Bal.	0.70–0.80	0.40–0.50	0.18	0.08	0.06	—	—	0.19
301L steel	—	—	1.00	—	2.00	16–18	6–8	0.03	Bal.

IMCs. The studies of Boumerzoug and Helal [17] and Ibrahim *et al.* [18] showed that the relatively low heat input is the reason for the thin layer of Al–Fe IMCs, which contributed to the joint strength improvement. In addition, introducing zinc element by adding zinc interlayer or using galvanized steel is proved as an available method to inhibit the formation of Al–Fe IMCs [19]. In FSLW, thanks to its high automatic feature, it is feasible to apply auxiliary processes in the welding process. It has been proved that the ultrasonic vibration can effectively improve the atomic diffusion and the material flow during welding [20], and this ultrasonic assisted friction stir lap welding (UaFSLW) technique has been successfully applied in the joining of aluminum/magnesium alloys [21] and aluminum/titanium alloys [22]. However, the researches on the surface morphology, microstructure, and mechanical properties of aluminum/steel hybrid joint by UaFSLW are insufficient [23].

In this study, the UaFSLW of 6061-T6 aluminum and 301L steel alloys was carried out. The strong plastic flow of the upper aluminum material at the interface was achieved by the dual effects of mechanical stirring and ultrasonic vibration, which aimed at improving the metallurgical bonding of dissimilar material interface,

controlling the formation of Al–Fe IMCs and then obtaining high-quality hybrid joint. This study is meaningful for expanding the applications of light alloy materials and the FSW technique in the industries.

2 Experimental procedure

In this study, 6061-T6 aluminum alloys and SUS301L austenitic stainless steel alloy plates were the base materials to be welded, and the material compositions are presented in Table 1. The dimensions of the plates were $180 \times 150 \times 2$ mm. The UaFSLW process diagram is shown in Figure 1a. The aluminum alloy plate was placed on the top of the steel plate for lap welding, and the ultrasonic system consisting of ultrasonic generator and horn was applied to the bottom surface of the 301L steel plate. The ultrasonic frequency was set as 20 kHz, and the ultrasonic power was 2,000 W. The adopted welding tool is shown in Figure 1b. The shoulder diameter and the pin length of the welding tool were 15.0 and 1.7 mm, respectively. In this study, the non-threaded pin was used. In the welding process, the shoulder plunge depth was

Figure 1: Images of (a) UaFSLW process diagram, (b) welding tool geometry, and (c) joint cross-sectional diagram.

selected as 0.15 mm, so the pin tip has a close distance of 0.15 mm away from the lap interface, as shown in Figure 1c. The distance between the pin tip and the interface has a great influence on the joining of the interface. In this study, the displacement control mode of the equipment can ensure the accuracy of this distance and its uniformity along the weld during the welding process.

The welding speed was set as 20 mm/min, and the rotational speeds were selected as 1,500 and 1,800 rpm in this study. After welding, the metallographic specimens and tensile samples were taken along the direction perpendicular to the weld, and the tensile sample was fabricated according to the standard of ISO 4136 [24]. The joint microstructure and mechanical properties were observed and tested by the Olympus-GX71 optical microscope and the Instron-8801 tensile testing machine, respectively. The interface elements were analyzed by the scanning electron microscope (SEM) with an energy dispersive X-ray spectrometer. After the tensile test, the fracture morphology of the joint was observed by the SEM.

3 Results and discussion

3.1 Joint surface morphology

The joining mechanism of aluminum/steel hybrid joint without tool pin penetration is mainly the interfacial metallurgical bonding, and the previous experiments in our research group showed that sufficient heat generation

and welding time were essential for the hybrid joint strength. Therefore, the welding parameter configuration of high rotational speed and low welding speed was selected to ensure stable and reliable welding of hybrid joint.

The joint surface morphologies are shown in Figure 2. In general, under the selected welding parameters, the welding heat inputs are adequate, and the sufficient material flows result in the well-formed joint surfaces with clear arc lines. In FSLW joints welded under 1,500 and 1,800 rpm (Figure 2a and c), uneven flashes appear on the advancing side (AS) and retreating side (RS) of the weld. For the UaFSLW process, the flashes are uniform, and the joint surfaces present relatively smooth features (Figure 2b and d). Ultrasonic vibration has the effect of reducing the material flow stress, which is helpful to improve the joint surface quality [25].

3.2 Cross sections and microstructures

The typical cross section of UaFSLW joint under 1,800 rpm is shown in Figure 3a. According to the uneven thermal-mechanical cycles experienced by materials in different zones, the upper aluminum material in the joint can be generally divided into shoulder-affected zone, pin-affected zone (PAZ), thermo-mechanically affected zone, and heat-affected zone. The joint lap interface remains flat because no penetration of the interface occurs during welding. The lap joining mainly depends on the metallurgical bonding between dissimilar materials at the lap

Figure 2: Joint surface morphologies obtained under 1,500 rpm of (a) FSLW and (b) UaFSLW; under 1,800 rpm of (c) FSLW and (d) UaFSLW.

Figure 3: (a) Joint cross section under 1,800 rpm by UaFSLW; PAZ bottom regions under 1,800 rpm by (b) FSLW and (c) UaFSLW.

interface below PAZ. During welding, the violent mechanical stirring driven by the rotational tool pushes the plasticized aluminum material to downwards flow to the lap interface, which has an active effect on the interfacial joining. As shown in Figure 3b and c, the distance L_s between the PAZ bottom and the lap interface is 31 μm at 1,800 rpm by FSLW, and the L_s is 15 μm at 1,800 rpm by UaFSLW. The ultrasonic vibration significantly promotes the material flow [26], and the enlarged PAZ area under the pin tip is beneficial to enhancing the interface joining.

As shown in the microstructures of the joint in Figure 4, along with the lap interface, the thickness of the layer of IMCs is constantly changing, so the thickness values for different positions are different. In this study, Image J software was used to measure the thickness of the layer of IMCs at an interval of 10 μm along with lap interfaces made by different parameters, and the average of 10 measured values was taken. As shown in Figure 4a and c, the layers of Al-Fe IMCs with the average thicknesses of about 5 and 10 μm are observed under 1,500 and 1,800 rpm by FSLW, respectively. This indicates that the Al-Fe IMCs grow heavily with the increase in heat input, resulting in the thicker layer of IMCs under 1,800 rpm. Under UaFSLW, the average thicknesses of the layer of IMCs at 1,500 and 1,800 rpm are 2 and 6 μm , respectively, as shown in Figure 4b and d. The ultrasonic vibration enhances the material plastic flow of aluminum alloy at the PAZ bottom and then restrains the formation of a continuous thick layer of IMCs at the interface. Besides, the ultrasonic vibration can smash the layer of IMCs, forming the separated IMC fragments close to the thin layer of IMCs, as shown in Figure 4b.

The assisted ultrasonic can promote the atomic diffusion and then thicken the layer of Al-Fe IMC, whereas in this study, a thinner layer of IMC is observed by UaFSLW both at 1,500 and 1,800 rpm. It is considered that the strong plastic flow close to the interface induced by ultrasonic smashes away the IMC fragments during

Figure 4: Joint interfacial microstructures obtained at 1,500 rpm by (a) FSLW and (b) UaFSLW, at 1,800 rpm by (c) FSLW and (d) UaFSLW; (e) element analysis by SEM line scanning of interface marked in (d).

the dynamic formation process of Al-Fe IMCs, and this effect is greater than the thickening effect on the layer of IMC caused by the atomic diffusion. The path perpendicular to the interface of UaFSLW joint is selected for the element line scanning analysis, as shown in Figure 4d. It is found that the element concentration at the lap interface shows a gradual trend because of atomic diffusion behavior (Figure 4e), and the layer of IMCs is distributed on both sides of the aluminum and steel alloys. Most of the layer of IMC is located on the aluminum side, and the thickness of the layer of IMCs at the steel side is relatively thin. Along the selected scanning line, the concentration of the two elements changed alternately. According to the previous studies of van der Rest et al. [27] and Movahedi et al. [28], the layer of Al-Fe IMCs at the interface is mainly composed of FeAl_3 close to the aluminum alloy side and Fe_2Al_5 close to the steel alloy side.

3.3 Joint tensile property and fracture behavior

Three tensile specimens of joint under each welding condition were used to perform the tensile test, and their average tensile loads and standard deviations of measurements were calculated for analyzing. The tensile loads under different welding conditions are displayed in Figure 5. The tensile load of the FSLW joint at 1,500 rpm is 15.3 kN. The tensile load of the UaFSLW joint at 1,500 rpm is 17.4 kN, which is 13.7% higher than that of the FSLW joint. At 1,800 rpm, the UaFSLW joint has a tensile load of 16.5 kN, which presents an obvious increase of 27.9% compared to the 12.9 kN of FSLW joint. In fact, there is no linear relationship between the thickness of the layer of Al-Fe IMC and the tensile load of aluminum/steel

hybrid joint. Generally, the existence of the layer of IMC is beneficial to the joint strength when the IMC is reasonably thin. However, with the excessive increase in the IMC layer thickness, the joint strength will be deteriorated [14]. The joint-strength improvement rate of UaFSLW to FSLW at 1,800 rpm is higher than that at 1,500 rpm, which is related to the effective thinning of the layer of IMCs under higher welding input condition.

The fracture paths of the joints under 1,800 rpm by FSLW and UaFSLW are shown in Figure 6a and b. The upper aluminum plate bears the tensile force from the AS, and the cracks are initiated at the regions of lap interface at the AS where the effective bonding is not formed. The cracks propagate rapidly along the layer of IMCs at the lap interface to the RS, resulting in the joint failure. The stress concentration is more likely to occur at the interface of the hard and brittle layer of IMCs and the aluminum alloy side, because of the greater difference of physical properties between these two heterogeneous materials. In the process of joint fracture, the boundary between the hard and brittle layer of IMCs and the aluminum alloy side is more prone to induce crack propagation [29]. According to the research by Chen et al. [30], local deformation occurs in the tensile specimen under the external tensile load, and then the tensile load on the

Figure 5: Joint tensile properties by different processes.

Figure 6: Joint fracture paths under 1,800 rpm by (a) FSLW and (b) UaFSLW; (c) the typical fracture diagram during the lap-shear test.

Figure 7: Joint fracture morphologies in (a) position A in Figure 6(a) by FSLW, and (b) position B in Figure 6(b) by UaFSLW.

layer of IMCs is increased. As the typical fracture diagram shown in Figure 6c, during the lap-shear test, the non-parallel and opposite tensile forces provide a torque effect to the lap joint, which drives the bending and then the

local deformation of the interface. This effect aggravates the stress concentration on the interface between the layer of IMCs and the aluminum alloy. Therefore, the crack easily initiates and then quickly propagates along this boundary, thus resulting in the shear fracture of the joint.

As the fracture path is located at the boundary between the aluminum alloy plate and the Al–Fe IMCs, the fracture morphologies as shown in Figure 7 are observed on the steel alloy side at positions A and B marked in Figure 6a and b. Figure 7a shows the fracture morphology of the FSLW joint, which presents the typical brittle fracture features of the thick IMCs. The diffusion rate of dissimilar materials at the interface of the UaFSLW joint has been enhanced, and the adequate element diffusion increases the metallurgical bonding of the interface [31,32]. Therefore, the shear

Figure 8: Diagrams of interfacial joining of dissimilar aluminum/steel alloys: (a) UaFSLW process and (b) FSLW process.

fracture of the UaFSLW joint leaves the thin and dispersive IMCs in its fracture morphology of Figure 7b. This indicates that the ultrasonic vibration inhibits the formation of continuous layer of IMCs and also improves the metallurgical bonding at the interface.

3.4 Interfacial joining enhancement in aluminum/steel UaFSLW

For the non-penetration FSLW of aluminum/steel alloys, the tensile properties of the joint deeply depend on the metallurgical bonding of dissimilar materials at the interface. The material flow close to the lap interface driven by the rotational pin tip accelerates this effect, which can produce fine grains and ensure to attain an effective diffusion bonding. However, because the welding temperature satisfies the thermodynamic condition of Al-Fe metallurgical reaction, the atomic interactive diffusion leads to the formation of Al-Fe IMCs. Generally, the thin and smashed IMCs are conducive to improving the joint strength [14], but the excessively thick layer of IMCs provides a crack propagation path when the joint is tensile loaded. Therefore, enhancing the material flow and controlling the layer thickness of Al-Fe IMCs are both important to attain the high-quality hybrid joint. As shown in Figure 8, the material flow in UaFSLW is strongly enhanced by the dual effects of mechanical stirring and assisted ultrasonic vibration. On the contrary, the assisted ultrasonic also promotes the atomic diffusion. Because of the dominant effect of strong plastic flow, some of the thick IMC layer at the aluminum side is smashed into IMC fragments, and the thickness of IMC layer is kept in a thin status which is beneficial to the enhancement of aluminum/steel hybrid joint strength.

4 Conclusions

To achieve high-quality aluminum/steel hybrid joint, 6061-T6 aluminum and 301L steel alloys were lap joined by UaFSLW. Meanwhile, the surface morphology, microstructure, tensile property, and fracture behavior of the hybrid joint were investigated, and the brief conclusions can be drawn as follows:

- (1) The surface of aluminum/steel UaFSLW joint was well formed with uniform flashes and even arc lines. The assisted ultrasonic enhanced the fluidity of the material near the pin tip in UaFSLW, and the distance

between the PAZ bottom and the interface was shortened compared to that of the conventional FSLW joint.

- (2) The strong plastic flow of the aluminum material on the joint lap interface driven by the dual effects of mechanical stirring and ultrasonic vibration inhibited the excessive growth of the layer of Al-Fe IMCs. At 1,800 rpm, the average thickness of the continuous layer of IMCs was reduced from 10 μm by FSLW to 6 μm by UaFSLW.
- (3) In the tensile test, the joints shear fractured along the lap interface. The tensile load of the UaFSLW joint under 1,800 rpm reached 16.5 kN, which was an increase of 27.9% compared to that of the conventional FSLW joint.

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