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Effect of lap configuration on magnesium to aluminum friction stir lap welding assisted by external stationary shoulder

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ABSTRACT

In the present study, friction stir lap welding (FSLW) assisted by external stationary shoulder was firstly used to weld magnesium to aluminum alloys. Effects of the assisted stationary shoulder on joint surface appearances, cross-sections, microstructure and mechanical properties were mainly studied. Lap joints using different lap configurations were also discussed. Results show that lap joints with smooth surface and very small flash can be obtained by the assisted stationary shoulder. When using different sheet configurations, joint cross-section morphologies and microstructure changed significantly. The main intermetallic compounds (IMC) formed in the stir zone (SZ) boundary on the Al/Mg joint is $Al_{12}Mg_{17}$. The main IMC formed in the Mg/Al joint SZ is Al_3Mg_2. With increasing the welding distance, tunnel defect appears in the Al/Mg joint. Lap shear failure load of the Mg/Al joints are much bigger than that of the Al/Mg joints. All the lap joints present shear failure and dimples can be observed on all joints.

1. Introduction

To produce more economical and better mechanical vehicles, lightweight materials such as aluminum (Al) alloys and magnesium (Mg) alloys have been increasingly used in automotive industries in the last few decades [1,2]. Consequently, the joining technologies of Al to Al alloys, Mg to Mg alloys and dissimilar Al to Mg alloys have gained more and more attentions [3]. Fusion welding technologies, which always accompanies with solidification cracking, porosity and high residual stress, are not suitable for joining Al or Mg alloys [4]. Besides, attempts using fusion welding for joining Al/Mg alloys were unsuccessful for formation of brittle intermetallic compounds (IMCs). IMC, which always owns higher hardness and lower ductility, is one of the important factors influencing the strength of the dissimilar alloys joint [5–8].

As a solid-state joining technology, friction stir welding (FSW) was invented by The Welding Institute, UK in 1991 [9]. Owning advantages of smaller distortion, less energy consumption and less welding defects, FSW is more suitable to join Al and Mg alloys [10,11]. In terms of the joint sheets arrangement, FSW can be classified into friction stir butt welding and friction stir lap welding (FSLW) [12]. Since invented, FSW has been extensively utilized for joining Al to Al alloys [13–15], Mg to Mg [16–17] alloys and Al to Mg alloys [18–25]. Especially, dissimilar Al to Mg FSW joints have become the hotspot recently [25]. Kostka et al. [18] found that the 1 μm IMC layer formed in the Al/Mg FSW joint mainly consisted of fine-grained $Al_{12}Mg_{17}$ phase. Mohammadi et al. [19] reported that the tapered threaded pin was beneficial to obtain sound Mg to Al joint with better mechanical properties. Firouzdor et al. [6] showed that IMCs formed in the stir zone (SZ) and significantly reduced the joint strength. They also reported that the IMC formation was due to liquated material solidification instead of the solid state diffusion. Mofid et al. [7] found out that the IMC was significantly reduced under liquid nitrogen because of lower temperature. Furthermore, Liang et al. [8] found three weak zones in the Al/Mg FSW joints: (1) Al/Mg bottom interface, (2) banded structure zone and (3) softened Al alloy on the retreating side (RS).

According to the republished papers, lots of published papers used Mg alloy as the upper sheet in FSLW joints or friction stir spot welding (FSSW) joints [4,5,18,19], while few used Al alloy as the upper sheet [6,20]. Shen et al. [21] reported that when the Mg alloy sheet was placed as the upper sheet, FSSW joint owned better mechanical properties. Rao et al. [4] placed AM60 Mg alloy as the upper sheet during FSSW and found out that bigger lap shear failure load was attained when using lower rotating speed. Mohammadi et al. [5] reported that during FSLW of Al to Mg alloys, different welding speeds significantly changed the SZ microstructure. Firouzdor et al. [6] used 6061 Al alloy as the upper sheet and crack can be observed in the joint center. Chen et al. [20] used AC4C Al alloy as the upper sheet during FSLW and discovered that a lower welding speed improved the joint strength.

Stationary shoulder FSW (SSFSW) was initially invented to weld titanium alloy in order to overcome the uneven temperature distribution during welding [26]. Compared with traditional FSW, SSFSW owns a ~30% lower heat input and therefore resulted in a reduced heat affected zone (HAZ) width [27]. In recent years, SSFSW has been extensively

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applied to weld many kinds of Al alloys [29–34]. Stationary shoulder can diminish flash and eliminate groove by preventing plastic material from escaping out of the joint. Besides, Li et al. [34] found out that the assisted stationary shoulder can significantly increase joint bonding width and mechanical properties of the FSLW joints. However, so far, studies about stationary shoulder FSLW of Al to Mg alloys have not been reported yet.

In the present study, stationary shoulder technology is applied to fabricate Al to Mg alloys lap joint. The focus is concentrated on effect of the assisted stationary shoulder on joint surface appearance, microstructure and mechanical properties of the lap joints. Influence of sheet configuration was also discussed. Microstructure features and elemental distribution were studied. Lap shear failure load test was used to investigate the joints qualities.

2. Methods and experiments

2.1. Methods

6061 Al alloy and AZ31 Mg alloy were chosen as the research objects. Dimensions of all sheets were 300 mm × 140 mm × 3 mm. Two sheets were lap combined with a width of 50 mm. For convenience, the lap joint, which AZ31 Mg alloy is placed as the upper sheet, is called the Mg/Al joint, as shown in Fig. 1a. Accordingly, the Al/Mg joint refers to the joint which 6061 Al alloy is placed as the upper sheet, as shown in Fig. 1b. All the lap joints were welded according to B configuration, which means that the RS bears the load during the lap shear tests

The FSW-3LM-4012 machine was used during the FSLW experiment. The stationary shoulder system includes an inner rotating tool and an external stationary shoulder. During SSFSW, void can be observed when using lower rotating speed [35]. Hence, the inner rotating shoulder is mainly used to increase heat input during welding. The detailed geometries of the assisted external stationary shoulder system are shown in Fig. 2.

2.2. Experiment

Prior to welding, all sheets were cleaned with emery paper to wipe off the oxidation layer. Then the lap joints were welded along the center line of the overlap area. Constant rotating and welding speeds of 1000 rpm and 20 mm/min were chosen during welding. Tilting angel of the tool axis was 2.5° during the experiment. Shoulder plunge depth was 0.2 mm. After welding, metallographic samples and lap shear specimens were cut perpendicular to the joint using an electrical discharge cutting machine. Width of the lap shear specimens is 35 mm. The metallographic specimens were burnished, polished and then etched with 5 ml acetic acid, 10 ml distilled water, 4.2 g picric acid in 100 ml ethanol for 10 s to reveal the microstructure of the AZ31 Mg alloy. Metallographic analysis was carried out on optical microscopy (OM, Olympus-GX71). The joint microstructure and elemental distribution were analyzed by a scanning electron microscopy (SEM-SU3500) equipped with an energy-dispersive X-ray spectroscopy (EDS) analysis system. Moreover, XRD analysis was carried out for examining the IMCs in the SZ. Lap shear tests were performed on a computer-controlled universal tensile testing machine using a constant speed of 5 mm/min. After the lap shear tests, fracture positions of the specimens were observed using a stereoscopic microscope (ZSA403) and fracture surfaces were analyzed using SEM.

3. Result and discussion

3.1. Joint surface appearances

Fig. 3 shows the surface appearances of the lap joints using different sheet configurations. It can be seen that both joint surfaces are smooth. No arc corrugation and other surface defects can be observed. Due to non-rotating, the rear part of the stationary shoulder brings a scraping effect on the joint surface, which is beneficial to eliminate the arc corrugation. Smooth joint surfaces are therefore attained. Moreover, the external stationary shoulder exerts a big forging force on the joint surface, which is beneficial to the joint formation [27].

On the Mg/Al joint, relative big flash can be observed near the keyhole region. The flash morphology is very much like the flash in ref [31]. Very small flash can be observed along the joint edge, as shown in Fig. 3a. On the Al/Mg joint, very small flashes can be observed along the joint edge and near the keyhole, as shown in Fig. 3b. During the traditional FSW or FSLW process, plastic material is driven by the inner rotating tool to flow from the advancing side (AS) to the RS. Some material is squeezed out of the joint, forming flash [34]. In the present study, the external stationary shoulder effectively prevents plastic material from escaping out of the joint, reducing the flash [34]. However, the stationary shoulder cannot collect 100% of the material. Hence, very small

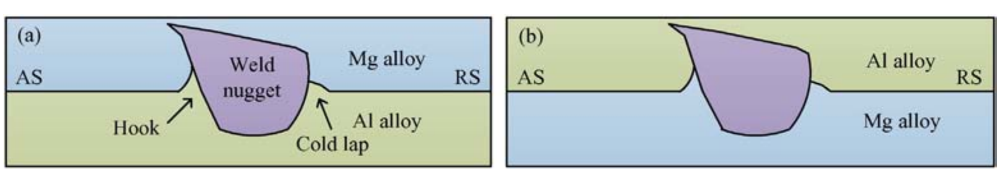

Fig. 1. Joints configuration in the present study: (a) Mg/Al joint and (b) Al/Mg joint.

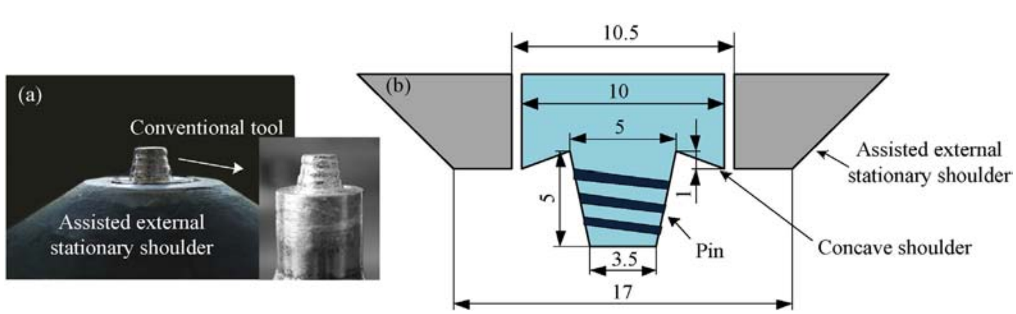

Fig. 2. The assisted external stationary shoulder: stationary shoulder system (a) and its dimensions (b).