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Influencing mechanism of Zn interlayer addition on hook defects of friction stir spot welded Mg–Al–Zn alloy joints

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ABSTRACT

2.4 mm thick Mg–Al–Zn alloy sheets were friction stir spot welded (FSSW) without and with the addition of 0.1 mm thick Zn interlayer. The influence of interlayer addition on the microstructural features and mechanical properties of FSSW joints was investigated by optical microscope, scanning electron microscope, transmission electron microscope, X-ray diffraction and tensile testing. The results show that the addition of Zn interlayer resulted in complex alloying reactions between Mg substrate and Zn interlayer, forming a bonded zone composed of α-Mg, (α-Mg + MgZn) eutectoid structure and a mixture of Mg_4Zn_7 and unreacted Zn, thereby increasing the area of bonded zone and reducing the hook defects. This results in a significant increase in tensile–shear load from 2.4 kN to about 4 kN.

1. Introduction

Magnesium alloys are excellent candidates for lightweight structural applications in the automotive and aerospace industries due to their low density, high specific strength and acceptable ductility [1]. However, they are difficult to weld by conventional fusion welding techniques due to the active behavior of Mg. This problem could be solved by friction stir welding (FSW) that is a solid-state joining technique [2–5].

In FSW, friction stir lap welding (FSLW) is the most common weld configuration for automotive and aerospace industries [6,7]. Especially, friction stir spot welding (FSSW) is one of the most important FSLW [8,9]. However, a characteristic feature of FSSW is the formation of a geometrical defect originating at the interface between the two welded sheets, called as hook defect [10]. The presence of hook defects in the weld zone decreases the integrity of the bonded region and thus significantly reduces the weld strength since the failure (crack propagation) occurs along the hook line.

For FSSW of Mg alloys, the effect of hook defects on the joint load has attracted much attention in recent years [11]. Many studies focused on changing the dimensions and curvatures of the hook by the optimization of process condition and tool geometry. However, the formation of hook defects could not be completely avoided in the FSSW joints [11–13]. In order to reduce the effect of the hook defects and enhance the load of joints, some hybrid FSSW methods were applied to the Mg alloys, such as bonding-FSSW [14] and FSSW with a heating process [15].

For the bonding-FSSW of AZ31 Mg alloy, the area of bonded zone of joints was increased by adhesives, so the load of joints was improved [14]. However, the aging and poor high-temperature performance of adhesives were the main drawbacks for this process. For the FSSW AZ31 Mg alloy with a heating process, the area of the bonded zone was increased remarkably by heating the joints in the FSSW process [15]. However, the troublesome operation limited its wide application. In fact, above two hybrid technologies increased only the area of bonded zone, but could not avoid the appearance of hook defects. Therefore, new processes are still needed for reducing the hook defects of FSSW Mg alloy joints.

According to the Mg–Zn phase diagram [16], Zn could react with Mg at a low temperature, forming the Mg–Zn intermetallics. Therefore, the idea of reducing the hook defects by the alloying reaction was proposed with Zn as the alloying element. Prior to FSSW, Zn interlayer was added at the interface between two welded Mg sheets with the aim to promote the bonding of faying surface of Mg sheets and reduce the formation of hook defects, thereby improving the load of FSSW joints.

In this study, 2.4 mm thick AZ31 and AZ80 sheets were FSSWed with the combinations of AZ31–AZ31, AZ31–AZ80 and AZ80–AZ80 and the influencing mechanism of Zn interlayer addition on the hook defects of FSSW joints was in detail investigated.

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2. Experimental details

The substrate materials used in the present study were 2.4 mm thick sheets of hot-rolled AZ31 Mg alloy with a composition of Mg–3.02Al–0.82Zn–0.30Mn–0.01Si (wt.%) and hot-rolled AZ80 Mg alloy with a composition of Mg–8.00Al–0.33Zn–0.25Mn–0.036Si (wt.%). The schematic of FSSW without and with the addition of Zn interlayer is shown in Fig. 1. Before welding, the sheets were ground by the $800^{\#}$ SiC paper, and then cleaned by acetone. For the FSSW with the Zn interlayer, 0.2 mm thick pure Zn interlayer was added between two welded Mg sheets prior to the welding operation. All the FSSW operations with and without the interlayer were conducted at a tool rotational rate of 3000 rpm and a plunge rate of 2.5 mm/s using a tool with a concave shoulder 10 mm in diameter and a threaded cylindrical pin 4 mm in diameter and 3.8 mm in length. The tool withdrawing rate was 30 mm/s at the end of each spot welding operation and the dwell time was 5 s.

The temperature profile of the interface zone during FSSW was measured by a K-type thermocouple 0.5 mm in diameter. A cylindrical hole 0.8 mm in diameter and 2.3 mm in length was machined in the bottom sheet of Mg alloy and a thermocouple was fastened at the top of the hole by high temperature glue. The schematic of temperature measurement is shown in Fig. 1c.

Specimens for microstructure examinations were sectioned through the center of the welded joints and parallel to the loading direction. After being mechanically ground and polished, the specimens were etched with an etching reagent consisting of 4.2 g picric acid, 10 ml acetic acid, 10 ml H_2O and 70 ml ethanol. Microstructures were examined by optical microscope (OM), scanning electron microscope (SEM, LEO Supra 35) with the energy dispersive spectrometer (EDS) and transmission electron microscope (TEM, Tecnai F20). The material of Mg–Zn interface zone in FSSW AZ31 joints was prepared into powders and then subjected to X-ray diffraction (XRD) analysis using Cu Kα radiation.

The lap-shear specimens with a length of 100 mm, a width of 30 mm and a 30 × 30 mm overlap area were electrical discharge machined from the FSSW joints. The lap-shear tensile tests were conducted using a Zwick/Roell Z050 tester at a tensile speed of 1 mm/min. The rolling direction was perpendicular to the shear tensile testing direction. The property values for each condition were calculated by averaging three test results. The fracture characteristics were examined using SEM.

3. Results and discussion

3.1. Microstructure of FSSW Mg alloy joints without the addition of Zn interlayer

Fig. 2a–c shows the typical cross-section photographs of the FSSW AZ31–AZ31, AZ31–AZ80 and AZ80–AZ80 joints without the addition of Zn interlayer, respectively. The hook defects were all detected in three spot joints, which further proved that the hook defects were easy to form in the FSSW Mg alloy joints. The average height of hook of three joints is 0.62, 0.68 and 0.72 mm, respectively.

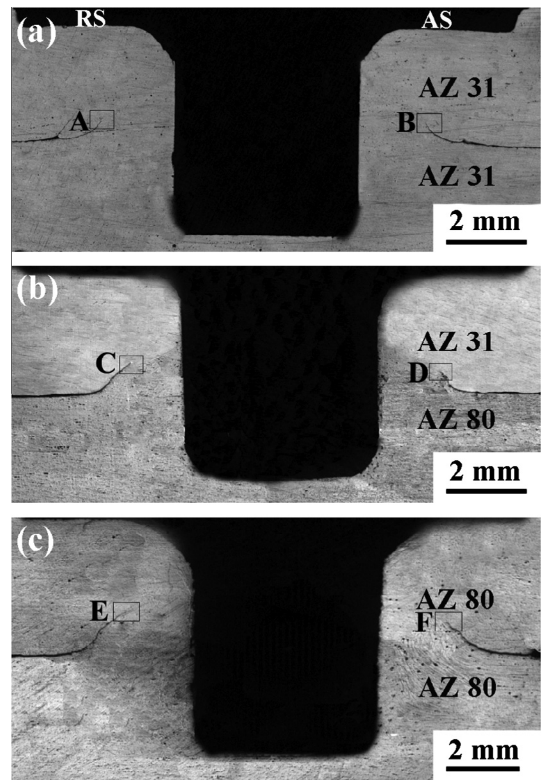

Fig. 2. Typical cross-section photographs of joints without the addition of Zn interlayer: (a) AZ31–AZ31, (b) AZ31–AZ80 and (c) AZ80–AZ80.

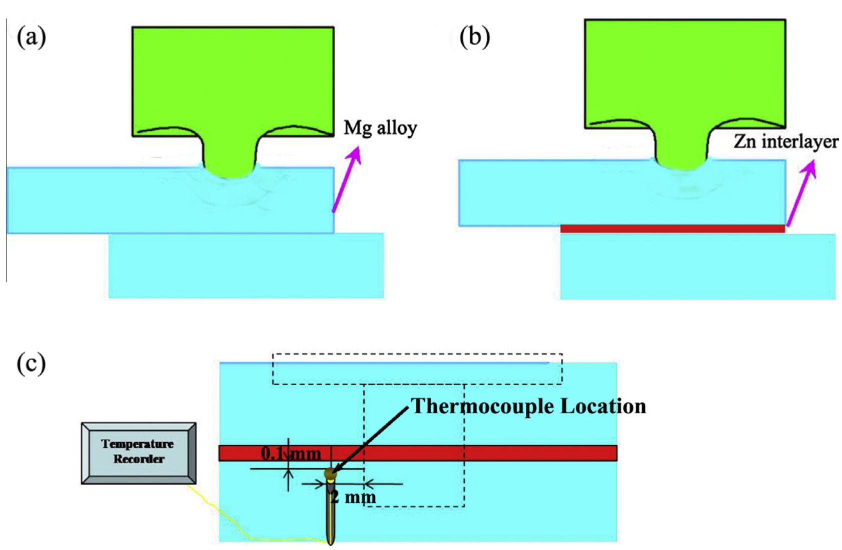

Fig. 1. Schematics of FSSW (a) without and (b) with the addition of Zn interlayer and (c) the position of temperature measurement.