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Influencing mechanism of Al-containing Zn coating on interfacial microstructure and mechanical properties of friction stir spot welded Mg–steel joint

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ABSTRACT

2.4 mm thick AZ31 Mg alloy sheet and 1.5 mm Q234 steel sheet with a hot-dipped Al-containing Zn coating were friction stir spot welded (FSSW) using a pinless tool. It was shown that the Al-containing Zn coating played a crucial role in joining the Mg alloy and steel during FSSW. The Zn coating observably improved the Mg–steel interfacial wettability during FSSW, and the Al_5Fe_2 phase in the Zn coating on the steel substrate surface promoted the metallurgical bonding of Mg alloy and steel. It was confirmed that the Al_5Fe_2 phase on the steel surface resulted from the reaction between the steel substrate and the Al in the Zn coating during hot-dipping, and was not related to the Al-containing Mg alloy substrate. The tensile-shear load of the FSSW Mg–steel joint reached 4.3 kN. The fracture of the joint occurred along the interface on the steel substrate side. The interface between the Al_5Fe_2 layer and Mg alloy substrate was the weakest region of the Mg–steel joint.

1. Introduction

In order to reduce vehicle weight and to save energy, special attention has been paid to hybrid structural components that take advantage of dissimilar metals [1,2]. In particular, composite structures consisting of ultra-lightweight Mg alloys and steels are considered promising for automotive applications. Among various manufacturing techniques, welding is one of the widely used methods for preparing the Mg–steel composite structures [3–8].

However, the marked differences in the metallurgical and physical properties between Mg alloys and steels, such as considerable melting point difference, almost no intersolubility, and no Mg—Fe intermetallic compound (IMC), resulted in the significantly increased difficulty of Mg–steel welding [9,10]. Previous studies have shown that Mg alloys and steels could be successfully joined using resistance spot welding [11,12], ultrasonic spot welding [13–15], laser welding [16,17], and laser-tungsten inert gas hybrid welding [18]. It was believed that the bond between Mg alloys and steels was achieved through Al—Fe IMCs [11,12,16–18]. Therefore, Al was considered as a necessary alloying element in Mg alloys for successful Mg–steel welds.

In the above-mentioned welding processes, it was reported that Al diffused from the Mg substrate to the Fe surface, thereby creating a metallurgical bonding between Mg alloys and steels by means of reaction between Al and Fe. Therefore, controlling the precipitation of Al from the Mg alloy substrate is a key factor for Mg–steel welding, which undoubtedly increases the difficulty of achieving optimal welds [19,20]. Furthermore, it is considered that the presence of a Zn coating is essential for the elimination of the negative effects of oxides during the welding process [11,18–21].

Friction stir spot welding (FSSW) is a new welding method, developed based on the friction stir welding technique [22,23]. As a solid state joining method, FSSW integrates the advantages of minimal thermal deformation, sound mechanical properties and green welding processes, and therefore has received considerable attention in the welding of dissimilar metals such as Mg alloy and steel [24].

The short heating time and the low heat input make FSSW more energy efficient and cleaner than other spot welding techniques [25,26]. However, the low welding temperature is liable to increase the difficulty of Al diffusion from the Mg alloy substrate to the steel sheet surface [27–29], thereby influencing the Mg–steel metallurgical bonding during FSSW. For example, in the AM60 (upper sheet)–DP600 dual phase steel FSSW joint, there was no evidence of IMC formation, so only a mechanical bond formed between the Mg alloy and steel. In addition, pure Zn coating on the DP600 steel surface did not promote Mg–steel interfacial bonding, but actually increased the cracking at the interface due to the influence of Zn in facilitating local melting [30].

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Table 1
Welding parameters for FSSW of Mg–steel.

Plunge depth (mm)	Plunge rate (mm/s)	Rotation rate (rpm)	Dwell time (s)	Withdrawing rate (mm/s)
1.0	2.5	3000	5.0	3.0

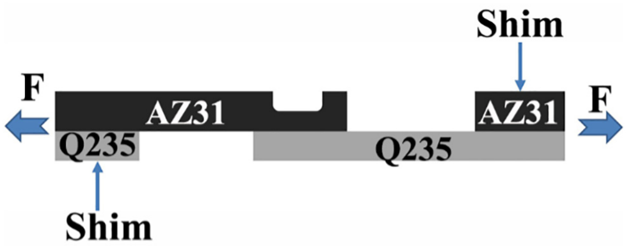

Fig. 1. Schematic of the tensile shear test specimens.

In FSSW, the pressure, reaction temperature and time required by the diffusion reaction among the Mg alloy, coating and steel are provided by the action of the rotation, plunge and dwelling of the stirring tool [31]. Therefore, knowing how to provide the Al element for the interfacial reaction is the key to realizing metallurgical bonding between Mg alloy and steel in FSSW. In fact, in a hot-dip galvanized process, a small quantity of Al is usually added to the Zn coating, forming Al-containing Zn coating [32]. Therefore, Al in the Zn coating may be beneficial to joining of the Mg and steel, thereby improving the mechanical properties of the FSSW joints.

In order to verify the beneficial effect of Al in the Zn coating on the Mg–steel joint, a steel sheet with a hot-dipped Al-containing Zn coating was selected for joining Mg alloy and steel by FSSW, with the goal of realizing the metallurgical bonding of Mg–steel. Pinless FSSW [21] was applied to increase the bonding area of the Mg–steel joint and reduce

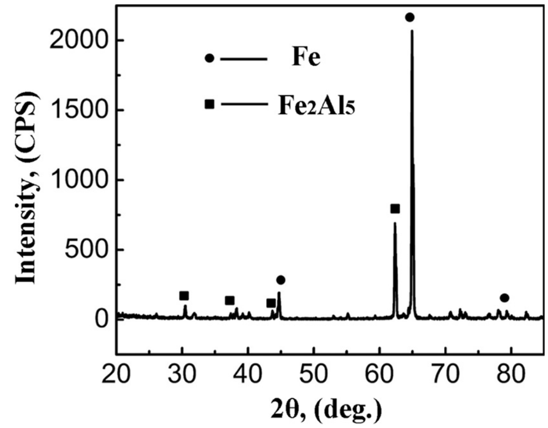

Fig. 4. X-ray result of Zn−Al coated steel surface after etching by fuming HNO_3.

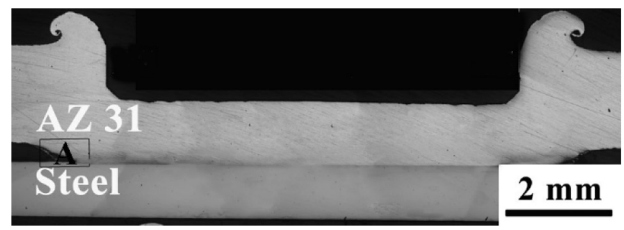

Fig. 5. Typical cross-section photograph of FSSW Mg–steel joint.

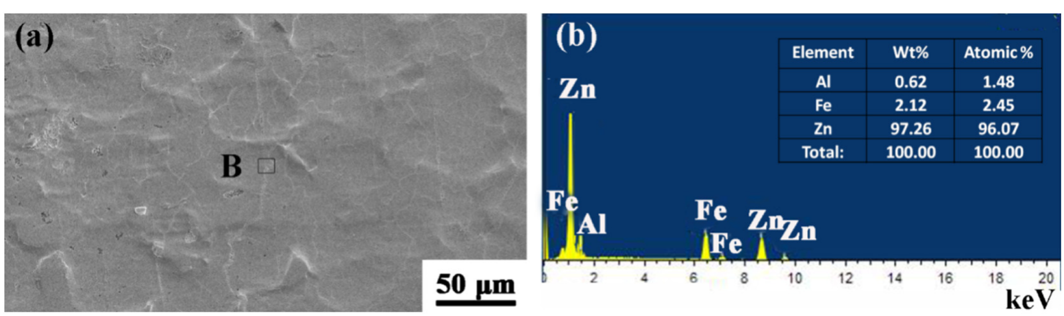

Fig. 2. (a) SEM micrograph of coating surface on Q235 steel and (b) EDS spectra obtained from zone B in panel a.

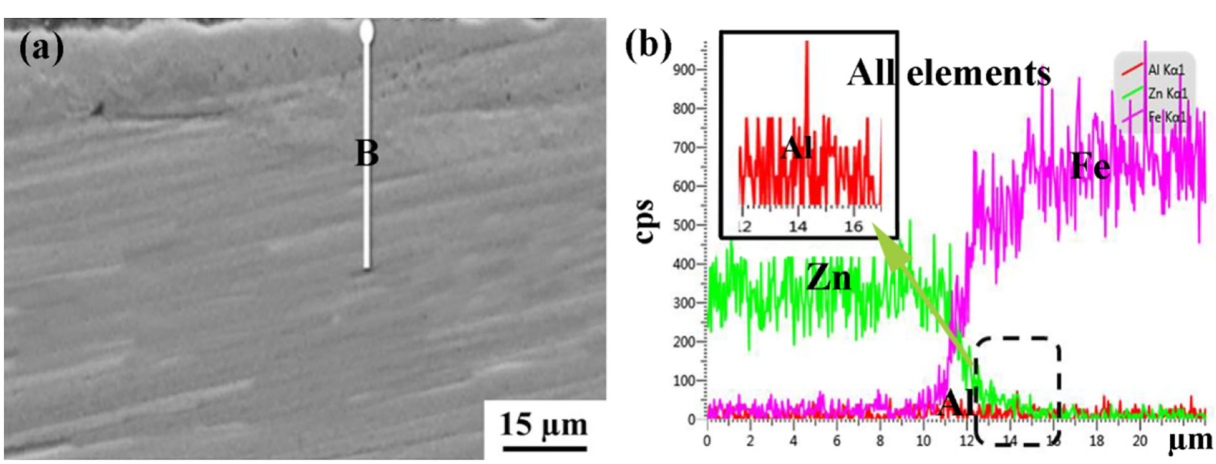

Fig. 3. (a) SEM micrograph of cross-sectioned Zn−Al coated steel and (b) elemental analysis of line B in panel a.