Welding Letters Vol.41 No.4 (2023) p.5 WL-8 WL DOI: 10.2207/qjjws.41.5WL

WELDING LETTERS

Microstructures at the Interface of Al alloy and galvannealed steel jointed by scrubbing refill friction stir spot welding

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Al alloy sheet and galvannealed steel sheet were joined by Sc-RFSSW, and the bonding process was analyzed by observing the microstructure of the bonded interface. The interface was divided into three regions. Al, Zn, and IMC flowed into the GA steel sheet at the interface produced under the inner and outer circumferences of the tool shoulder. Zn and Fe discharged by the scrubbing process were rolled into Al from the anchor at the interface produced under the outer periphery of the shoulder and expelled from the interface.

Key Words: Refill friction stir spot welding, Al alloy, GA steel, EDS, EBSD

1. INTRODUCTION

In recent years, in order to realize a low-carbon society, multi-material vehicle bodies have been actively studied. In the multi-materials, lightweight materials are combined with high-strength materials to reduce weight while maintaining the strength of the car body. In this study, we used Al alloy sheets as lightweight materials, and galvannealed alloy steel sheets (GA steel sheets), widely used in the automobile industry, are used as high-strength materials.

Generally, in joining dissimilar metals, such as Fe and Al, the type[1)], thickness[2)], and uniformity of the intermetallic compound (IMC) formed at the interface dramatically affects the strength of the joint, and controlling the IMC formation process is essential to realize a high-strength joint[3)].

The GA steel sheet used in this study has an alloyed layer of Fe and Zn that is heat-treated to form on the surface. The melting point of the surface layer is higher than that of the hot-dip galvanized steel sheet (GI steel sheet), leading to a different IMC production process during the interface reaction of the GI steel sheet and GA steel sheet to the Al alloy sheet[4)].

When a GI steel sheet and an Al alloy are diffusion-bonded, Zn is expelled to the edges by the production of Al-Zn eutectic melt, and Al and Fe directly react to form an IMC at the interface. In contrast, in the reaction between the GA steel sheet and the Al alloy, Al first diffuses into the coating layer and forms an IMC within the coating layer and between the coating layer and Fe. The thickness of the IMC is almost the same as that of the coating layer and is relatively thick. Thus, high-strength bonding is difficult for the GA steel and Al alloy sheets.

We used scrubbing refill friction stir spot welding（Sc-RFSSW）[5)] for bonding in this study. In RFSSW, the decrease in joint strength due to the reduction in plate thickness is prevented by backfilling the pin holes on the joint surface. Additionally, in Sc-RFSSW, the shoulder in the tool reaches down to the lower plate to stir the material. As a result, the bonding is less likely to be affected by the surface state of the lower plate, and high-strength bonding can be expected.

In this study, we analyzed the interface microstructure around the interface between Al alloy sheets and GA steel sheets joined by Sc-RFSSW. In particular, the morphology of the bonding interface, the reaction layer, and the distribution of Zn was analyzed. We discussed the joining process for controlling IMC production and realizing high-strength joints.

2. EXPERIMENTAL PROCEDURE

The materials to be joined are a 1.6 mm thick Al alloy A6061-T6 sheet and a 1.4 mm thick GA980 sheet. As shown in Fig. 1(a), these two sheets overlapped, and the rotating tool was pressed on the A6061-T6 sheet side. The welding conditions are a rotational speed of 2000 rpm, a holding time of 1 s, and an applied pressure of 13 kN. The bonded specimen was embedded in a resin, and the central part of the joint was cut perpendicular to the interface with a low-speed cutter. The surface of the cross-section of the interface (shown in Fig.1 (b)) was subjected to mechanical and ion polishing for microstructure observation and analyzed by field-emission scanning electron microscope (FE-SEM), energy dispersive X-ray spectroscopy (EDS), and electron backscatter diffraction (EBSD).

3. RESULT AND DISCUSSION

3.1 Morphology of the interface

Fig. 2 shows the overall morphology of a cross-section perpendicular to the bonded interface. The interface was

receivedber: 2023.3.6 ; accepted: 2023.5.30
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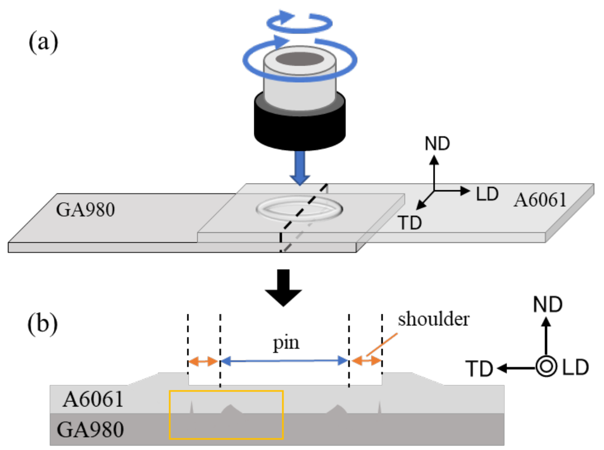

Fig. 1 Schematic of (a) Sc-RFSSW process and (b) cross-section of the bonded specimen.

divided into three regions from the center of the joint toward the outside: the region under the pin, under the shoulder, and outside the shoulder. Due to the plastic flow of Fe, a large anchor (black arrow on the right side in Fig. 2) was formed around the pin, and a small anchor (black arrow on the left side in Fig. 2) was formed around the shoulder. The morphology of the interface was almost flat under the pin, while it was wavy under the shoulder. In Al, three streak-like flows (right yellow arrow in Fig. 2) from the anker and thin white flows (left yellow arrow in Fig. 2) from the interface under the shoulder extended toward the outer region.

In the next section, each region was analyzed in detail.

3.2 Microstructure around the interface

3.2.1 Interface produced under the pin

Fig. 3 shows an SEM image of the interface produced by the pin of Sc-RFSSW. A third phase layer was observed between GA980 and A6061. The thickness of the layer was almost uniform and about 6 μm. A6061, in contact with this layer, showed a white contrast. Cracks and voids were sparsely observed in this region. Fig. 4 shows the elemental mapping of this region. The third phase at the interface contained Fe and Al and was considered to be a Fe-Al IMC formed during bonding. It was also found that the white contrast in A6061 adjacent to the IMC is the enrichment of Zn. Table. 1 shows the results of the chemical composition analysis of each region. The composition of the IMC layer was close to that of $FeAl_6$. When the GA steel sheet and Al alloy sheet were joined by FSSW, Fe_4Al_{13} was frequently observed at the interface[6]. The present experiment shows $FeAl_6$ also formed in the region produced under the pin of Sc-RFSSW.

The thickness of the Zn-enriched region was slightly thicker toward the outer periphery of the pin.

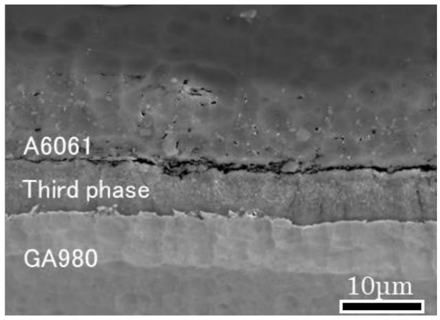

Fig. 3 SEM image of the interface produced under the pin.

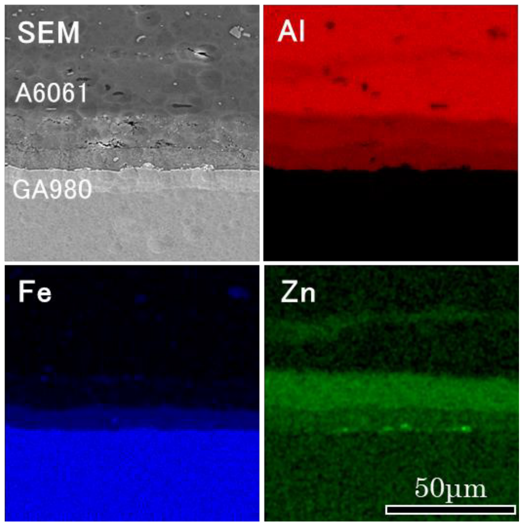

Fig. 4 Chemical mapping around the interface produced under the pin.

Table. 1 Chemical composition of each region.

	Al [at%]	Fe [at%]	Zn [at%]
The Al base	99.76	0.15	0.08
Zinc layer	90.53	0.74	8.74
Reaction layer	79.52	17.14	3.34

The large anchor formed under the outer periphery of the pin is shaped to bend to the pin side slightly, and the small anchor bends to the opposite side. During the bonding, the tool shoulder scrubs the GA980 while the pin is pulled out. It is considered that the anchor tends to bend by the shoulder during the scrubbing process, and the large anchor protrudes to the pin side with the lack of the pin.

3.2.2 Interface produced under the shoulder

At the interface produced by the shoulder, Al significantly flowed into the Fe side, especially at the inner and outer circumferences of the region (blue arrows in Fig.

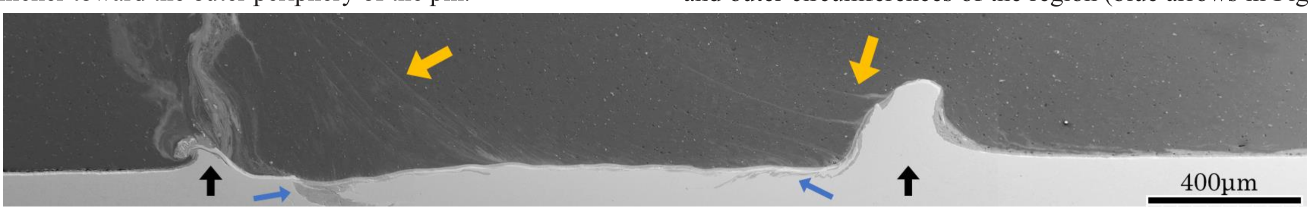

Fig. 2 SEM image of the interface morphology of the area corresponding to the boxed area in Fig. 1 (b).

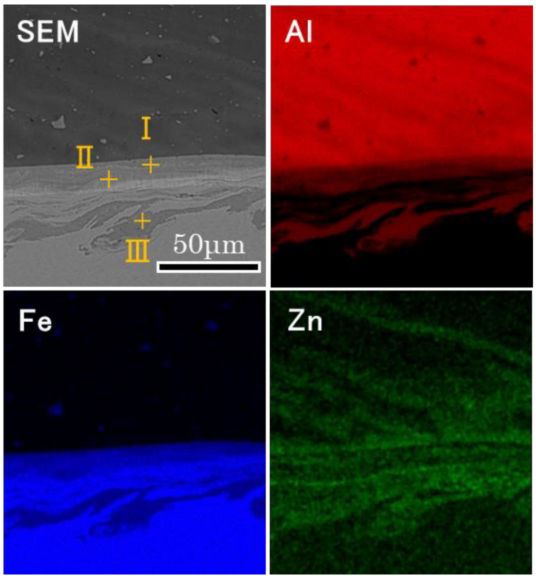

Fig. 5 Chemical mapping around the interface produced under the shoulder.

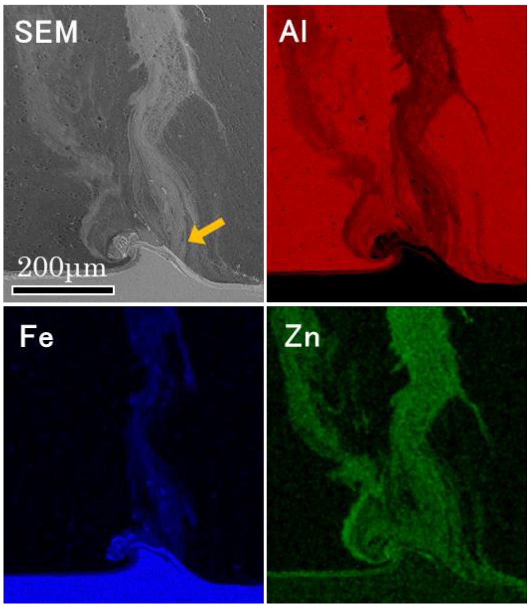

Fig. 6 Chemical mapping around the small anchor.

Table. 2 Chemical composition of each point in Fig. 6.

	Al [at%]	Fe [at%]	Zn [at%]
Ⅰ	77.18	21.37	1.45
Ⅱ	50.36	48.02	1.62
Ⅲ	71.13	25.03	4.84

2). Fig. 5 shows the interface's elemental mapping produced by the shoulder's inner circumference. It was found that Al and Zn flowed into the Fe sheet in layers. The morphology of this layered structure was similar to the one observed in the interface between the GI steel sheet and the Al produced by Sc-FSSW[5]. However, little periodicity was observed in the layers in this experiment. This morphology suggests that the tool holding time, during which the shoulder scrubbed GA980, was as short as 1 s, and there was not enough time for the plastic flow stabilizing, leading to the lack of the periodic structure.

Table 2 is the results of the point analysis of the reaction phase. It showed that the layered structure contains phases with compositions close to FeAl and Fe_4Al_{13}. The white contrast region with Zn extended from the interface into Al, suggesting that Zn was discharged into Al from the galvannealed layer that existed before joining.

Fig. 6 shows the elemental mapping around the small anchor at the interface produced by the outer periphery of the shoulder. Zn and Fe regions rose from the anchor on the interface toward the inside of Al. In a study of joining a GI steel sheet and an Al alloy sheet by RFSSW, Zn was rolled up into Al from the outer periphery of the interface[7]. In this study, Fe was also rolled up from the interface in addition to Zn. During the bonding process, the shoulder scraped the GA980. Produced Fe particles were thought to be stirred and rolled up in the Al.

Unlike the interface produced by the inner periphery of the shoulder, there is no escape for the stirred material at the interface produced by the outer periphery. Therefore, the anchor's size is considered small, and the intercalation of Al into Fe around the small anchor is large, as shown in Fig. 2.

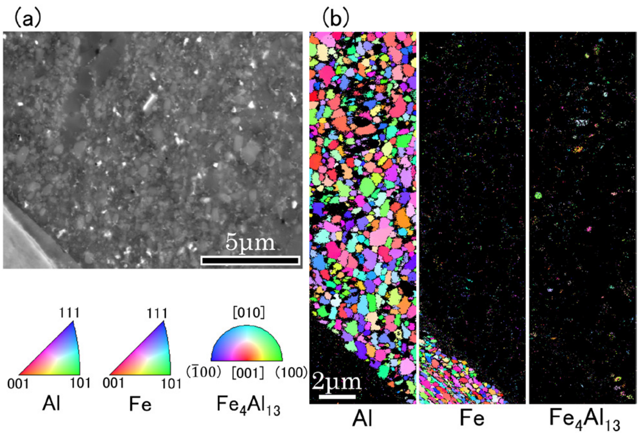

Fig. 7 (a) SEM image of the small particles in the rolled-up region denoted by yellow arrows in Fig. 6 and (b) IPF map.

Fig. 7 (a) shows an enlarged SEM image of the area indicated by the yellow arrow in Fig. 6. Fine particles were observed in this rolled-up region. Fig. 7 (b) are the IPF maps of Al, Fe and Fe_4Al_{13}. Few Fe particles were observed. Since Al, Fe, Zn were present in this region, it is considered that most fine particles were Al-Fe-Zn reaction phases with Fe_4Al_{13} and most Fe particles reacted with Al to form reaction phases.

3.3 Al texture around the interface

Around the large anchor, the texture was observed in Al. Fig. 8 (a) is the IPF map of Al around the anchor. Most Al grains shows the <110> direction to be parallel to the LD direction. Fig. 8 (b) is the pole figure taken from the same region in (a) which is the Al just above the anchor. The {111} plane of the Al was parallel to the TD direction and showed the shear texture around the anchor. In the case of FSW, the {111} plane is strongly oriented perpendicular to the ND direction in the Al stirring region, forming a shear texture in the joint[8]. In the present bonding, shear deformation of Al due to tool rotation is expected to form a shear texture in which the {111} slip plane and <110> slip direction of Al are aligned. The shear texture strongly appeared around the anchor produced by the inner periphery of the shoulder, suggesting plastic flow of the tool rotation is dominant at this region.

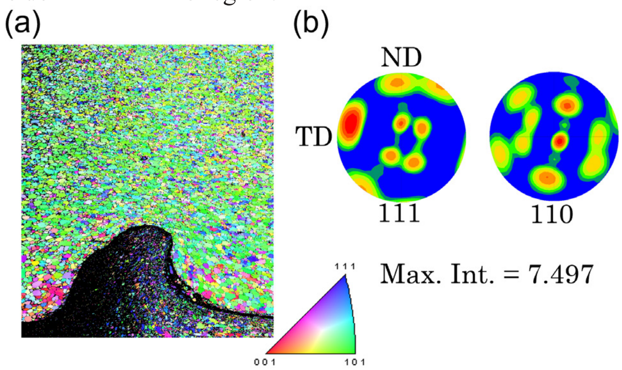

Fig. 8 IPF map around the small anker taken from the LD direction and pole figure.

3.4 Welding process of Sc-RFSSW

Based on the above analysis, the bonding process of Sc-RFSSW was considered as follows. Fig. 9 is a schematic diagram of the process.

First, after the rotating tool contacts the upper sheet to be joined, the shoulder is pressed into the lower sheet, and the pin is withdrawn. Fig. 9-1 shows the schematic configuration just after the shoulder press. An anchor is then formed at the interface under the inner and outer circumferences of the shoulder. The anchor under the inner circumference of the shoulder protrudes significantly. At the interface under the shoulder, Al and Zn flow into the Fe, and the shaved Fe is rolled up with Zn to the outer periphery. An IMC is formed at the interface. Fig. 9-2 shows the backfilling process by the pin. During this process, Zn and IMC are discharged from the interface toward the outer periphery of the tool along with the flow of Al. Al formed a shear texture by the tool rotation. Finally, the tool returns to its initial position, and the bond is achieved.

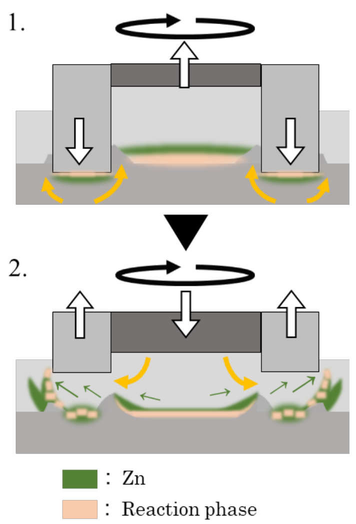

Fig. 9 Schematic of the welding process of Sc-RFSSW.

4. CONCLUSIONS

The following findings were obtained by observing the microstructure of Al alloy, and GA steel sheets joined by Sc-RFSSW.

・The interface was almost flat in the region produced below the pin and had a wavy shape in the region produced below the shoulder. At the interface produced under inner and outer circumferences of the shoulder, Al and Zn flowed into the Fe side in a layered manner.

・A IMC layer was formed at the interface, and the composition was close to $FeAl_6$ and Fe_4Al_{13} phases.

・In Al, Zn flowed from the interface to the outer periphery of the tool. While there is a Zn-enriched layer on the IMC at the interface produced under the pin, Zn was effectively discharged and rolled up into Al at the region produced by the outer periphery of the shoulder.

・A shear texture was formed in Al around the anchor produced by the inner periphery of the shoulder.

Acknowledgments

This research is based on results obtained from a project, JPNP14014, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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