Weld formation mechanism during friction stir spot welding of 6061 Al

Yutaka S. Sato*, Mitsuo Fujimoto**, Natsumi Abe*, Hiroyuki Kokawa*

*Department of Materials Processing, Graduate School of Engineering, Tohoku University, 6-6-02 Aramaki-aza-Aoba, Aoba-ku, Sendai 980-8579, Japan

** System Technology Center, Kawasaki Heavy Industries, Ltd., 3-1-1 Higashi-Kawasaki-Cho, Chuo-ku, Kobe 650-8670, Japan

Abstract

Friction stir spot welding (FSSW), developed based on principle of friction stir welding, has been paid attention as a new solid-state spot welding process. Since FSSW can produce high-quality weld in Al alloys more easily than resistance spot welding, this process has been already used for construction of Al components in the automotive industries. Despite the large industrial interests in FSSW, fundamental knowledge on welding phenomena of this process has not been fully understood. In this study, FSSW phenomena, such as the consolidation mechanism, the microstructural evolution and the material flow, were examined in Al alloy 6061. This study clarified that the elliptical zone found in the vicinity of the pin hole on the cross section was characterized by the initially lapped surface of two sheets. Moreover, the following material flow was proposed: capture of the upper material with the threads on the pin surface, spiral flow along the tool rotation, and then release at the tip of the pin.

Key Words: Friction stir spot welding, Al alloy, Material flow, Microstructure

1. Introduction

Weight reduction of vehicles is a key issue for the energy saving in automotive industries. In order to reduce weight of the vehicles, substitution of Al alloys for steels has been recently promoted. Resistance spot welding (RSW) has been widely used in automotive industries, but it is known that RSW of Al alloys results in some industrial problems, such as large power consumption and short life of the electrode, due to the low electrical resistance of Al alloys [1].

Recently, friction stir spot welding (FSSW), developed based on principle of friction stir welding (FSW), has been paid attention as a new spot-welding process to solve these problems [2,3]. FSSW is a solid-state process resulting in low distortion of the products, low energy consumption, and simple production line, compared to RSW. Taking advantages of the positive factors, FSSW has been used for construction of Al components in the automotive industries [4]. To ensure reliability of FSSW of Al alloy, furthermore, Fujimoto et al. [5–7] examined the microstructural features, the plastic flow behavior, and effect of process parameters on mechanical properties in friction stir spot welded (FSSWed) Al alloy 6061, and reported such fundamental knowledge on the FSSW phenomena.

In this paper, knowledge on the consolidation mechanism, the microstructural evolution and the material flow during FSSW of Al alloy is succinctly summarized by reviewing recent studies of the authors.

2. Experimental

The base material used in this study was Al alloy 6061–T6 sheet, 1 mm in thickness. The two sheets were overlapped and then FSSWed. The welding tool had a threaded pin similar to the general FSW tool. The pin diameter, pin length and shoulder diameter of the tool were 3.0 mm, 1.5 mm and 10 mm, respectively. The tool with left-handed thread was rotated clockwise to create downward motion of the material around the pin. During FSSW, the tool load and the rotational speed were kept to be
constant at 4508 kN and 2000 rpm, respectively. The process time varied between 1.5 s and 4.0 s.

Sample for cross sectional observation was cut from the weld and then etched in a NaOH aqueous solution. Distributions of the grain structure and the crystallographic texture in the weld were examined by electron backscatter diffraction (EBSD) method. Sample for EBSD analysis was electrolytically polished in 50ml HClO4 + 150 ml C2H5OH solution. Orientation data collection was conducted for the base material and the vicinity of the pin hole.

To examine movement of the lapped interface during FSSW, FSSW was applied to two sheets with an Au thin foil sandwiched between them. Following FSSW, the Au distribution was examined by scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) analysis system. Moreover, the material flow was examined through FSSW of the dissimilar Al alloys 6061 and 5052.

3. Results and discussion

Cross sectional overviews of the welds produced at various processing time are shown in Fig. 1. Since the tool load was kept constant, plunge depth of the tool increased with processing time, which resulted in thinning of the upper sheet at the edge of the shoulder. An elliptical zone was formed in the bottom sheet in the vicinity of the pin hole, which looks like typical stir zone of the friction stir weld. Periphery of the elliptical zone moved farther at the longer processing time.

Microstructural features of wide region including the elliptical zone were examined by EBSD. The base material had a pancake-shaped grain structure with average grain size of about 15 μm, while the wide region including the elliptical zone exhibit finer equiaxed grain structure than the base material. Crystallographic texture analysis revealed that the base material had a relatively random texture component, while simple shear texture components were found in the wide region including the elliptical zone [5]. There was no discontinuity of texture across the periphery of the elliptical zone in the wide region. Moreover, the texture analysis clearly showed that the shear direction was roughly parallel to the rotating direction of the welding tool, which suggests that the material mainly moved along the rotating direction of the welding tool.

In general, the stir zone of friction stir weld has fine equiaxed grain structure with the strong texture arising from recrystallization during FSW [8–10]. This situation suggests that the stir zone is not limited to the elliptical zone and that strong shear deformation occurred throughout the wide region during FSSW. Shear deformation could fragment continuous oxide layers on the initial lapped interface, resulting in metallic bonding of oxide-free surface [11]. This might be a reason for the well consolidation of the lapped interface near the pin hole. The additional examination revealed that the fine grain structure spread in a region denoted as “fine-grained zone” in Fig. 1, which should correspond to the stir zone of the weld.

To clarify identity of the periphery of the elliptical zone, precise microstructural examinations were conducted by BSE and EBSD. The periphery of the elliptical zone had relatively finer grains than the surrounding region, but did not contain any inclusions and precipitates with the different chemical compositions from the Al matrix. From these results, this study concluded that the periphery...
of the elliptical zone in the present weld is characterized by only finer grain structure.

To examine movement of the lapped surface during FSSW, FSSW was applied to two sheets with an Au thin foil sandwiched between them. SEM images and Au distributions of region near the pin hole are shown in Fig. 2. At the processing time of 2.0 s, the fragmented interface with Au moved upward and then downward from outside of the stir zone toward the pin hole. The Au distribution was more dilute near the pin hole. When the process time was 4.0 s, the Au distribution was much more dilute and widened outward the pin hole. Besides the vicinity of the pin hole, the periphery of the elliptical zone also had the dilute distribution of Au. This means that the periphery of the elliptical zone corresponds to the initially lapped interface of two sheets. This result is supported by cross sections of the dissimilar FSSW between Al alloys 6061 and 5052 (Fig. 3), which clearly show that the upper material completely occupies the elliptical zone after FSSW.

Considering these results, the following material flow would be proposed, as shown in Fig. 4 [6]. The material near the top surface is captured with the threads on the pin, and then the material spirally moves along the pin rotation toward the bottom of the pin (Fig. 4(b)). When the captured material reaches at the bottom of the pin, it would be released at the pin tip (Fig. 4(c)). Since the capture and release of the material occur continuously, the initially released material moves from the pin tip toward the outside of the pin hole (Fig. 4(d)). This material flow results in the elliptical zone around the pin hole and hooking of the lapped interface.

**4. Summary**

This study applied FSSW to two sheets of Al alloy 6061 using a threaded pin tool, and then examined the welding phenomena, especially the consolidation mechanism, the microstructural evolution and the material flow, during FSSW. FSSW produced defect-free welds in this alloy. Periphery of the elliptical zone, found in the vicinity of the pin hole on the cross section, was identical to the initially lapped surface of two sheets. The material flow characterized by simple shear deformation occurred in wide region including the elliptical zone during FSSW, and the lapped interface was well fragmented. The following material flow was proposed: capture of the upper material with the threads on the pin, spiral flow
along the tool rotation, and then release at the tip of the pin.

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