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Microstructure in Friction Stir Welded SPCC / 6022 Aluminum Alloy Joints

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Abstract

The 2 mm thick 6022 aluminum alloy plate was lapped over the 1 mm thick steel (SPCC) plate and welded using Friction Stir Welding (FSW). Penetration depth of the tool tip was controlled. When the tool tip was kept at 0.1 mm above the interface, any macroscopic microstructual change was not observed. An Fe - Al base intermetallic compound layer was formed at the interface, when the tool tip was located at 0.1 mm beneath the interface. Lamellar structure consisting of steel and Fe - Al base intermetallic compounds were also observed in the steel matrix near the interface.

1. Introduction

The demand of aluminum alloy products in the automobile industry increases, because of strong requirement of weight reduction of automobiles in order to reduce CO_2 emission for global environment al protection. In order to facilitate the applications of aluminum products as a structural material for automobile, welding of dissimilar materials, in particular, steel / aluminum welding is strongly desired [1].

Several special welding methods have been used to produce the steel / aluminum joint. They include diffusion bonding, hot rolling and laser welding. However, reliable and practical welding method for the joint has not developed yet [1,2].

Recently, several solid-state welding processes were developed, and some of them were applied for the joining of dissimilar metals [3,4]. FSW, which is currently being widely explored for joining light materials [5], is also one of the promising candidates for the welding process of dissimilar materials.

The purpose of the present study is to obtain the steel / aluminum joint with high bonding strength by using FSW. Microstructural and mechanical properties were investigated for the lap-jointed plates produced at several welding conditions. Special attention was paid to the effect of the relative position of the rotating tool tip to the steel / aluminum interface during FSW.

Table 1: Chemical compositions of steel (SPCC) and 6022 aluminum alloy (mass%).

	Si	Cu	Mn	Mg	Cr	Zn	Ti	P	S	C	Fe	Al
Steel	1.0	0.00	0.07	0.6	0.01	0.01	0.02	-	-	-	0.13	Bal.
6022	0.01	-	0.14	-	-	-	-	0.02	0.01	0.04	Bal.	-

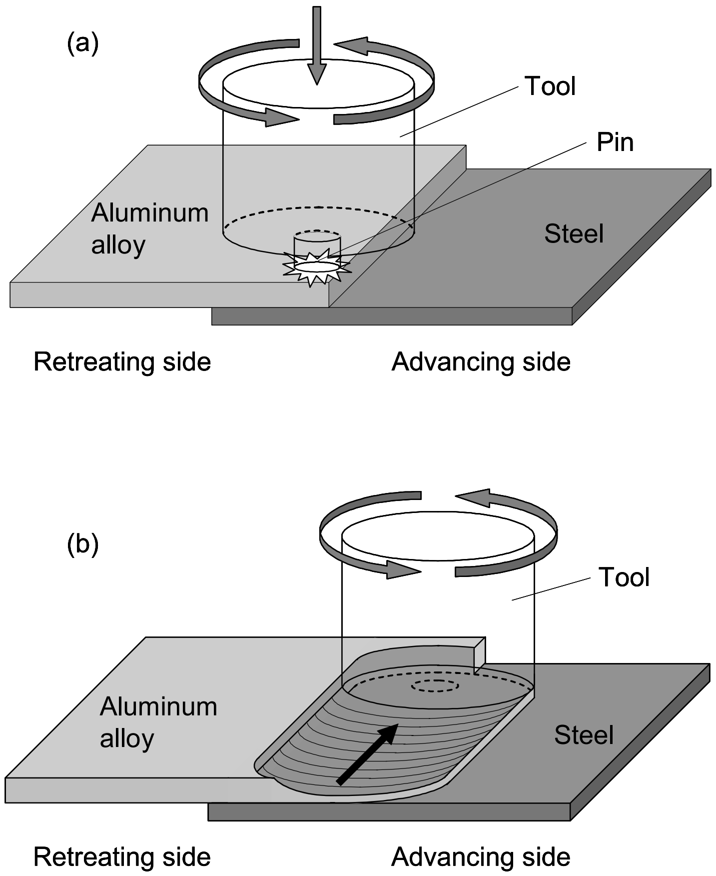

Figure 1: Friction stir welding process of steel / 6022 aluminum alloy joint. (a) A rotating tool is plunged into a aluminum alloy plate and (b) The tool is moved along the steel / aluminum interface.

2. Experimental Procedure

The materials used in the present study are SPCC (commercial cold rolled steel plate) and 6022-T4 aluminum alloy plate (provided by Kobe Steel, Ltd.). The thickness of the steel plate and the aluminum alloy plate is 1.0mm and 2.0 mm, respectively. The chemical compositions are listed in Table 1. Lap-joining of steel and 6022 aluminum alloy plates were carried out using FSW technique, as shown in Figure 1. The aluminum plate was lapped over the steel plate. The rotating pin with a cylindrical tip was plunged into the edge of the aluminum plate, and then the pin was traveled along the edge of aluminum plate. The rotational speed and traveling speed were 3,000 rpm and 25 mm/min. The tool was made of rapid tool steel (ASTM M2). Diameter of the shoulder part was 10 mm. The length and diameter of the pin was 1.7 mm and 3 mm, respectively. The length of the pin was slightly shorter than the thickness of the present aluminum alloy plate. The axis of the hard pin was tilted 4 degrees from the plate normal direction. The tool was impressed into the aluminum plate. Three initial impressing depth was chosen (1) 1.9 mm, (2) 2.0 mm and (3) 2.1 mm. Since the thickness of aluminum plate was 2 mm, the tip of the tool was located at 0.1 mm above the steel / aluminum interface for 1.9 mm, just on the interface for 2.0 mm, and 0.1 mm beneath the interface for 2.1 mm, respectively. This means that the tool tip was plunged into the steel by 0.1 mm, in the case of 2.1 mm.

The 50 mm long tensile specimens with 12.5 mm gage length were machined from the FSW joints so that their longitudinal direction was perpendicular to the welding direction. Tensile tests were performed at room temperature using an Instron type testing machine at a cross-head speed of 1.0 mm/min.

Microstructural observation of steel / aluminum interface was made using a optical microscope and a scanning electron microscope (SEM). Energy dispersive X-ray spectroscopy (EDX) was also used to analyze the intermetallic compounds formed at the steel / aluminum interface.

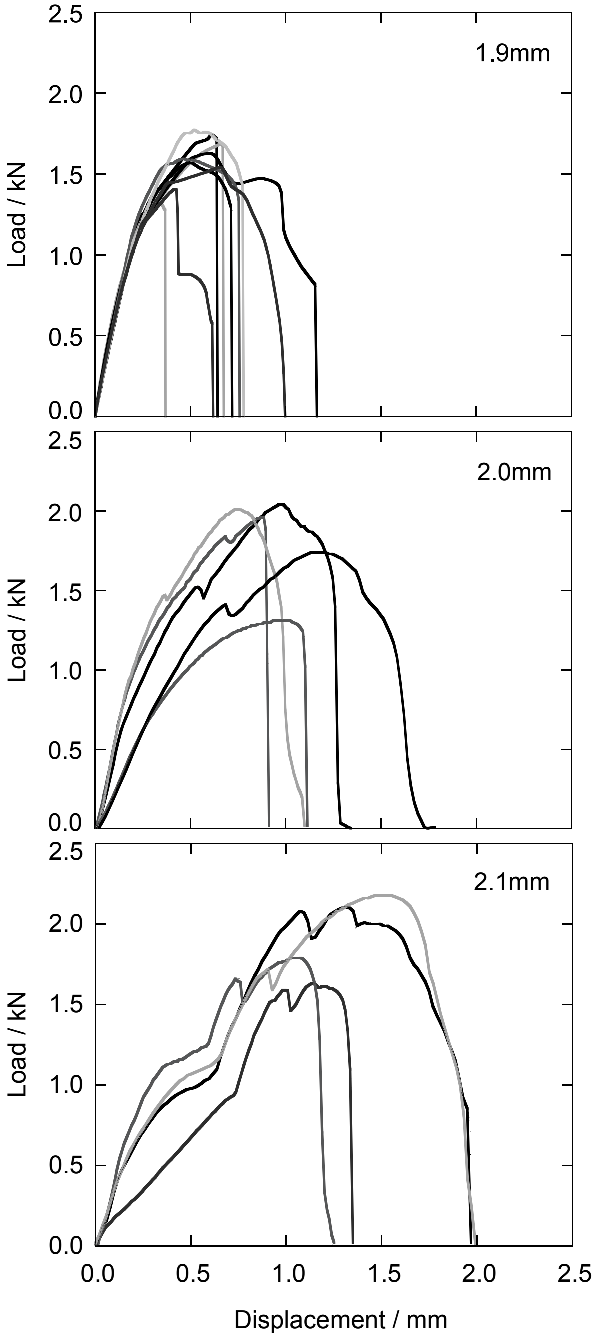

Figure 2: Load – displacement curves of the steel /6022 aluminum alloy joint.

3. Results and Discussion

3.1 Effects of penetration depth of the tool on tensile properties of the weld joints

Figure 2 shows load - displacement curves of the joints fabricated under the several penetration depth conditions. For 1.9 mm, the load increased with increasing displacement and reached the peak value and reduced to fracture. Mean value of the peak load was 1.6 kN. Majority of the joints fabricated at 2.0 mm and 2.1 mm conditions exhibited characteristic load - displacement curves showing two peaks. Kinks occurred during the initial load increase. Mean value of the first peak was 1.6 kN, and 1.8 kN for the second one for 2.0 mm condition. They were 1.8 kN and 1.9 kN for 2.1 mm condition.

3.2 Effects of penetration depth of the tool on the steel / aluminum interface structure

Figure 3 shows the optical micrograph of transverse cross section of the 2.1 mm joint. Macroscopic material flow of the aluminum alloy was observed. It took place from the retreating side to the advancing side. Joining was achieved just under the area whose width corresponded to the pin diameter. No significant difference was observed for macroscopic appearance among three conditions.

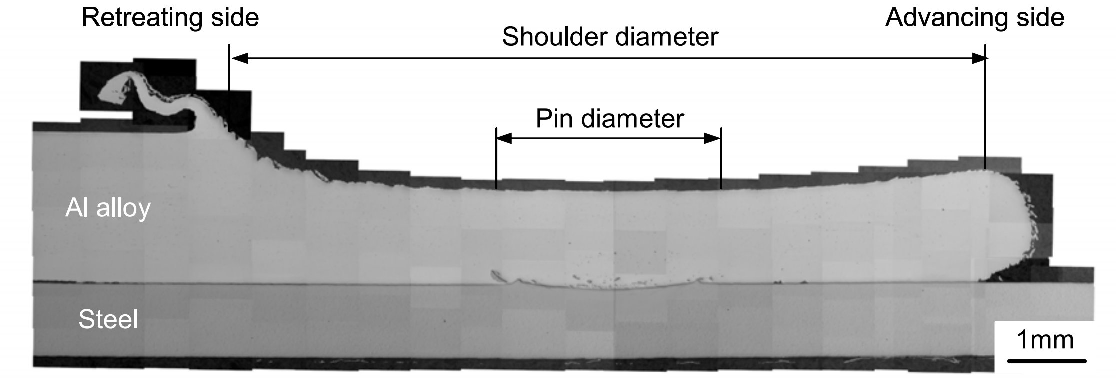

Figure 3: Optical micrograph of the transverse cross section of the steel / 6022 aluminum alloy joint fabricated at penetration depth : 2.1 mm.

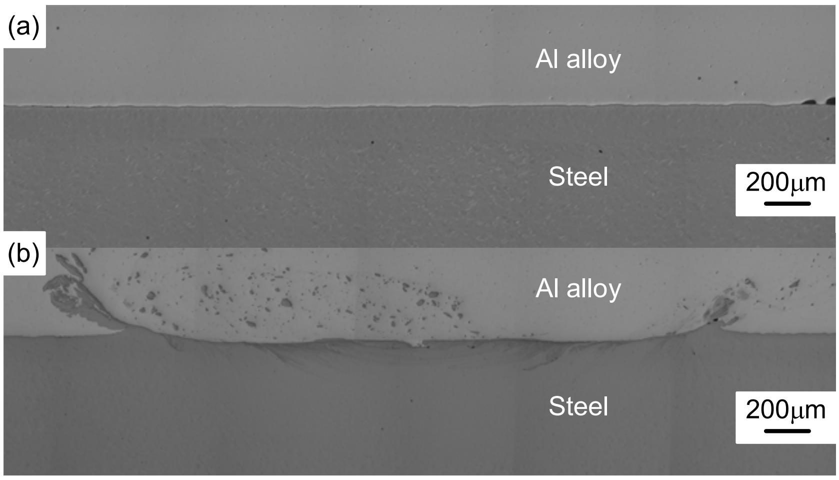

Figure 4: Optical micrographs of the cross section of steel / 6022 aluminum alloy interface. (a) penetration depth : 1.9 mm and (b) penetration depth : 2.1 mm.

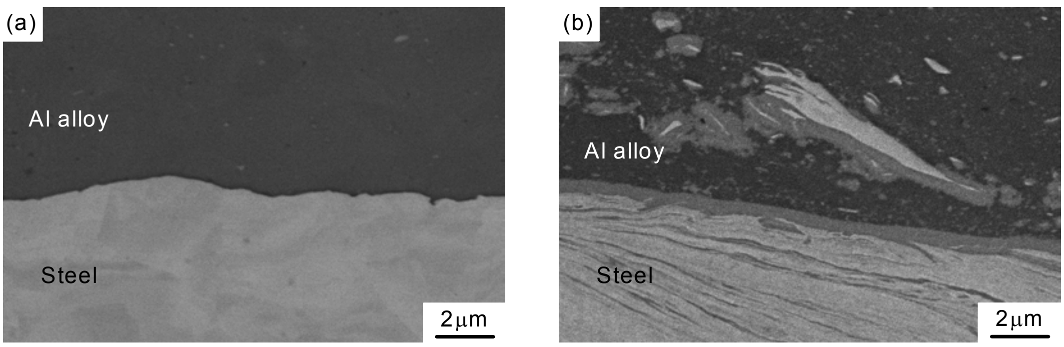

Figure 5: Back scattering electron images of steel / 6022 aluminum alloy interface. (a) penetration depth : 1.9 mm and (b) penetration depth : 2.1 mm.

Figure 4 is optical micrographs of the interface for 1.9 mm and 2.1 mm specimens. Figure 5 is BEI (Back Scattering Electron Image) of the interface for 1.9 mm and 2.1 mm specimens. We could not detect formation of any intermetallic compounds for 1.9 mm specimen. In contrast, for 2.1 mm specimen, several characteristic features were detected at the steel / aluminum interface. The first is formation of the intermetallic layer at the interface, as shown in Figure 5 (b). EDX analysis found that the interface layer was Fe - Al base intermetallic compounds. Secondary, small particles with bright contrast were observed in the aluminum alloy matrix. BEI observation and EDX analysis revealed that these particles are either steel or Fe – Al intermetallic compounds. It is considered that these particles were broken pieces of steel originally. The third characteristic feature was lamellar structure in the steel. The lamellar structure consists of Fe - Al intermetallic compounds and steel. This indicates that significant solid - state material flow took place at the vicinity of the interface in steel. The characteristic load - displacement response for 2.0 mm and 2.1 mm specimens is considered to be due to such a complicated interface structure.

4. Summary

Steel / aluminum alloy lap – joints were fabricated using FSW technique. The microstructure of the steel / aluminum interface and tensile properties of the joint depended on the tool penetration depth. When the tool tip was kept at 0.1 mm above the interface, any macroscopic microstructual change was not observed in spite that good bonding was achieved. An Fe - Al base intermetallic compound layer was formed at the interface, when the tool tip was located at 0.1 mm beneath the interface. Lamellar structure consisting of steel and Fe - Al base intermetallic compounds were also observed in the steel matrix near the interface. Layer bonding strength was obtained in this case. Tool penetration depth, or the relative position of the tool tip to the original steel / aluminum interface is considered to be the important controlling factor of the interface microstructure and mechanical properties of the FSW steel / aluminum joint.

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