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Analysis of material flow in the sheet forming of friction-stir welds on alloys of mild steel and aluminum

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ABSTRACT

The deep drawability of and material flow in friction-stir welds of dissimilar steel/aluminum were investigated in this study. Steel/Al tailor-welded blanks (TWBs) were found to possess sufficient joint strength and deep drawability with limiting drawing ratios (LDRs) as low as 1.7. However, the drawability of these TWBs was lower than that of the two base materials. Fracturing was observed near the weld line on the flat bottom of the aluminum alloy side. In addition, the aluminum alloy near the fractured area in the TWB cup was subjected to significant strain near the forming limit, correlating to a significant loss in their deep drawability. Numerical simulation results indicated that slightly enhancing the friction coefficient between the punch and the blank significantly mitigated the significant strain near the fracture area. Deep drawing tests verified that the LDRs of TWBs obtained using rosin were increased by nearly 19% compared with that obtained using conventional press oil. Therefore, this approach of enhancing the friction coefficient can be effectively applied to improve the formability of dissimilar steel/aluminum TWBs.

1. Introduction

In the automotive industry, the development of new materials with superior mechanical properties, namely, strength, formability, and low weight is in high demand. In particular, the reduction of vehicle weight is extremely important. For example, Schubert et al. (2001) explained the importance of lightweight components in all applications that produce moving masses. Recently, thinner high-strength sheets and tailor-welded blanks (TWBs) have been widely utilized to address this problem. TWBs combine sheets of different materials that are welded together prior to the forming process; each base sheet has unique physical or material characteristics. TWBs suit the development of unique materials with locally different properties, namely, heterostructures; their use permits the reduction of the cost of the materials and assembly. In addition, TWBs are generally used in the production of complicated press-work, requiring high-quality mechanical properties and formability. Many experimental and numerical reports have discussed TWBs. Merklein et al. (2014) explained the potential practical uses and technical issues in tailor-welded blanks, patchwork blanks, tailor-rolled blanks, and tailor heat-treated blanks. Xu et al. (2014) investigated the mechanical characteristics of high-strength steel TWBs. Panda et al. (2007) examined the formability of laser-welded interstitial-free steel blanks with different thicknesses via stretch-forming tests and finite element analysis. In addition, Choi et al. (2000) investigated the characteristics of weld-line movement in TWBs during deep-drawing processes. However, these reports have primarily addressed TWBs made with steels of different thicknesses or strengths.

In contrast, the automotive industry has begun using aluminum alloys to reduce vehicle weight. Therefore, interest in dissimilar TWBs of aluminum and steel has recently increased. However, the production of sound aluminum and steel welds is difficult using conventional fusion methods, because of the formation of considerable intermetallic compounds (IMC) by the high heat input. These IMCs are generally extremely hard, leading to fast rapture in joints. Therefore, a joining technology utilizing low-heat input, such as solid-state welding, is required to produce these dissimilar TWBs. Friction bonding is one typical technology used to achieve solid-state welding. Ikeuchi et al. (2005) examined the microstructures of the friction-bonded interfaces between steel and aluminum alloys, and indicated that the IMC layer thickness could be controlled by the friction time. Thomas et al. (1991) developed a new solid-state welding technology called friction stir welding (FSW). In FSW, joining is achieved by a combination of the heat generated by friction and the strong material flow induced by a rotating tool. FSW can

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prevent heat generation during the welding process, for which it has attracted attention in the production of sound aluminum and steel welds. Fukumoto et al. (2004) examined the possibility of welding between a cast aluminum alloy and mild steel using FSW, establishing the basis for the dissimilar butt-welding technique. Kimapong and Watanabe (2004) reported adequate FSW conditions for butt-welding a plate of A5083 aluminum alloy to a mild steel plate. Uzun et al. (2005) investigated the microstructural, hardness, and fatigue properties of A6013 aluminum alloy friction-stir-welded to stainless steel. Lee et al. (2006) examined in detail the IMCs of dissimilar FSW joints between stainless steel and A6056 aluminum alloy, using transmission electron microscopy (TEM). Sun et al. (2013) reported on the formation of an amorphous structure along the joint interface between A6061 aluminum alloy and mild steel. Movahedi et al. (2013) examined the effect of annealing treatments on the joint strength of dissimilar A5083 aluminum alloy and steel friction-stir lap welds. Tanaka et al. (2009) reported on the relationships between welding temperature, IMC thickness, and bond strength of friction-stir welds between various aluminum alloys and mild steel. In addition, Tanaka et al. (2011) investigated the initiation and growth mechanisms of IMCs during FSW. As described, most studies concerning dissimilar friction-stir welds to date focused on their bond strengths and microstructures. Morita et al. (2009) reported on the deep drawability and bendability of friction-stir-welded TWBs of a commercial A6061 aluminum alloy and one variety of mild steel. However, the effects of combining different base materials on the formability of TWBs remain ambiguous. A thorough understanding of the formability of dissimilar friction-stir-welded TWBs is required to adopt them for industrial applications.

This study was undertaken to clarify the formability of several different types of friction-stir-welded TWBs, consisting of mild steel and three different aluminum alloys. In addition, the material flow behaviors and severity of forming during deep drawing were investigated by both numerical analysis and experimental measurements. Finally, an effective improvement method of deep drawability was proposed to facilitate the use of dissimilar TWBs in the fabrication of wide varieties of complex parts.

2. Experimental procedures

2.1. Base materials and welding conditions

Zinc-coated steel sheets and sheets of the three A1100-O, A5052-O, and A5182-O aluminum alloys were used in this study. The sheet thickness for all materials was 1 mm. A FSW tool with a screw thread probe made of SKD61 tool steel was used with specifications as follows: 10 mm shoulder diameter; 3 mm probe diameter; 0.9 mm probe length. The inclination angle during FSW was 2°. FSW was performed at a tool rotation speed of 1500 rpm and a weld travel speed of 300 mm/min; these welding conditions were determined from preliminary examinations. Similar welded blanks (A5052-A5052) and four dissimilar TWBs (A5182-A5052, steel-A1100, steel-A5052, and steel-A5182) were made by FSW. When the same types of materials were treated by FSW (A5052-A5052 and A5182-A5052), the center of the moving tool conformed to the butt line, as shown in Fig. 1(a). Fukumoto et al. (2004) and Kimapong and Watanabe (2004) described the plunging of the rotation tool into the aluminum, successfully producing dissimilar welds by placing the aluminum alloy on the retreating side. The advancing side of welds is the side on which the rotation of the tool proceeds in the same direction as the motion of the tool itself; the opposite side is referred to as the retreating side. Therefore, the probe was placed directly into the aluminum alloy, fixed on the retreating side, for dissimilar FSW, as shown in Fig. 1(b). In this study, the probe was offset from the steel's faying surface by approximately 0.2 mm.

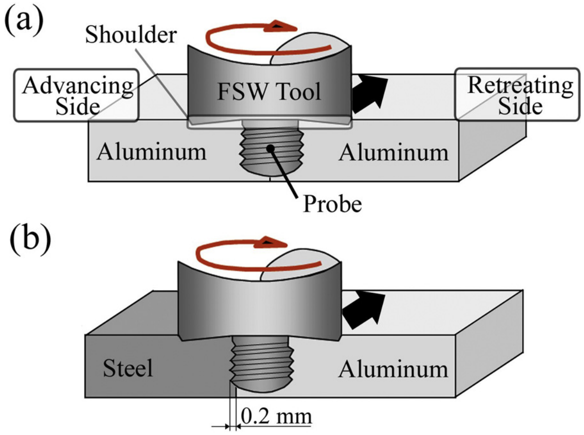

Fig. 1. Schematic of friction-stir welding: (a) similar welding and (b) dissimilar welding.

2.2. Tensile and deep drawing tests

The tensile properties of the base materials were measured at angles of 0°, 45°, and 90° to the rolling direction (RD). The dimensions of the tensile specimens are shown in Fig. 2(a). The tensile specimen was cut using an electrical discharge machine; the yield stress, tensile stress, elongation, work-hardening exponent (*n*-value), and Lankford value (*r*-value) were determined to mechanically characterize the materials. The *n*-value was calculated from the slope of the true stress–true strain curve between the true strains of 0.1 and 0.15. The crosshead speed in the tensile tests for all cases was 3 mm/min. Tensile specimens of the friction-stir welds were also machined transverse to the welding direction, as shown in Fig. 2(b) and (c), and the tensile strengths of the joints were measured using these samples.

Cylindrical deep drawing tests were performed to measure the formability of the base materials and the dissimilar FSWs. The tool geometries for the deep drawing testing were as follows: 40 mm punch diameter; 4 mm punch shoulder radius; 42.5 mm die hole diameter; and 10 mm die shoulder radius. Conventional press oil (Model Number: S-3) manufactured by HOKOKU OIL Co., Ltd. was used as the lubricant, with a kinetic viscosity at 313 K of approximately 85 mm^2/s. The punch speed and the blank holder force were 60 mm/min and 3 kN, respectively. The geometry of the initial blank was circular with the diameter ranging from 74 to 90 mm to reveal the limiting drawing ratio (LDR), calculated as:

$$\mathrm{LDR} = \frac{D_{\max}}{d_{\mathrm{p}}}$$

where $D_{\max}$ is the maximum blank diameter drawn without fracture and d_{p} is the punch diameter. In the TWBs' deep drawing tests, the weld line was located at the center of the blank.

2.3. Metallurgical analysis of material flow during deep drawing

The material flow behaviors during the deep drawing of both the base metals and the TWBs were investigated using electron backscatter diffraction (EBSD) analysis and the grid-marking method. For EBSD analysis, the deep-drawn cups of the A5052 base material and the steel-A5052 TWB were sectioned transverse to the rolling direction and to the weld line, respectively. A section of the flat bottom of each section was polished by an Ar ion beam. The EBSD analysis was performed by a field emission scanning elec-