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Texture and microstructure evolution and mechanical properties during friction stir welding of extruded aluminum billets

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ABSTRACT

Extruded, solid solution-hardened A5083, and aging heat-treated A6082, 15 mm-thick aluminum alloys were separately welded by friction stir butt-welding (FSW). The evolution of microstructure and texture, as well as variations in the strength and hardness, was examined in detail. The microstructure of the as-extruded billets of both alloys possessed major deformation textures of Brass and Copper components, as well as minor recrystallization texture of a Cube component. The initial microstructure drastically changed during the FSW process. Uniaxial tension and micro-hardness tests were also carried out to determine the mechanical behavior of the welded regions. The features of each region of the base metal (BM), heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ) were investigated regarding variation in the microstructure and hardness. The differences between the two alloys, in terms of their microstructures and strength and hardness levels, were compared.

1. Introduction

Friction stir butt-welding (FSW) is a solid-state joining process that has many advantages over other conventional types of fusion welding [1–3]. Melting of the materials is not involved during this welding process, and shrinkage or defects in the weld zone are not common. The joining of various types of similar or dissimilar materials, such as aluminum, magnesium, copper and brass alloys, is enabled by FSW, and it is likely that industrial applications of this process will gradually increase [4].

The microstructure and mechanical properties of the welded zone are usually better in the FSW process compared to fusion welding. Usually, the microstructure of fusion welds (e.g., laser or arc welding) is mainly composed of the fusion zone and HAZ (heat-affected zone). The fusion zone undergoes melting and solidification, which causes changes in the original microstructure. In the HAZ, the distribution of precipitates or secondary particles is also strongly affected by the conduction of weld-heat. Changes in the microstructure of the HAZ and fusion zones result in changes in the mechanical properties of the welded zone. During FSW, the welded zone is mainly composed of three parts: the HAZ, TMAZ (thermo-mechanically affected zone) and weld nugget (stir zone). A complicated and dynamic variation in the microstructure also occurs without melt. Similar to the fusion weld, the distribution of precipitates or secondary particles drastically changes in the HAZ, TMAZ, and weld nugget. The TMAZ and weld nugget in FSW are unique, and their grain orientation, shape, and size change dynamically from those of the base metal. The weld nugget possesses refined and recrystallized grains. The TMAZ, located between the HAZ and the weld nugget, shows a narrow and dynamic lattice reorientation. The HAZ is the weakest part in the whole weld zone of both FSW and fusing welding, and failures mainly occur there during external loading. Based on hardness profile and microstructural features, the variation of each weld region (i.e., width and depth of the weld nugget) can be indirectly examined according to various welding conditions. The overall strength of the welded region also can be understood based on its microstructure and hardness.

Various aspects of the FSW process have been studied. These include the evolution of microstructure and texture [5–11], mechanical properties [12–15], flow patterns [16–20], and the geometric effects of the tool pin and shoulder on the welding [21,22]. Further assessments of the metal flow and thermo-mechanical behaviors were also conducted by modeling and simulation [23–27].

A range of global, environmental issues now require weight reductions and higher fuel efficiency in several industrial sectors (i.e., shipbuilding, automobile and aerospace industries). Due to its lighter weight, extruded aluminum billets can be used as alternatives to steel structural metals. High strength, age-hardened (A2xxx, A6xxx, A7xxx) and solid solution-hardened (A5xxx) aluminum alloys, in particular, are promising materials in this area. A lot of FSW applications using those alloys have been reported. The microstructural and mechanical behaviors of A6063 during FSW have been investigated [28,29].

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The hardness profiles mainly depended on the volume fraction and growth of the strengthening, needle-shaped precipitates. Metallurgical changes during the FSW of A7075 alloys were also presented for various regions of a dynamically recrystallized zone (DXZ), a thermo-mechanically affected zone (TMAZ), and a heat-affected zone (HAZ) [30]. The microstructure and mechanical properties of welded A5083 were also discussed [31]. It was pointed out that the FSW process hardly caused solute loss by evaporation and segregation by solidification. The hardness profile of A5083 was mainly determined by the particle distribution and not by the grain refinement characteristics.

Here, we compared variation of microstructure and mechanical properties during FSW of two different types of aluminum alloys, A5083 and A6082. The former is a solid solution-hardened alloy, and the latter is a precipitation-hardened alloy. Each alloy responds differently to the thermo-mechanical process. The microstructural and textural evolution in the base metal (BM), heat-affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ or nugget) was investigated using electron backscatter diffraction (EBSD). The hardness and uniaxial strength behaviors were also examined.

2. Experimental procedure

The materials used were extruded A5083 and A6082 aluminum alloys. The chemical compositions of the extruded billets are listed in Table 1. Each billet (15 mm thick) was machined to a size of 300 × 150 mm. Two billets were firmly fixed using steel fixtures, and the tool was then inserted at the interface of the two work-pieces. The microstructure and texture were investigated on the top surface and in the cross-section of the welded zone. Vickers hardness and uniaxial tension tests were also carried out. The welding tools were made of SKD11 tool steel, and the tool design for each alloy differed in each case. The tool comprised a concave shoulder prolonged by a pin. The probe was a left-threaded conical pin. The tilting angles of the pin toward the work-piece were kept constant at 2° during the FSW process.

The microstructural and textural evolution was closely examined using electron backscatter diffraction (EBSD). For sample preparation of the EBSD measurement, conventional steps were followed. Welded samples were cut and cold-mounted. Mechanical polishing was carried out down to 1200 grit SiC paper, using water as a lubricant. Finer polishing was done with a 0.25 μm, self-lubricating, diamond suspension. The final auto-polishing involved the use of a colloidal silica solution for about 1 h under 13 N. Both the top surface (in contact with the tool shoulder) and the cross-section (mainly in contact with the tool pin) were examined. An automatic high-resolution EBSD system (Hitachi SU6600) with a TSL 6.0 device was used. The operating condition was a power of 20 kV, and the step size varied with the mapping region from 1 μm to 5 μm. Macro-etching of the welding zone was carried out using Keller's reagent (5 mL HNO_3, 3 mL HCl, 2 mL HF, and 190 mL H_2O).

Microstructure and precipitates were examined in detail using a JEM-2100F TEM, operating at 200 kV. TEM samples were prepared by mechanical polishing down to approximately 100 μm; followed by electro-polishing using methanol (60 ml), glycerin (30 ml), and nitric acid (10 ml). Electro-polishing was carried out at a temperature and voltage of −10 to −15 °C and 20–25 V. TEM and EBSD sample preparations were finalized by ion milling to prevent oxidation or other surface contamination, if necessary. Quantitative analysis was carried out using energy dispersive spectroscopy (EDS).

Table 1
Chemical compositions of aluminum alloys A5083 and A6082 (wt%).

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A5083	0.15	0.15	0.02	0.7	4.5	0.15	0.02	0.15	Bal.
A6082	1.0	0.15	0.02	0.7	1.15	0.15	0.02	0.1	Bal.

Tensile specimens were cut from the as-welded region. The top and bottom surfaces were eliminated and only the center part was used for the tension tests. The gauge length contained both unwelded (BM) and welded zones. The tensile axis was perpendicular to the welding direction. At least three tension tests for each working condition were performed. A standard universal testing machine (Instron 4206) was used with a strain rate of 0.0025/s at room temperature. The gauge length and the diameter of the tension samples were 25 mm and 6.25 mm, respectively.

The hardness values were measured using a micro Vickers hardness testing machine (Mitutoyo HM-100) under a force of 4.9 N (500 gf). Hardness values were obtained from the base metal (BM), through the welded region, to the other side of the BM.

3. Results and discussion

The as-extruded textures of the A5083 and A6082 billets are presented in Fig. 1. The pole figures (PFs) and orientation distribution functions (ODFs) were computed from EBSD mapping results obtained from the cross-sections, revealing the typical features of the extrusion process. Near the billet surface, severe lattice reorientations arose during the extrusion process due to the strong frictional effect on the crystals. In order to minimize the frictional effect, the mapping region was some distance away from the billet surface. The grains of the A5083 sample had a wider aspect ratio than those of the A6082 sample. The elongated grain-shape caused by the extrusion process was more easily observed along the extrusion direction (or from the top surface) than along the cross-section. Detailed discussion about microstructure will be presented later.

There is some similarity between the extrusion of thick and wide billets, and the rolling of the sheets or plane strain compression (PSC) with friction. Contact between the dies or rolls, and the work-pieces, had a frictional effect on the surface of the work-piece. Inside the billets or sheets, the deformation mode was close to the condition of PSC. To reveal the similarity between the extrusion and the rolling processes, the sample coordinate system of the extrusion billet can be rotated to match that of the rolling plate. As a result, the rolling direction (RD) is parallel to the extrusion direction (ED). Note that the top of the (111) PFs in Fig. 1 (a) and (c) is parallel to the extrusion direction (ED).

Considering the small amount of rotation along the RD (or ED), overall, the (111) PFs reveal three major textural components: Brass, {1 1 0}⟨1 1 2⟩, Copper, {1 1 2}⟨1 1 1⟩, and Cube {1 0 0}⟨0 0 1⟩. From the orientation distribution function (ODF, ϕ=0, and 45°sections), the Brass, Copper, and Cube components also appear to be dominant. Brass and Copper components are known to constitute a deformation texture, which is usually found during the PSC of FCC (face centered-cubic) metals. The Cube component is a typical recrystallization texture associated with FCC metals. In fact, the extruded billets experienced severe deformation at temperatures above 500 °C. Some amount of dynamic recrystallization can occur during the extrusion process. For the A5083 billet, the Brass and Cube components were dominant, whereas the Copper component was relatively weak. For A6082, the Brass component was dominant, and the Copper component was second. The Cube component was comparatively weak. Depending on the alloying system, the dynamic process can vary. It appeared that this resulted in a different mixture of deformation and recrystallization textures in the A5083 and A6082 samples in this study. A detailed discussion of ideal orientations can be found in the literature [32,33].