Evolution of microstructure and mechanical properties during friction stir welding of A5083 and A6082

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Abstract

Friction stir welding (FSW) is a solid-state welding process. Using tools with a concave shoulder and a threaded conical pin, we tested various welding conditions for two different aluminum alloys of A5083 and A6082. A6082 alloys were aging heat-treated materials and their softening in strength by frictional heating was evidently observed during FSW. The crystallographic orientation in the stir zone of A5083 revealed a random distribution, and that of A6082 was close to strong shear texturing. Temperature profiles were measured near the heat-affected zone (HAZ) using thermocouples. Evolution of microstructure and texture was also examined using electron backscatter diffraction.

Keywords: Aluminium alloys; Friction stir welding; Texture and Microstructure; Precipitates; Hardness

1. Introduction

Friction stir welding (FSW) has been known as an advantageous welding process compared with other fusion welding processes [1]. The fundamentals of the FSW process and its metallurgical consequences were comprehensively reviewed in [2]. Various aspects of the FSW process, such as heat generation, heat transfer, plastic flow, tool design, understanding of defect formation and the structure and properties of the welded materials were widely discussed.
The welding tool for FSW usually consists of a pin and a shoulder. Most heat generation occurs due to friction between the tool and materials, particularly the tool shoulder and the surface of abutting the workpieces. The tool pin mainly breaks and shatters abutting workpieces, and stirs the refined grains. A strong compaction or bonding of welded regions filled with soft and shattered grains is induced by both the tool shoulder and the undeformed workpieces, which surround the welded region. This overall process resembles an extrusion process.

In aluminum alloys, aging heat-treated (A2xxx, A6xxx, A7xxx) and solid solution-hardened (A5xxx) alloy systems play important roles in industrial application. Age heat-treated alloys were examined in [3, 4].

### Table 1. Chemical composition of aluminium 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.|

### Table 2. Geometry of working tools with a tapered screw.

| Shoulder diameter [mm] | Shoulder concave angle [°] | Pin root diameter [mm] | Pin diameter [mm] | Pin length [mm] |
|------------------------|----------------------------|------------------------|-------------------|-----------------|
| A5083                  | 38                         | 15.1                   | 9.1               | 13.8            |
| A6082                  | 26                         | 9.9                    | 5.5               | 14              |

The microstructure and mechanical properties of these materials heavily changed during FSW. The hardness of age heat-treated alloys mainly depended on the density distribution of strengthening needle-shaped precipitates. The microstructure and mechanical properties of solid solution-hardened alloys, particularly A5083, were discussed in [5] in detail. Many studies on the evolution of microstructure and texture, and material flow during FSW, have also been carried out in references [6–13].

In this study, we carried out friction stir welding of A5083 and A6082 alloys under various working conditions, and investigated the evolution of microstructure and mechanical properties of these materials. Temperature distribution is critical to aging heat-treated alloys, and temperature variation was measured near the heat affected zone using thermocouples. Microstructure and texture in the weld zone were discussed based on results of electron backscatter diffraction (EBSD). Various precipitates inside the weld region were also observed using transmission electron microscopy (TEM).

### 2. Experimental procedure

The chemical compositions of the extruded A5083 and A6082 aluminium alloys are listed in Table 1. Each billet was machined into dimensions of 15 mm thickness, 300 mm length, and 150 mm width. One A5083 billet was welded to another A5083 billet (welding between similar materials), and this process was also used for the A6082 billets. Two billets were firmly fixed using steel fixtures, and then a rotating welding tool was inserted at the interface of the two workpieces.

The working window of FSW was affected by many parameters such as, material properties, tool design, and capacity of the welding equipment, in addition to welding and rotational speeds. SKD11 tool steel was used for the welding tools. Different design of the tools was applied for each alloy. The tools were comprised of a concave shoulder and a left-threaded conical pin. The tilting angles of the tools were $2^\circ$ during FSW. The overall geometry of the tools is listed in Table 2. Various conditions of the FSW process were successfully tested for both A5083 and A6082 alloys. Tables 3 and 4 summarize the overall working window of the A5083 and A6082 alloys, based on welding and rotating speeds. The welding and rotating speeds are the primary working parameters, and
mainly determine the amount of heat input. Heat input decreases with increase in welding speed, and more rotation of the tool results in greater heating.

The microstructure and texture evolution was examined using scanning electron microscopy (SEM) and EBSD. For the sample preparation for the EBSD measurement, colloidal silica solution or electropolishing was used. Mechanical polishing was carried out down to 1200 grit SiC papers using water as a lubricant. Finer polishing proceeded using 0.25 μm self-lubricating diamond suspension. The final auto-polishing sequence involved colloidal silica solution for about 1 hr. under 13 N. For the electropolishing, a solution of perchloric acid (5 ml) and methanol (30 ml) was used at a voltage of 15 V and a temperature of 243 K ($-30^\circ C$). An automatic high resolution EBSD system of Hitachi SU6600 with a TSL 6.0, and Jeol7001F with an HKL Channel 5 were used to obtain the microstructural features of A6082 and A5083, respectively.

Table 3. Summary of the working window of A5083.

| Rotating Speed [rpm] | 100  | 150  | 200  | 250  | 300  |
|----------------------|------|------|------|------|------|
| 1200                 | O    | O    |      |      |      |
| 1500                 | O    | O    | O    | O    | O    |
| 1800                 | O    | O    | O    | O    | O    |

Note: Welding speed: millimeters per minute [mmpm]. Rotational speed: rounds per minute [rpm].

Table 4. Summary of the working window of A6082.

| Rotating Speed [rpm] | 50   | 100  | 150  | 200  | 250  | 300  |
|----------------------|------|------|------|------|------|------|
| 1000                 | O    | O    | O    | O    | O    | O    |
| 1500                 | O    | O    | O    | O    | O    | O    |
| 2000                 | O    | O    | O    | O    | O    | O    |

3. Results and discussion

3.1. Temperature profiles during FSW

Friction between workpieces and tools during FSW caused extensive heating through plastic dissipation. Heating strongly affected the strength of the workpieces and played an important role in the thermo-mechanical welding process. Fig. 1(a) is a temperature image taken by infrared camera during FSW. Most heating occurred between the workpiece and the tool. The maximum temperature was almost 530 °C in the hot spot (HS). Using thermocouples (TC), the temperature profiles of A5083 (Fig. 1(b)) and A6082 (Fig. 1(c)) were obtained at welding and rotating speeds of 100 millimeters per minute (mmpm) and 1500 rounds per minute (rpm), respectively. Two thermocouples were inserted into the holes drilled in each direction, and the ends of the thermocouples reached the heat-affected zone region. The thermocouple 1 and thermocouple 2 were located along the advancing side, and thermocouple3 and thermocouple4 were located along the advancing side. It is generally known that heating is more intensive along the advancing side and higher temperature was obtained along that direction [14]. Welding of A5083 and A6082 alloys revealed similar temperature distribution near the heat-affected zone, even though the strengthening mechanisms were totally different. The peak temperature of about 350°C (or 623 K) was high enough to affect the aging precipitates of A6082 [15], and this resulted in changes in the hardness of the A6082 alloys in the weld zone.

3.2. Microstructural features

Extruded A5083 and A6082 billets possessed a microstructure typically found after an extrusion process. Overall metal flow during FSW of A5083 was identified from SEM microscopy images shown in Figs. 2(a), 2(b), 2(c), and 2(d). Detailed microstructure can also be observed in the inverse pole figure maps of EBSD given in Figs. 2(e), 2(f), 2(g), and 2(h). Mapping region 1 belongs to the base metal. Mapping region 2 reveals a bent grain structure, and belongs to the thermo-mechanically affected zone. The thermo- mechanically affected zone usually separates the stir zone and heat-affected zone, and is very narrow. The other regions, 3 and 4 possess a refined and
equi-axed grain structure called a weld nugget or stir zone (SZ). There are some minor differences between regions 3 and 4, although both of them were located in the stir zone. Region 3 was relatively close to the thermo-mechanically affected zone and possessed more dynamic flow patterns, as can be seen in the SEM microscopy. On the other hand, region 4 was close to the center of the stir zone. The overall grain size of each region is also different. The grain sizes of the base metal (region 1), thermo-mechanically affected zone (region 2) and stir zone (region 3 and 4) are about 12.8, 9.2, 7.0 and 7.8 μm, respectively. The grain size of region 4 is greater than that of region 3. Region 4 is located in the weld center and the overall temperature of this region is highest in the weld zone. This can result in more grain growth of recrystallized grains during FSW.

Fig. 1. Temperature profiles at a welding speed of 100 mmpm. (a) Infrared photo showing temperature distribution during FSW, (b) A5083, and (c) A6082.

Pole figure (not shown in here) of region 1 represents a typical texture distribution of as-extruded billets. During FSW, initial grains near thermo-mechanically affected zone were bent and swirled into the weld zone. Region 3, which has dynamic flow patterns, shows a strong shear texturing, and the texturing of region 4 possesses a low intensity and similarity to random texture.

The microstructure and texture evolution of the as-welded A6082 was shown in Fig. 3. Inverse pole figure (IPF) maps at welding conditions of 1500 rpm and 200 mmpm are presented. Three different regions, the top, middle, and bottom of the weld zone, were investigated. The overall outline of the weld region was wedge-shaped because of the tool shape. inverse pole figures in Figs. 3(a) to 3(i) cover most of the welded region.

The top region was influenced by both the tool shoulder and the tool pin, and thus the wider region was thermo-mechanically affected more in the top than in other regions during FSW. Five different areas, covering the
advancing side (AD) to the retreating side (RT) (Figs. 3a to 3e), were measured in the top section using EBSD. The tool pin was mainly located in the middle layer, which location affected the weld. The weld region was relatively narrow compared with the top region. Three different areas (Figs. 3f to 3h) were measured from the advancing side via the stir zone to the advancing side. For the bottom layer, only one location (Fig. 3i) was measured. Figs. 3(a), (e), (f), (h) and (i) show the boundaries between the base metal and the stir zone. In Fig. 3(i), both the stir zone and the thermo-mechanically affected zone can be seen. The stir zone, with fine grains, was located in the center area, and the thermo-mechanically affected zone, with larger and rotated grains, was found at the bottom.

The crystallographic texture of the stir zone in the A6082 alloys reflected a strong shear texturing. In the middle layer, a strong intensity was found in the center of the (111) pole figures (not shown here). The intensity is related to the initial (111)//ED (extrusion direction) fiber. At the bottom, strong shear texturing was found in the (111) pole figure.

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4. Conclusion

In conclusion, the microstructure and the mechanical properties of FSW-welded solid-solution hardened A5083 and aging heat-treated A6082 aluminum alloys were investigated. Microstructural features of the base metal, heat-affected zone, thermo-mechanically affected zone, and stir zone were examined in detail. There was variation in the crystallographic orientation, and grain size in the weld zone. A fine and equi-axed grain structure in the stir zone revealed dynamic recrystallization during FSW. The crystallographic orientation in the stir zone of A5083 revealed a random distribution, and that of A6082 was close to strong shear texturing. Using thermocouples, temperature profiles were obtained near the heat-affected zone for both A5083 and A6082. The overall peak temperatures of A5083 and A6082 were similar. The peak temperature of A6082 near the heat-affected zone was high enough to affect the aging precipitates in A6082.
Fig. 3. Inverse pole figure (IPF) maps of as-welded A6082 at welding conditions of 1500 rpm and 200 mmpm. (a), (b), (c), (d), and (e) are inverse pole figures for the top surface region. (f), (g), and (h) are inverse pole figures for the middle region, and (i) is for the bottom.

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