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SUPPRESSION OF ABNORMAL GRAIN GROWTH IN FRICTION-STIR WELDED 6061-T6 ALUMINUM ALLOY BY PRE-STRAIN ROLLING

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ABSTRACT

In this work, the effect of pre-strain rolling on the annealing behavior of friction-stir welded 6061-T6 aluminum alloy was studied. To this end, the as-welded material was rolled to 10 or 20 pct. of thickness reduction prior to the standard post-weld T6 heat treatment. Three rolling directions were the 3-mm thick sheet were considered: along the welding direction, perpendicular to the welding direction, and at the angle of 45° to the welding direction. At relatively low pre-strains (10 pct.), the annealing behavior was found to be very sensitive to the rolling path, and rolling along the welding direction was most effective in suppressing abnormal grain growth. On the other hand, increasing the pre-strains to 20 pct. of thickness reduction inhibited abnormal grain growth irrespective of the rolling path.

KEYWORDS

Al-Mg-Si alloys, Friction-stir welding, Abnormal grain growth, Post-weld heat treatment, Pre-strain rolling

INTRODUCTION

Heat-treatable wrought Al-Mg-Si alloys are widely used due to attractive combination of strength, ductility, excellent corrosion resistance and low cost (Polmear, 2006). To provide the optimal balance of mechanical properties, these materials are typically commercially available in appropriately work- and precipitation-hardened conditions (Polmear, 2006). During conventional fusion welding, however, the prior strengthening effect is totally lost due to elimination of the work hardened structure and dissolution of the strengthening precipitations. An innovative friction-stir welding (FSW) technology may partially overcome this problem. Due to the solid-state character of this process, which involves very large strains, the welded material is characterized by fine-grained microstructure with moderate-to-high dislocation density, and thus the prior work hardening effect may be preserved or even enhanced (Threadgill et al., 2009; Mishra & Ma, 2005). However, heat input associated with FSW inevitably leads to dissolution and/or coarsening of strengthening precipitates, thus giving rise to the undesirable material softening. In an attempt to restore the strength of the friction-stir welded material, the standard T6 post-weld heat treatment has been applied, but this approach was found to lead to abnormal grain growth (Malopheyev et al., 2016; Mironov, 2013, Mironov et al., 2015).

The known abnormal grain growth may be suppressed by pre-straining. The pre-straining should create a driving force for recrystallization, promote high number of nucleation sites and thus provide a competitive character of grain growth during subsequent heat treatment. The purpose of this work, therefore, was examination of the feasibility of this approach in the case of the friction-stir welded 6061-T6 aluminum alloy.

MATERIAL AND EXPERIMENTAL PROCEDURE

The program material used in this work was commercial AA6061 aluminum alloy with measured chemical composition (wt.%) of 0.88 Mg, 0.66 Si, 0.72 Fe, 0.26 Cu, 0.12 Mn, 0.12 Cr, 0.09 Zn and balance Al. To provide an optimal balance of mechanical properties, the received material was extruded at 380°C (653K) to 75 pct. of area reduction and then subjected to the standard T6 heat treatment, i.e. solutionized at 550°C (823K) for 1 hour, water quenched and then artificially aged at 160°C (433K).

The 3-mm-thickness sheets of the T6-tempered material were friction-stir butt welded at a tool rotational speed of 1100 rpm and a welding speed of 760 mm/min by using an “AccuStir” 1004 FSW machine. The welding tool consisted of a shoulder having a diameter of 12.5 mm and an M5 cylindrical pin of 1.9 mm in length. During FSW, the welding tool was tilted by 2.5° from the sheet normal to ensure appropriate consolidation of the welded material. To provide full-thickness joining, double-side FSW was applied in mutually opposite directions. The principal directions of the FSW geometry are denoted throughout as the welding direction (WD), transversal direction (TD) and normal direction (ND).

To recover the strength of the friction-stir welded material, the obtained joints were subjected to the standard T6 tempering. To investigate the effect of the pre-strain rolling on the annealing behavior, the selected welds were cold rolled to either 10 or 20 pct. of thickness reduction. To examine an influence of the rolling path, three rolling directions were used, viz. (1) along the WD, (2) at the angle of 45° to the WD, and (3) perpendicular to the WD.

Microstructural observations were performed by electron backscatter diffraction (EBSD) technique and transmission electron microscopy (TEM). The final surface finish for EBSD and TEM was obtained by electro-polishing in a solution of 25% nitric acid in methanol. The EBSD analysis was conducted using a FEI Quanta 600 field-emission-gun scanning electron microscope (FEG-SEM) equipped with TSL OIM^{TM} software. In the EBSD maps shown throughout this work, low-angle boundaries (LABs) ($2°<\theta<15°$) and high-angle boundaries (HABs) ($\geq15°$) are depicted as red and black lines, respectively. The TEM observations were performed by using a JEM-2100EX TEM operating at 200 kV.

RESULTS AND DISCUSSION

Base Material

The base material microstructure was dominated by the relatively coarse grains elongated in extrusion direction and contained developed substructure (Figure 1a). As normally expected for the T6 tempered condition, the microstructure was characterized by nano-scale coherent dispersoids, which were evenly disturbed in the grain interior (Figure 1b).

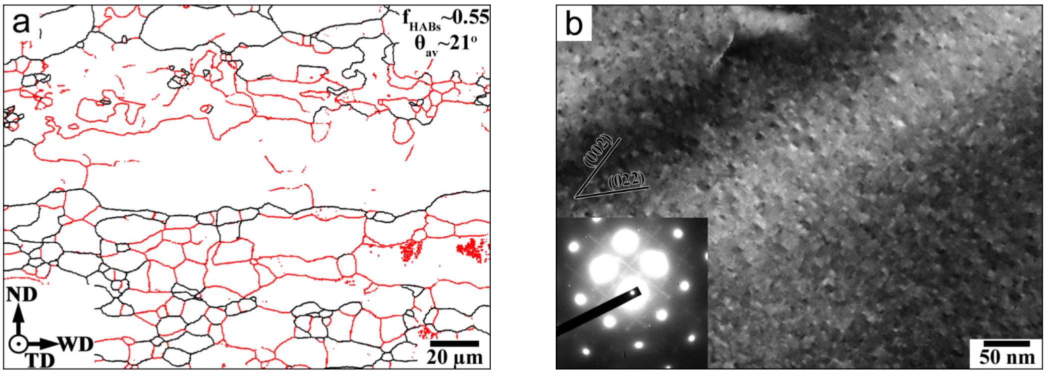

Figure 1. Microstructure of the base material: EBSD grain-boundary map (a) and TEM image (b). In (a), f_{HABs} and θ_{av} are the HABs fraction and mean misorientation, respectively. In (b), the insert shows the characteristic diffraction pattern

Friction-Stir Welded Condition

FSW promoted significant grain refinement, as shown in Figure 2a. The mean grain size in the stir zone was measured to be 5.7 µm. However, the subsequent T6 tempering gave rise to the abnormal grain growth in the stir zone (Figure 2b). This undesirable effect is often observed during annealing of friction-stir welded aluminum alloys (Mironov, 2013; Mironov et al., 2015) but its mechanism is still not completely clear.

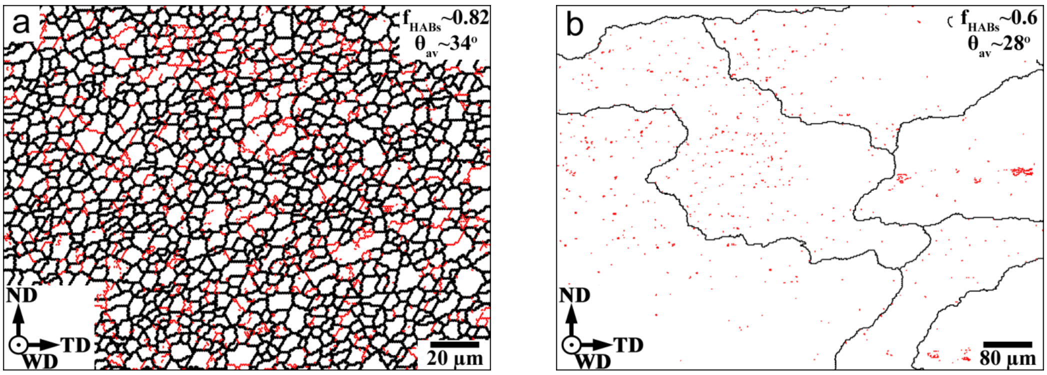

Figure 2. EBSD grain-boundary maps showing stir zone microstructure in the as-welded condition (a), and after subsequent T6 heat treatment (b)

Effect of Pre-Strain Rolling

The pre-strain rolling effectively suppressed the abnormal grain growth in the stir zone, as exemplified in Figure 3. The influence of the magnitude of the pre-strain, as well as the rolling path on the mean grain size of the final material after T6 heat treatment is summarized in Table 1.

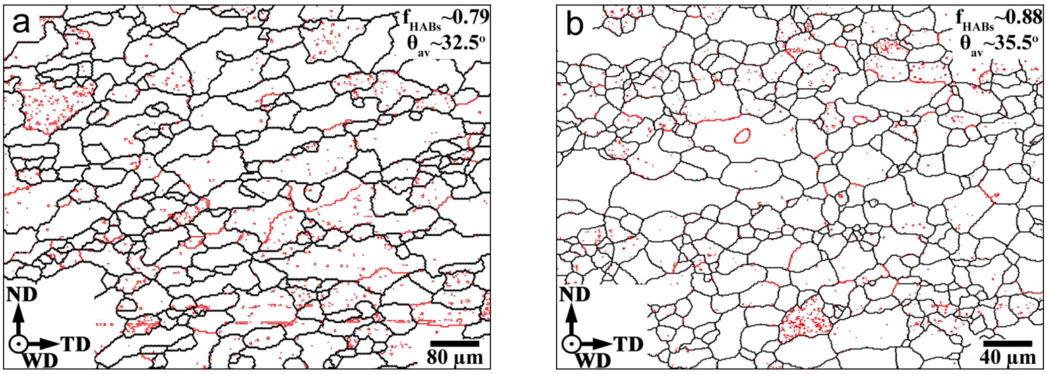

Figure 3. EBSD grain-boundary maps showing stir zone microstructure after 10 pct. of pre-strain rolling and subsequent T6 tempering (a), and after 20 pct. of pre-strain rolling and subsequent T6 tempering (b). In both cases, the rolling direction was parallel to the WD

It is seen that the increment of the accumulated strain resulted in finer grain structure, presumably due to an increase of the density of recrystallization nuclei (Humphreys & Hatherly, 2005). At relatively low pre-strains (10 pct.), the annealing behavior was found to be very sensitive to the rolling path, and the rolling along the WD was most effective in the inhibition of the abnormal grain growth (Table 1). On the other hand, the increase of the pre-strains to 20 pct. of thickness reduction suppressed the abnormal grain growth irrespective on the rolling path (Table 1).

Table 1. Effect of pre-strain rolling on the mean grain size of the final material after T6 heat treatment

Rolling direction	**Thickness reduction (%)**	**Mean grain size in the stir zone (µm)**
Along the WD		42
45° to the WD	10	100
Perpendicular to the WD		76
Along the WD		19
45° to the WD	20	26
Perpendicular to the WD		23

Therefore, this preliminary study clearly shows the feasibility of pre-strain rolling for suppression of the abnormal grain growth during post-weld heat-treatment of friction-stir welded AA6061-T6 alloy. However, the mechanism of this phenomenon is not completely clear and thus warrants further work.

CONCLUSIONS

In this work, the effect of pre-strain rolling on the annealing behavior of friction-stir welded 6061-T6 aluminum alloy was studied. To this end, the as-welded material was rolled to 10 or 20 pct. of thickness reduction prior to the standard post-weld T6 heat treatment. The main conclusions derived from this study are as follows:

1) The pre-strain cold rolling is very effective for suppression of the abnormal grain growth.
2) At relatively low pre-strains (10 pct.), the annealing behavior was found to be very sensitive to the rolling path, and rolling along the WD was most effective in the inhibition of the abnormal grain growth. On the other hand, increase in the pre-strains to 20 pct. of thickness reduction suppressed the abnormal grain growth, irrespective of the rolling path.

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