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Abnormal grain growth in a double-sided friction-stir welded Al-Mg-Si alloy

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Abstract. In this work, a standard T6 tempering (involving solution annealing followed by artificial aging) was employed to a fine-grained Al-Mg-Si alloy produced by double-sided friction-stir welding (FSW). The material was found to exhibit abnormal grain growth, thus demonstrating a relatively low thermal stability. The kinetics of abnormal grain growth in the joint was studied.

1. Introduction

Friction-stir welding (FSW) is an innovative and rapidly-developing technology of solid-state joining of structural materials [1–4]. In heat-treatable aluminum alloys, FSW normally leads to the dissolution or coarsening of strengthening precipitates thus degrading the mechanical properties of the welded material. For its recovery, the produced joints typically undergo post-weld heat treatment [5-8]. Such treatment, however, often gives rise to abnormal grain growth in the stir zone [1,2,5–10], which may essentially deteriorate service characteristics of the joints. Despite the extensive recent research in this area, the mechanism of this undesirable phenomenon is still not clear.

There is some limited evidence from the scientific literature that double-sided welds demonstrate relatively good thermal stability [4]. It is believed that this variation of the FSW process promotes a relatively uniform thermal field through the weld thickness thus resulting in a reasonably homogeneous distribution of the microstructure. However, the feasibility of this approach for suppression of abnormal grain growth is still not completely clear. Therefore, the present work has been undertaken to shed more light on this issue.

2. Material and experimental procedure

The material for the present study was a commercial AA6061 alloy produced by direct continuous casting. The obtained ingot was appropriately homogenized and then extruded at 380 °C to ~75% of area reduction. From the extruded billet, 3-mm-thick sheets were sliced along the extrusion direction (ED) and then subjected to a standard T6 tempering, i.e., solutionized at 550 °C for 1 h, water quenched and subsequently artificially aged at 160 °C for 8 h.

The T6-tempered sheets were friction-stir butt welded using an AccuStir 1004 FSW machine equipped with a welding tool with a 12.5-mm-diameter shoulder and a M5 cylindrical probe; the length of the tool probe was 1.9 mm. Welding trials were conducted under optimized condition involving a spindle rate of 1100 rpm and a feed rate of 760 mm/min [8]. The principal directions of the FSW geometry were denoted throughout as the welding direction (WD), transversal direction (TD) and normal direction (ND). To provide a full-thickness joining, a double-sided FSW was applied in mutually opposite directions.

To recover the mechanical properties of the welded material, the obtained joints were subjected to various post-weld heat treatments. Specifically, some welds were artificially aged at 160 °C for 8 h, whereas other ones were subjected to the T6-tempering in the manner described above.

Microstructural observations were performed mainly by the electron backscatter diffraction (EBSD) technique. The final surface finish was obtained by electro-polishing in a 25 pct. solution of nitric acid in methanol. EBSD analysis was conducted by using a FEI Quanta 600 field-emission-gun scanning electron microscope (FEG-SEM) equipped with TSL OIMTM software. In the EBSD maps shown, the low-angle boundaries (LABs) (2°<θ<15°) and the high-angle boundaries (HABs) (≥15°) were depicted as white and black lines, respectively.

3. Results and discussion

3.1. Base material
In the base material, the microstructure was dominated by relatively coarse grains, ~200 μm in length, aligned along the WD and having a developed sub-boundary structure. TEM observations revealed a high density of nanoscale dispersoids. As follows from the scientific literature [11,12], these particles are a mixture of needle-shaped β” precipitates with minor fraction of lath-shaped Q’ precipitates. Detailed microstructural characterization of the base material is given elsewhere [8].

3.2. Aged joint
A typical microstructure of the central portion of the stir zone of the obtained aged joint is shown figure 1a. FSW with subsequent aging led to the formation completely recrystallized fine grains with a mean size of 7.5 μm and low fraction of low-angle boundaries. From comparison with other works[1–4,8], this microstructure is typical for FSW/FSP aluminium alloys without post-weld heat treatment or subjected to low-temperature post-weld treatment.

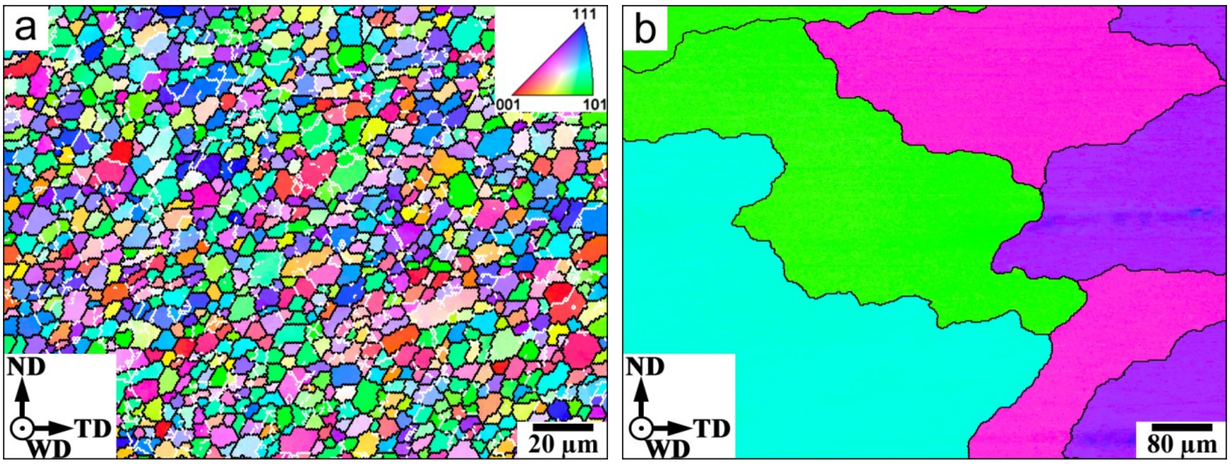

Figure 1. EBSD orientation maps showing the grain structure in the central portion of the joints after either post-weld aging (a) or post-weld T6 tempering (b). In the maps, individual grains are colored according to the orientation code shown in the top right corner of (a).

3.3. T6-tempered joint
The post-weld T6 tempering led to abnormal grain growth in the stir zone (figure 1b). This phenomenon is often observed in the heat-treated friction-stir welded/processed aluminum alloys [1,2,8,9]. However, its origin is still unclear. Despite the catastrophic grain growth in the stir zone, the strength of T6-tempered joint was fully recovered [8,9].

3.4. *Kinetics of abnormal grain growth at a double-sided FSW*

To examine kinetics of the abnormal grain growth in the T6-tempered welds, the as-weld joints were subjected to a series of annealing at 540 °C for 1, 4 or 10 minutes with subsequent water quenching. After each annealing step, the examined surface was slightly polished to remove the oxide layer for EBSD analysis.

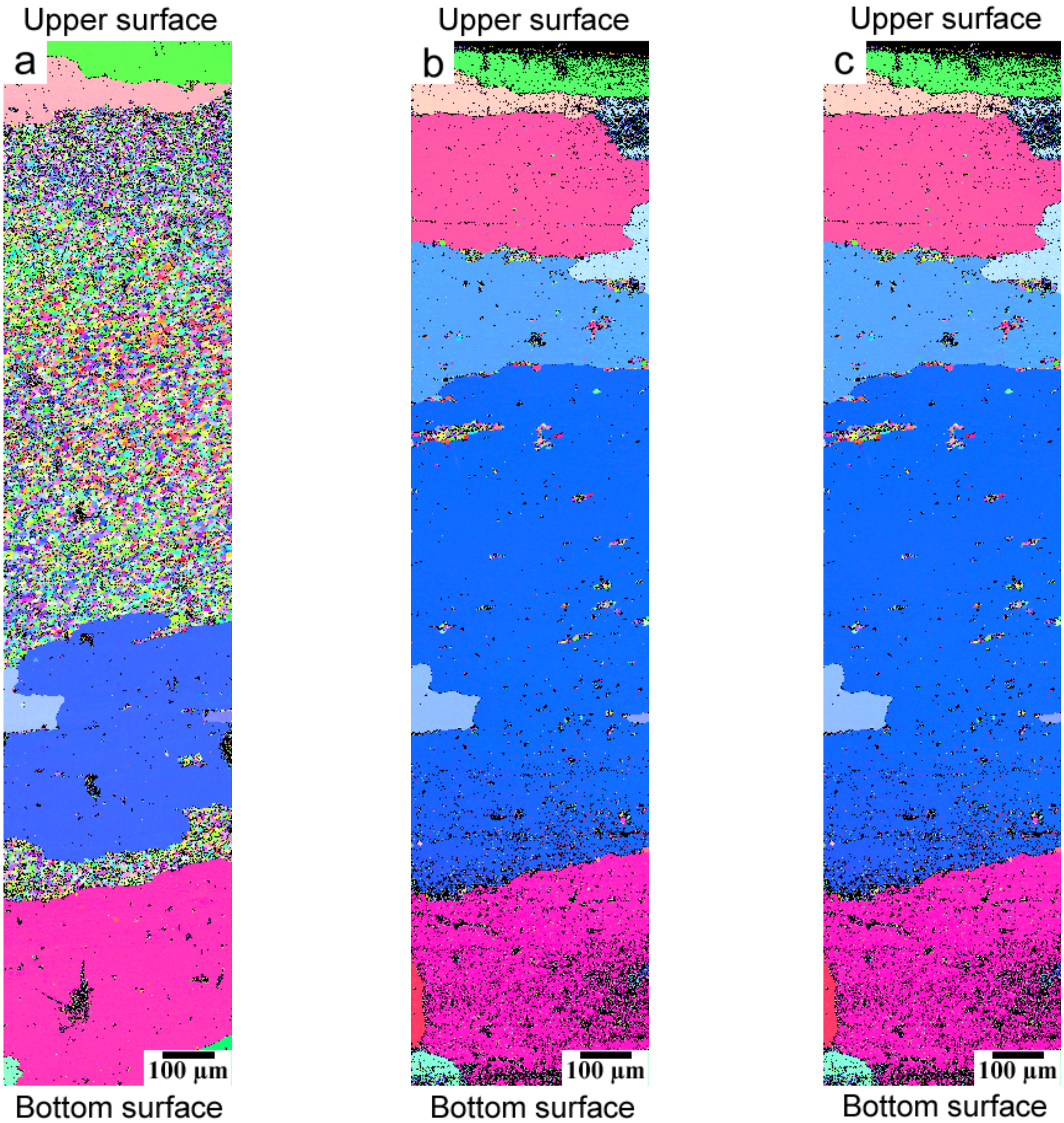

Figure 2. Low-magnification EBSD orientation maps in the ND×TD plane of the joint subjected to post-weld annealing at 540 °C for 1 min (a), 4 min (b), or 10 min (c). The surface of the joint at the second pass is marked.

The abnormal grain growth was observed at a very early annealing stage (figure 2a). Remarkably, the abnormally coarse grains were found to preferentially nucleate in the near-surface layer of the stir zone. With further annealing, however, the abnormal grains also evolved in its central section (figure 2b). The catastrophic growth of the latter grains eventually consumed the entire stir zone (figure 2c).

It is evident therefore that the double-sided FSW was not effective for suppression of the abnormal grain growth and thus the initial idea of this work was not correct. Moreover, considering the preferential nucleation of abnormal grains in the shoulder-affective region, the double-sided FSW appears to be even deteriorating for the thermal stability of the welded material.

4. Conclusions

In this work, the stability of the double-sided FSWed material against the abnormal grain growth was studied. It was found that the abnormally-coarse grains preferentially nucleated in the shoulder-affected region of the stir zone. Therefore, the thermal stability of the double-sided FSWed material was concluded to be relatively low.

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