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Investigation of an early stage of the abnormal grain growth in the friction-stir welded 6061-T6 aluminum alloy

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Investigation of an early stage of the abnormal grain growth in the friction-stir welded 6061-T6 aluminum alloy

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Abstract. In this work, quasi in-situ electron backscatter diffraction (EBSD) was applied to study an early stage of the abnormal grain growth occurring in the friction-stir welded 6061 aluminium alloy during post-weld solution heat treatment. It was found that the catastrophic grain growth completed during the heating stage of the annealing treatment, and further static storage at the solutionsizing temperature provided almost no microstructural changes.

1. Introduction

Friction-stir welding (FSW) is often considered as a promising technique for joining of heat-treatable aluminum alloys. Due to the solid-state character of the welding process, FSW avoids numerous solidification defects intrinsic to conventional fusion technologies and thus produces sound joints with excellent mechanical properties [1, 2]. An essential drawback of FSW, however, is the relatively low stability of the welded material against the abnormal grain growth [e.g. 3-6]. This undesirable phenomenon typically occurs during solution heat treatment of welded joints and may essentially degrade their service properties. Currently, this process is usually interpreted in terms of Humphrey's cellular theory [7], being usually attributed to the coarsening- and/or partial dissolution of second-phase particles occurring during FSW [e.g. 4]. In this context, it is worth noting that the constituent precipitates should *completely dissolve* at the solutionizing temperature and therefore, *they cannot exert any influence on the grain growth behavior*.

This apparent controversy may be explained assuming that the abnormal grain growth occurs during the *heating stage* of the solution heat treatment. In this case, the secondary particles still retain in the material and thereby they may affect the microstructural processes. The present work was undertaken in order to check this simple idea. To this end, the early stage of the abnormal grain growth in a friction-stir welded heat-treatable aluminum alloy was studied by using a quasi in-situ electron backscatter diffraction (EBSD) technique.

2. Experimental

The program material used in the present study was a commercial 6061 aluminum alloy. This is a typical heat-treatable alloy which is widely applied in industry and whose FSW behavior is studied relatively well. The material was produced by semi-continuous casting, homogenized at 380°C for 1 hour and then extruded at the same temperature to a cross-area reduction 75%. To provide the peak-hardened condition, the hot extruded material was undergone to the T6 tempering treatment, i.e., solutionized at 550°C for 1 hour, water quenched and then aged at 160°C for 8 hours.

The tempered material was friction-stir welded at the spindle- (rotation) rate of 1100 rpm and the feed rate of 760 mm/min. This particular welding regime was selected on the basis of previous works [8, 9] which showed that this combination of FSW variables promotes excellent mechanical characteristics under both the static- and cyclic loading conditions. The welding tool was fabricated from a tool steel and consisted of a concave-shaped shoulder (with a diameter of 12.5 mm) and an M5 cylindrical probe of 1.9 mm in length. To provide a full-thickness joining of 3-mm-thick welding sheets, double-side FSW was applied in the same welding direction.

Microstructural observations were focused on the transverse cross-section of the welded material. These were conducted by EBSD using a FEI Quanta 600 field-emission-gun scanning electron microscope equipped with TSL OIM software. A suitable surface finish for EBSD was obtained by mechanical polishing in a conventional fashion followed by electro-polishing in a 25% HNO_3 solution in methanol.

To investigate the early stage of the abnormal grain growth, the same welded specimen was placed into a 550°C preheated furnace and sequentially kept at this temperature for 1, 4, and 10 minutes. For comparison, the *heating time* for achieving the annealing temperature (i.e., 550°C) was measured to be ~6 min. Therefore, two first annealing steps represented the heating stage of the solution heat treatment. After each annealing step, the microstructural specimen was immediately quenched in water, and EBSD maps were taken from the same microstructural region within the stir zone without any surface polishing. This provided a quasi in-situ condition for the EBSD experiment. For the aid of comparison, appropriate EBSD maps were also obtained from the as-welded material condition as well as from the fully-annealed sample subjected to the standard solution heat treatment (550°C, 1 hour).

3. Results and Discussion

3.1. Preliminary analysis

The typical microstructure found in the stir zone in the *as-welded* material condition is shown in Figure 1a. It is seen, the microstructure was dominated by fine- nearly-equiaxed grains with a mean boundary intercept of ~5 μm. Such microstructures are typically observed in friction-stirred aluminum alloys, and are usually attributed to the continuous recrystallization operating during FSW [e.g. 10-12].

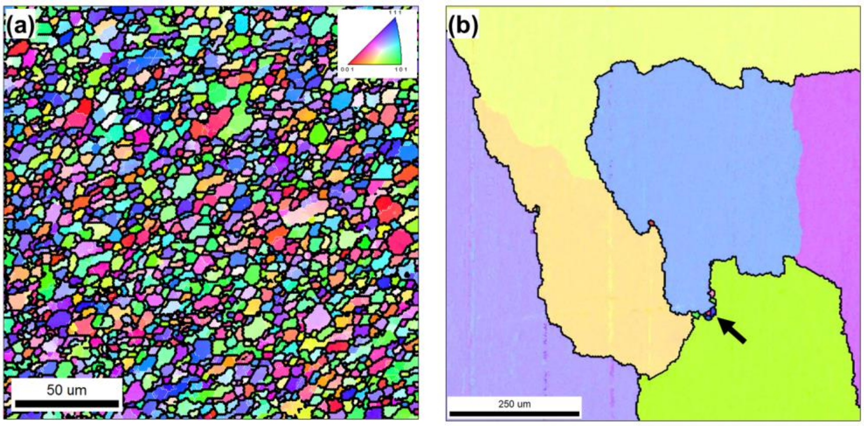

Figure 1. EBSD orientation maps taken from the central section of stir zone (a) in the as-welded material condition and (b) after subsequent solution heat treatment (550°C, 1 hour). In the maps, individual grains are colored according to their crystallographic orientations relative to welding direction; low- and high-angle boundaries are depicted as white and black lines, respectively. In (b), arrow exemplifies the survived remnant of fine-grained structure. Note difference in scales

Subsequent solution heat treatment resulted in the development of mm-scale irregular-shaped grains (Figure 1b). Importantly, the material also contained a minor fraction of the survived fine-grained structure (an example is arrowed in Figure 1b). This microstructural bimodality evidenced the obvious abnormal character of the grain growth, in close agreement with the literature data [3-6].

3.2. Quasi in-situ EBSD observations

A series of sequential EBSD maps taken during the quasi in-situ experiment is shown in Figure 2. It is seen that the abnormal grain growth initiated at the early stage of the heating period (Figure 2a) and virtually completed after achieving the solitionizing temperature (Figure 2b). On the other hand, the subsequent static storage at the annealing temperature provided almost no further microstructural changes (compare Figures 2b & 2c). Thus, the present study confirmed the proposed idea on the preferential development of the abnormal grain growth during heating stage of the solution heat treatment.

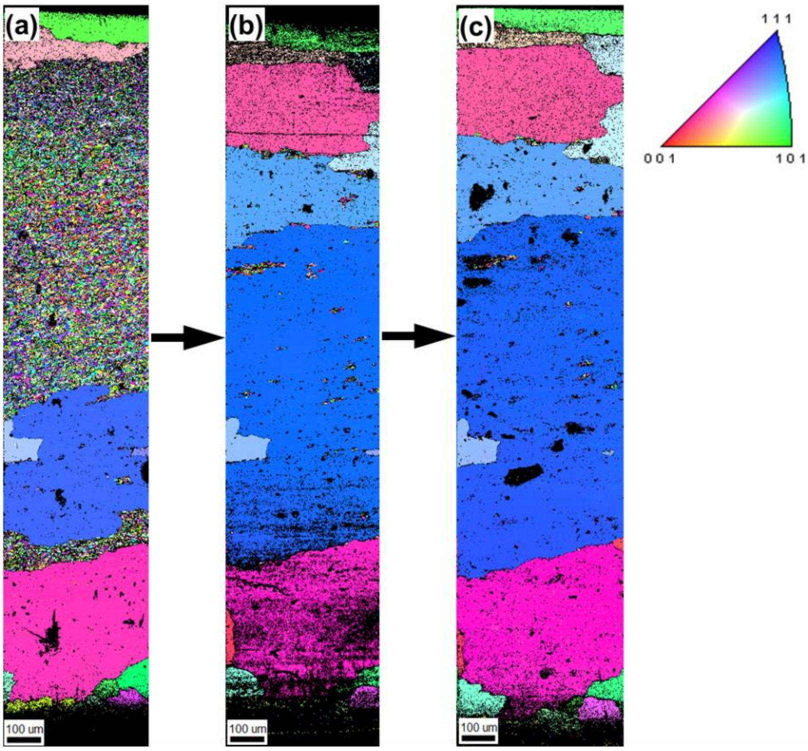

Figure 2. A series of the cross-thickness EBSD orientation maps showing the abnormal grain growth in the stir zone as a function of annealing time at 550ºC: (a) 1 min (i.e., the initial step of the heating stage), (b) 1+4 min (i.e., the nearly-completion of the heating stage), and (c) 1+4+10 min (i.e. a static storage at the annealing temperature). In the maps, individual grains are colored according to their crystallographic orientations relative to welding direction. The black pixels are the EBSD data with confidence index below 0.1

This result could be rationalized by considering the characteristic temperatures for the onset of the grain growth and the particle dissolution. In fine-grained aluminum alloys, gross grain boundary migration is typically observed above 250ºC [13], i.e. it should normally develop during the heating stage. On the other hand, the constituent β-phase precipitates in the examined 6061 alloy should completely dissolve only at 500ºC [14]. Thus, the secondary particles should influence the grain growth and this presumably resulted in the activation of the abnormal mechanism.

It is interesting to note that the abnormal grains nucleate at the peripheral regions of the stir zone, i.e. at its upper surface and near the weld root (Figure 2a). This agrees well with reports in scientific literature [e.g. 15, 16], and is sometimes explained by the very specific microstructure evolved in these areas during FSW [17]. Subsequently, however, the abnormally coarse grains also evolve in the stir zone interior (Figure 2b) thus indicating that the abnormal grain growth was not a surface phenomenon.

4. Conclusion

This work was undertaken in order to investigate an early stage of the abnormal grain growth in the friction-stir welded 6061 aluminum alloy. To this end, a quasi in-situ EBSD technique was applied. It was shown the abnormal grain growth preferentially develops during the heating stage of the solution heat treatment. Moreover, it seems from the experimental results that the abnormal grain growth almost completely ceased after achieving the solutionizing temperature and subsequent static storage provides almost no microstructural changes.

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