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Grain structure evolution during friction-stir welding of 6061-T6 aluminum alloy

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Abstract. In this work, electron backscattered diffraction (EBSD) was used to examine the evolution of the grain structure during friction stir welding of aluminum alloy 6061-T6. In the entire FSW range studied, the microstructure evolution was found to be governed by continuous recrystallization. An increase in the welding temperature resulted only in microstructural coarsening.

Keywords – Friction-stir welding, Heat-treatable aluminum alloys, Electron backscatter diffraction

1. Introduction

From a thermo-mechanical standpoint, friction-stir welding (FSW) represents a unique combination of very large strains, high temperature and relatively high strain rate [1]. Such extreme deformation conditions lead to significant changes in the grain structure. Many researchers suppose that these changes mainly take place in the thermo-mechanical affected zone (TMAZ) and the stir zone (SZ).

In the SZ, deformation and temperature reach their highest values. Accordingly, the most significant microstructural changes occur in this zone and, accordingly, this microstructural region attracts the greatest interest of researchers. An extensive research in this area has demonstrated a significant grain refinement [2, 3]. The microstructures formed in the SZ are usually characterized by equiaxial grain morphology, as well as a relatively high proportion of high-angle boundaries (HABs). Remarkably, the misorientation distribution in this area is often found to be nearly random [4]. The dislocation density is usually low [5-9]. All these microstructural features indicate an occurrence of recrystallization during FSW. The grain size in the SZ is known to be very sensitive to the FSW conditions [10]. Typically, the average grain size increases with the tool rotation speed but decreases with a tool translation speed. This effect is most likely associated with the concomitant variations of welding temperature.

On the other hand, the microstructure formed in the TMAZ has received relatively low attention in scientific literature. It is only known that the grains in this area are significantly elongated, orienting themselves approximately parallel to the SZ [1]. It is accepted that the material in this microstructural region experiences large shear deformation, and the change in grain morphology is explained by the geometric effect of deformation. It is also assumed that a developed subgrain structure is formed within the elongated grains [1].

Considering a transition nature of TMAZ between the original material and the final stir zone, it should be emphasized that the microstructural changes in this region are a key issue in ascertaining of the recrystallization mechanism operating during FSW. In this work, electron backscatter diffraction

(EBSD) was applied to examine the TMAZ microstructure evolved during FSW of 6061 aluminum alloy.

2. Material and experimental procedure

The material used in this study was a commercial aluminum alloy AA6060-T6 with nominal 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. The material was produced by semi-continuous casting, homogenized at 380 °C for 1 h and then extruded at the same temperature to 75% of area reduction. To obtain the peak-aged condition, the extruded material was T6-tempered, i.e., solutionized at 550 °C for 1 h, water quenched at then artificially aged at 160 °C for 8 h. Sheets with a thickness of 3 mm was friction-stir butt welded using an AccurStir 1004 FSW machine. The welding tool consisted of a shoulder having a diameter of 12.5 mm and an M5 cylindrical probe of 2.7 mm in length. Two FSW trials were performed. To investigate the microstructure evolution at relatively low welding temperature, FSW was conducted at the spindle rate of 500 rpm and a feed rate of 380 mm/min. To explore the microstructural changes at relatively high welding temperature, FSW was performed at the spindle rate of 1100 rpm and a feed rate of 125 mm/min. The produced welds were denoted throughout as 500-380 weld and 1100-125 weld, respectively. In all cases, the tool tilting angle of 2.5° was employed and stainless steel was used as a backing plate.

Microstructural observations were conducted by EBSD technique by using a FEI Quanta 450 Nova field-emission-gun scanning electron microscope equipped with TSL OIM^{TM} software. A suitable surface finish for EBSD was obtained by electro-polishing in a solution of 25% nitric acid in methanol. A 15° criterion was employed to differentiate low-angle boundaries (LABs) from high-angle boundaries (HABs).

3. Results and discussion

To understand the mechanisms of evolution of the grain structure during FSW, microstructural changes in the TMAZ of both welds were analyzed. To this end, the appropriate EBSD maps were acquired and shown in Figures 1 and 2. From the maps, it was seen that the microstructure evolution in both cases was associated with progressive development of LABs.

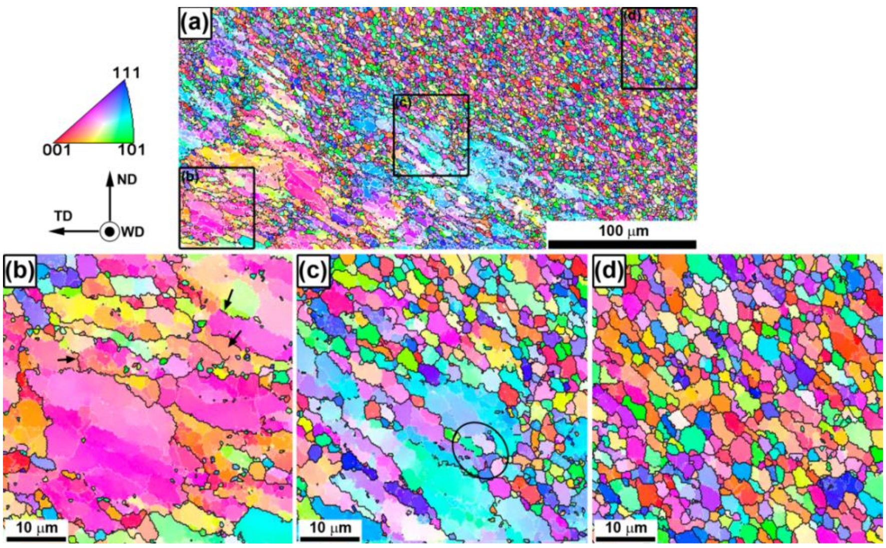

Figure 1. EBSD orientation map taken from TMAZ of the 500-380 weld. LABs and HABs are depicted as white and black lines, respectively.

In the cold periphery of the deformation zones of both welds, under the condition of relatively low temperatures and low strains, an extensive formation of deformation-induced LABs was found (Figures

1b and 2b). The deformation-induced boundaries formed a developed subgrain structure in the grain interior (Figures 1b and 2b). With approaching to the SZ (and the concomitant increase in temperature and the accumulated strain, the LABs rapidly accumulated misorientation over 15° thus transforming into HABs (several examples are arrowed in Figures 1b and 2c). Accordingly, the subgrains tended to transform into grains (several examples are circled in Figures 1c and 2c). The observed process fits a definition of *continuous recrystallization*.

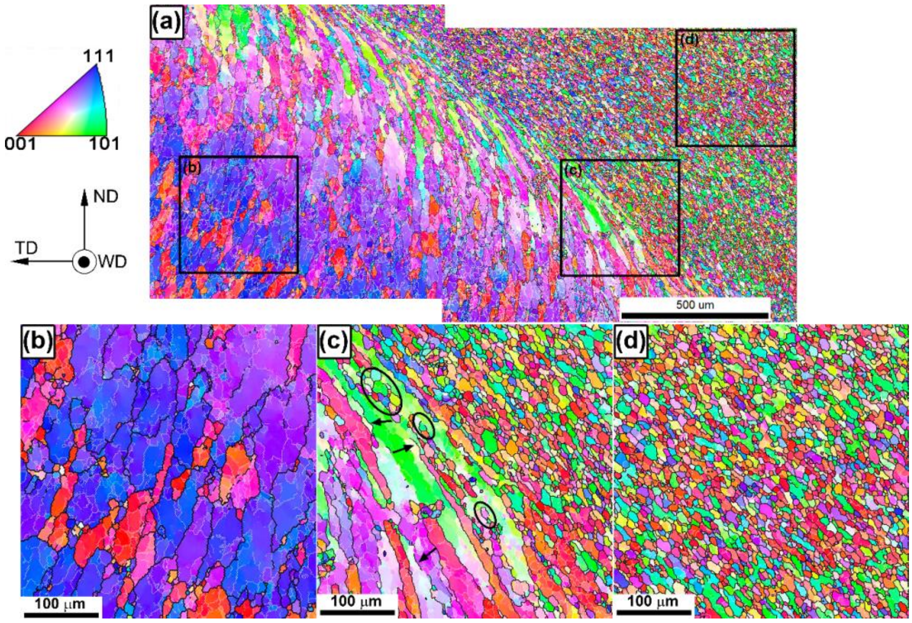

Figure 2. EBSD orientation map taken from TMAZ of the 1100-125 weld. LABs and HABs are depicted as white and black lines, respectively.

Moreover, the original grains were significantly sheared in a direction of material flow, thereby essentially thinning the grain cross-section; this effect was most pronounced in the high-temperature weld (Figure 2c). This phenomenon is usually attributed to a so-called *geometrical effect of strain*.

A development of both processes eventually resulted in a formation of fine-grained structure in the stir zone (Figures 1d and 2d). Therefore, the grain structure development in both cases was concluded to be driven by a superposition of continuous recrystallization and the geometrical effect of strain. The sole difference between two welds was a somewhat coarser stir zone microstructure evolved at higher welding temperature (with the mean grain intercept of 8.6 μm vs 2.4 μm).

4. Summary and conclusions

In this work, grain structure evolution in friction-stir welded 6061-T6 aluminum alloy was studied by EBSD. In the entire studied FSW range, the microstructure evolution was shown to be governed by the *continuous recrystallization*. An increase in the welding temperature promoted only a subtle microstructural coarsening.

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