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Abnormal grain growth in fine-grained aluminum produced by friction-stir welding

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Abstract. In this work, fundamental aspects of abnormal grain growth, which typically occurs during annealing of friction-stir welded (FSW) aluminium, were studied. To this end, crystallographic orientations of abnormally-coarse grains were systematically examined. Statistical analysis showed that those were not random. Specifically, it was found that the abnormal grain growth resulted in ~30º<111> rotation of FSW-induced B/-B {112}<110> texture. Accordingly, the abnormal character of the grain growth was interpreted in terms of increased mobility of 30º<111> boundaries.

1. Introduction

Friction stir welding or processing (FSW/P) is sometimes considered as a relatively new technique for grain refinement of structural alloys [1, 2]. In this approach, a material undergone very large strain at elevated temperature and relatively high strain rate, and this typically gives rise to the formation of a fine-grained microstructure with a mean grain size in the range from 1 to 10 μm [2]. Due to the complex character of the material flow during FSW, the resulting crystallographic textures are often weak, and thus the processed material is characterized by a relatively high fraction of high-angle boundaries. As a result, such materials normally exhibit excellent superplastic properties [1, 2]. Unfortunately, the FSWed materials had relatively low stability against abnormal grain growth [2-6]. This undesirable effect leads to significant degradation of mechanical characteristics. Accordingly, significant efforts have been undertaken recently to elucidate the mechanism of this phenomenon [2-6]. The extensive research has shown that the grain-growth behavior of the friction-stir welded (FSWed) materials could be often described in terms of Humphreys' cellular model, i.e. arises from an imbalance between the grain-growth pressure and the pinning force exerted by second-phase particles or low-angle boundaries [7, 8].

In an attempt to provide a further insight into this phenomenon, crystallographic orientations of the abnormally-growing grains were measured in the present study. To this end, the electron backscatter diffraction (EBSD) technique was used.

2. Material and experimental procedure

The program material used in the present study was a commercial aluminum alloy, supplied as 2-mm-thick cold-rolled sheets. The received sheets were FSWed in a bead-on-plate configuration at a spindle rate of 2000 rpm and a feed rate of 10 mm/s. The welding tool was manufactured from tool steel and consisted of a shoulder of 12 mm in diameter and a cylindrical threaded M5 probe of 1.7 mm in length. To maintain consistency with the FSW literature, the reference directions used in this work were denoted throughout as welding direction (WD), normal direction (ND), and transverse direction (TD). After FSW, the produced welds were section perpendicular to the WD for microstructural observations. The selected microstructural samples were annealed at temperatures ranging from 400 to 500 ºC for the soaking times ranging from 10 min to 1 hour. To preserve the high-temperature microstructure, the annealed specimens were quenched in iced water. The microstructures and crystallographic textures produced after FSW and the post-weld heat-treatment were examined by using EBSD. To this end, a Hitachi S-4300SE field-emission gun scanning electron microscope equipped with TSL OIM^{TM} EBSD system was employed. To eliminate spurious boundaries induced by orientation noise during EBSD mapping, a lower-limit boundary misorientation cut-off 2 degree was used. A 15-degree criterion was applied to differentiate low-angle boundaries (LABs) from high-angle boundaries (HABs).

3. Results and discussion

A sample-scale EBSD map taken from the cross-section of the friction-stir welded material is shown in figure 1. In the map, the grains are coloured according to their crystallographic orientations (the standard colour code triangle is given in the bottom right corner of the map). From the map, it was clear that distribution of the crystallographic texture was very inhomogeneous across the stir zone. This effect is well known from the FSW literature being usually attributed to the rotation of the welding tool and the respective variation of shear direction across the stir zone [9].

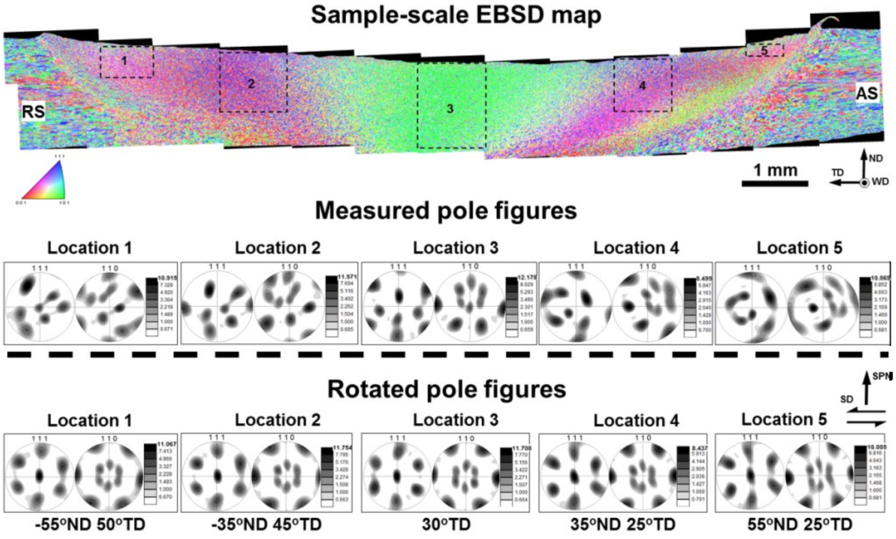

Figure 1. Sample-scale EBSD map taken from friction-stir welded material and 111 and 110 pole figures showing texture distribution in various sections of the stir zone. RS and AS are the retreating side and the advancing side, respectively. SPN and SD denote the shear plane normal and the shear direction, respectively. See text for details.

To provide a deeper insight into the evolved texture, orientation data were extracted from selected regions in the EBSD map, arranged as 111 and 110 pole figures, and also shown in figure 1. As expected the measured texture substantially varied. However, after transforming the measured textures into a standard reference frame for the simple-shear deformation (i.e. the local shear direction is horizontal and the local shear normal is vertical), all rotated pole figures showed a typical B/-B {112}<110> texture component (figure 1). Such a texture is often reported to develop during FSW of aluminium alloys [9].

To investigate the grain structure produced during FSW, high-resolution EBSD maps were taken from several locations within the stir zone. It was found that evolved microstructures were dominated by low-aspect-ratio grains of ~1 μm in size (not shown). Remarkably, the measured HAB fraction was found to vary from 63 to 77%, thus being relatively high. It is often believed that such a microstructure should be stable against the abnormal grain growth.

The annealing behaviour of the FSWed material is shown in figure 3. It is clear that the microstructure evolution was dominated by the abnormal grain growth.

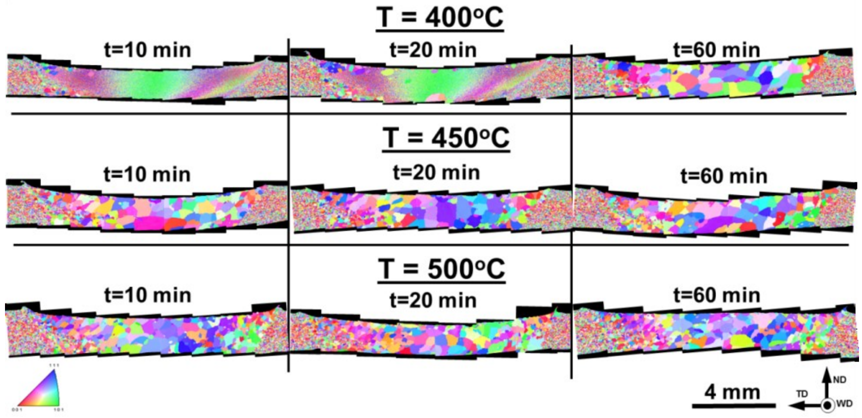

Figure 2. Low-resolution EBSD maps showing the annealing behavior of friction-stir welded materials at different temperatures. In the maps, grains are colored according to their crystallographic orientation relative to the WD. In all cases, the retreating side is on the left, and the advancing side is on the right. See text for details.

In order to get insight into this phenomenon, crystallographic orientations of the abnormally-coarse grains were measured and the obtained results were summarized in figure 3.

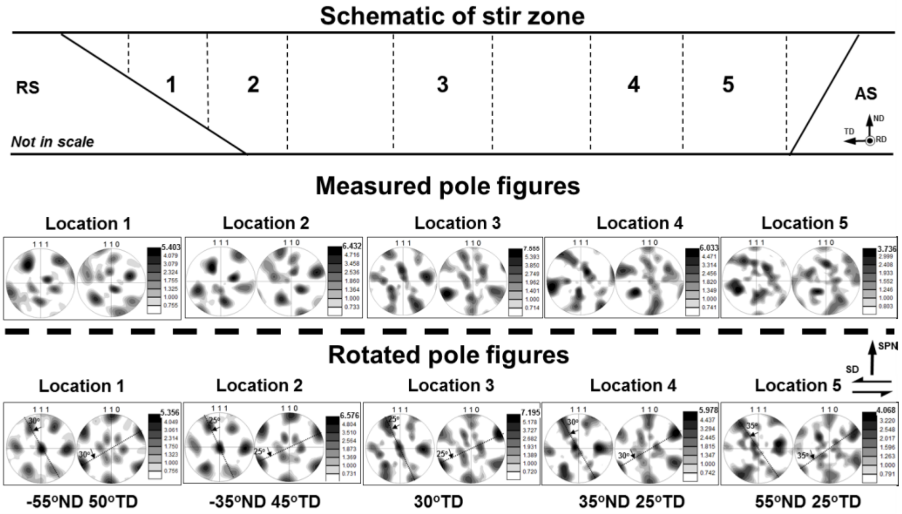

Figure 3. Schematic of the weld cross-section of fully annealed material together with 111 and 110 pole figures showing the texture distribution within the stir zone. SPN and SD denote the shear plane normal and the shear direction, respectively. See text for details.

To interpret the textural data taken from different locations within the stir zone, the measured pole figures were rotated appropriately to bring them into a standard reference frame for simple shear, similar to that applied to the as-welded material in figure 2. The applied rotations were noted beneath the rotated pole figures in figure 3.

From the rotated pole figures in figure 3, it was clear that the crystallographic orientations of the abnormal grains were not random. Moreover, from a comparison of the rotated pole figures in figures 1 and 3, it could be deduced that the abnormal grain growth resulted in a ~30-degree rotation of the as-FSWed texture around the <111> axis.

To the best of the authors' knowledge, this effect has never been reported so far for the FSWed materials. On the other hand, it is well known for annealing of cold-rolled cubic metals, being usually attributed to the theory of orientation growth [10]. According to this concept, the formation of annealing texture is associated with increased mobility of grain boundaries with a particular misorientation. Specifically, the boundaries with ~30-40°<111> misorientation are well accepted to have relatively high migration mobility in faced-centred cubic metals. As a result of the preferential migration of such boundaries, the rolling texture may experience a ~30-40°<111> rotation during grain growth, similar to that observed in the present study.

The obtained result suggests that the abnormal grain growth in FSWed aluminium was associated with increased migration mobility of ~30°<111> boundaries.

4. Conclusion

In this work, the EBSD technique was applied to directly measure the crystallographic orientations of abnormally-growing grains in friction-stir welded aluminium. The most important results derived from this work were as follows.

Crystallographic orientations of the abnormally-coarse grains were not random. Statistical analysis showed that these could be described in terms of the as-welded B/-B {112}<110> texture rotated by ~30 degrees around the <111> axis.

The above result suggests that the abnormal grain growth may be associated with increased migration mobility of ~30°<111> boundaries in face-centred cubic metals.

Acknowledgments

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