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Roughness of grain boundaries in partly recrystallized aluminum

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ABSTRACT

The roughness of grain boundaries in partly recrystallized microstructures has been quantified. Effects of material and processing parameters on the roughening behavior have been statistically investigated. Parameters are sample purity, deformation strain and boundary migration direction in two cold rolled aluminum samples. The results show that particle pinning is not the main reason accounting for recrystallization boundary roughness in the present samples. The roughness is however shown to relate to the deformation microstructure and possible effects of migration rate are discussed.

Recently both theoretical simulations and experiments have shown relations between the migration of recrystallization boundaries and the roughness of the boundaries at local as well as global scales. Phase-field modeling has shown that roughness in the form of protrusions and retrusions on recrystallization boundaries can result in an overall increased migration rate because of asymmetry in the protruding and retruding boundary segments [1,2]. It has also been shown by molecular dynamic (MD) simulations that boundaries with rough morphologies have high mobility while smooth boundaries can lead to stagnation of boundary motion [3]. Direct experimental observations of recrystallization boundary migration in 4 dimensions (4D – x, y, z and time) using synchrotron X-ray techniques have revealed that recrystallizing boundaries migrate in a non-homogeneous manner both temporally and spatially: the boundaries migrate in a 'stop-go' manner and the boundaries may be rough with protrusions and retrusions [4,5]. These rough features have also been observed using 2-dimensional characterization techniques such as electron channeling contrast (ECC) or electron backscattered diffraction (EBSD) [e.g. 6–8].

One may think of many parameters that can affect the roughening behaviors of recrystallization boundaries. In the present work, we investigate effects of sample purity, deformation strain and thus deformation microstructures, as well as grain boundary direction relative to the processing direction (here the rolling and normal directions for cold rolled samples) on the roughness of many recrystallizing boundaries in partly recrystallized microstructures. This leads first of all to an evaluation of which factors are important and which are not, and secondly to further the understanding of roughening mechanisms for recrystallization boundaries.

The recrystallization boundaries in two partly recrystallized aluminum materials were examined: 99.996% and 99.5% purity (AA1050). The AA1050 material contain 0.5% volume fraction of $FeAl_3$ and FeAlSi particles with an average diameter of 1.7 μm [4]. The aluminum of 99.996% purity, with an initial grain size of several millimeters was cold-rolled to 50% reduction in thickness and then annealed at 200 °C for 60 min to obtain approximately 50% partly recrystallized microstructures. This sample is designated as "pureAl50" in the following text. The AA1050 material, with an initial grain size of ~70 μm, was cold-rolled to two different reductions in thickness, 50% and 90%, and then annealed for 60 min at 325 °C and 300 °C, respectively, to obtain approximately 50% partly recrystallized microstructures. The two AA1050 samples are designated after the cold rolling reduction as "Al50" and "Al90" in the following text. For all three samples, the partly recrystallized microstructures were examined using EBSD in the sample longitudinal section, which is defined by the rolling direction (RD) and the normal direction (ND). A step size of 0.1 μm was used for the EBSD measurement. Based on the orientation maps, the recrystallizing grains were extracted from the surrounding deformed matrix using the DRG algorithm described in [9].

As examples, small parts of orientation maps of the three samples are shown in Fig. 1. In the Al50 sample, the recrystallizing grains are well distributed in the deformed matrix. The majority of the grains are elongated along RD. The average aspect ratio of the recrystallized grains in the Al50 sample is 1.9 ± 0.5. In the Al90 sample, the recrystallizing grains appear in bands aligned along RD and the grains are mostly elongated and impinged upon each other within the bands, with an average aspect ratio of 2.1 ± 0.4. The boundary segments aligned along ND in Al90 specimens are thus mostly between recrystallizing grains. In the pureAl50 sample, the recrystallized grain size is much larger and can extend up to several millimeters along RD. Therefore, most of the

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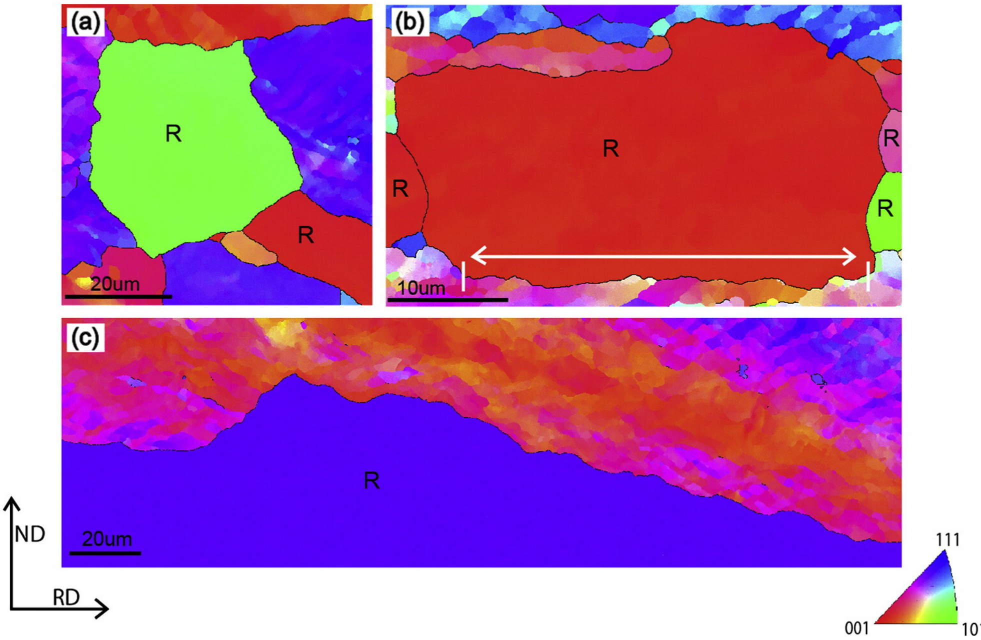

Fig. 1. Subsets of EBSD images (inverse pole figure coloring) showing recrystallization boundaries in (a) Al50, (b) Al90 and (c) pureAl50 specimens. The EBSD data was collected using a step size of 0.1 μm. The black line represents high angle boundaries with misorientations larger than 15°. 'R' represents the recrystallizing grains. The white arrow in (b) shows an example of a boundary segment used for the roughness calculation.

orientation maps show only incomplete recrystallized grains. It is generally observed that, in contrast to the boundaries between recrystallized grains, which are smoothly curved, the boundaries between recrystallized grains and deformed matrix are rough with protrusions and retrusions of various shapes and sizes. In the current study, only the boundaries between recrystallized grains and deformed matrix are considered, because only these boundaries will migrate further during recrystallization while the boundaries between recrystallized grains will typically only move during grain growth at higher temperatures. In the analysis, only extended boundary segments that distinctly align either along RD or ND (within 20° deviation) are considered, excluding grain boundary junctions and grain boundary 'corners'. An example of a boundary segment aligned along RD in the Al90 sample following these criteria is illustrated in Fig. 1(b), where the boundary segment is marked by the white arrow.

The roughness of the recrystallization boundary segments is quantified using the method described in [10,11], which is developed for characterization of roughness of 2-D line features. In this method, a morphological variable termed area integral invariant (*AII*) is employed to collect local morphological information of the boundaries. *AII* works by drawing a circle with a specified radius, termed sampling radius, and with the center of the circle positioned on the boundary. In this way, the area of the circle is separated into two parts by the recrystallization boundary: one part within the recrystallized grain and the other part within the deformed matrix. Then the *AII* value is calculated as the ratio of the circle area within the recrystallized grain to the area of the entire circle, with a numeric value between 0 and 1. If the boundary segment within the circle is planar, the *AII* value will be 0.5 as the circle area is divided by the boundary equally between recrystallized grain and the deformed matrix. If the circle encloses a protrusion, the *AII* value will be smaller than 0.5 as the circle area within the recrystallized grain will be less than half and reversely for a retrusion. Since the *AII* value is directly measured at a position on the boundary, this method works for complex boundary shapes [11]. As discussed in [11], it is very important to choose an appropriate sampling radius. If for example a very large sampling circle is chosen compared to the scale of the roughness, the *AII* value will be close to 0.5 and one may wrongly conclude that the boundary is planar.

When a proper sampling radius is chosen, the *AII* value at every position of a selected boundary segment is obtained with this sampling

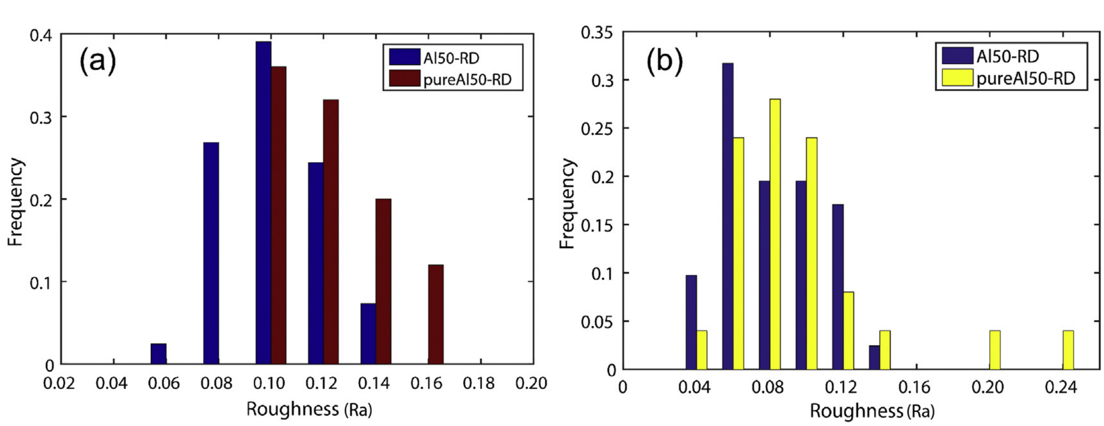

Fig. 2. Histogram of the roughness parameters for recrystallization boundary segments aligned along RD in the Al50 and pureAl50 samples. The roughness parameters were calculated with sampling radii of (a) 1 μm and (b) 3 μm.