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Quantitative correlation between slip patterning and microstructure during tensile elongation in 6xxx series aluminum alloy

S Ghodrat[1] H Pirgazi[2] and LAI Kestens[1,2]
[1] Delft University of Technology, Materials Science and Engineering Department, Mekelweg 2, 2628CD Delft, The Netherlands.
[2] Ghent University, Department of Materials Science and Engineering, Technologiepark 903, 9052 Zwijnaarde-Gent, Belgium
E-mail: s.ghodrat@tudelft.nl, hadi.pirgazi@ugent.be, leo.kestens@ugent.be

Abstract. To the purpose of evaluating the effect of deformation on the microstructure, aluminum structures were analyzed on tensile strained samples extended to 25% elongation. In the substructure of these deformed samples linear slip patterns were observed, generally confined to the bulk of the grain. In order to study the crystallographic aspect of these slip patterns, two methods were applied based on orientation contrast microscopy (EBSD). The first method is the statistical analysis of stereological nature, which allows us to determine the incidence of certain crystallographic planes with the slip patterns. In other to corroborate the statistical method, also a 3D analysis was carried out on two perpendicular planes of observation (TD and ND sections). The results of both methods were in a very good agreement. It was found that the linear features are predominantly parallel to the {111} crystal planes, although the frequency of {111} planes was not exclusive; also other crystal planes such as {112} and {110} are involved. These observations give a stronger statistical basis for similar observations earlier made by TEM on much smaller fields of observation.

1. Introduction

The evolution of crystal misorientation is an indication of local strains induced in the microstructure by plastic deformation involving dislocation glide in the metal matrix. The dislocations remaining in the microstructure configure themselves in cells or subgrains and more aggregate slip patterns, which will give rise to small orientation gradients. The microstructural effect of plasticity can be gauged by monitoring the crystallographic features of such slip patterns. Dislocation induced structures in aluminum have been extensively studied in the last decades [1-4]. Crystals and grains during deformation are subdivided on a macroscopic scale into deformation bands and on a more microscopic scale into cell blocks and cells. Parallelogram-shaped Cell Blocks (CBs), which are delineated by planar dislocation walls, contain cells surrounded by incidental dislocation boundaries [4]. Dense Dislocation Walls (DDWs) are of a thin planar nature, whereas Microbands (MBs) are thicker and can be distinguished as double boundaries in the TEM. There is a lot of controversy on the crystallographic nature of these phenomena. According to Delannay [4] the DDWs are formed parallel to the most stressed {111} plane. However, Hansen [2,3] also observed DDWs not showing any obvious alignment with the {111} planes.

Analyzing the crystallographic orientation of slip patterns will contribute to the understanding of mechanism by which they are generated and hence it will provide an improved insight in the deformation microstructure. Most of the previous investigations are base on TEM observations, which unfortunately lack statistical reliability. Even most EBSD mappings are done on a rather small scale. Therefore the aim of this work is to give a better statistical basis for the crystallographic aspects involved in the formation of the deformation substructures combining wide field data gathering with high spatial resolution.

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2. Experimental Procedure

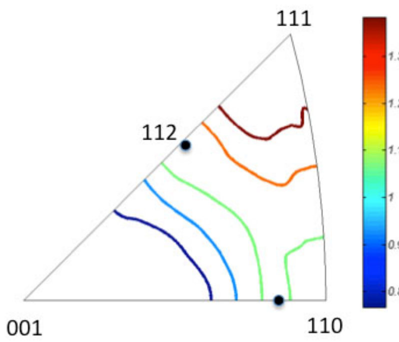
The material used in the current study is a conventionally 6016 aluminum alloy for automotive applications. The sheet from which the samples were extracted was in cold rolled and annealed T4 condition. Tensile specimens were cut from the sheet with the tensile access parallel to the rolling direction. The specimens were elongated to 25% strain. Samples for EBSD observations were cut from the middle of the gauge length of the tensile specimens. The planes of the observation were TD and ND planes (*i.e.* planes normal to TD and ND, respectively). Sample preparation for this work was very critical because we wanted to be sure that no extra deformation be induced to the samples. Therefore, after conventional mechanical polishing up to 0.25 μm with OPS, electropolishing was applied by using the Electrolyte A2 Struers electrolyte with a voltage of 39 V, flow rate 9 for 15 s. It should be noted that we mostly prepared a non-deformed reference sample jointly with the deformed sample. The EBSD system of type EDAX-TSL® that was used in the current study was mounted on a FEI quanta 450® SEM with Field Emission Gun (FEG) filament. The orientation contrast scans were collected and analyzed by the commercial OIM-TSL® software. Wide filed EBSD scans, covering an area of ~9 mm^2, in combination with good spatial resolution (step sizes between 0.5 and 1 μm), gave rise to huge data sets with as much as 10 Mpixels.

3. Results

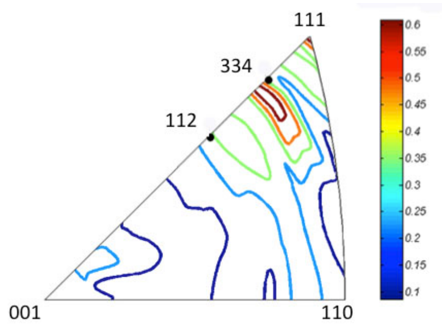
Figure 1 shows the orientation contrast map of the sample extended in tension to an elongation of 25%. We are interested to analyze the linear slip patterns observed in a subset of grains as shown in figure 1 (cf. white markers). In reality, these linear slip patterns in 3D are of a planar nature. The question that we would like to address here is whether these slip patterns are parallel to specific crystallographic planes, or in other words, we want to quantify the frequency of the coincidence of crystal planes {hkl} with the planar slip patterns. This question relates to the nature and the origin of the slip patterns.

Figure 1 IPF map overlaid by IQ map on a specimen loaded to 25% elongation. White markers indicate linear slip patterns.

A very large dataset, with more than 2000 grains, was analyzed covering a total scanned area of various square millimeters. The line segments corresponding to the linear slip patterns were considered as intersections of an unknown crystal plane with the plane of observation. These unknown planes can be represented as pole traces on unit triangle of standard stereographic projection. Figure 2a shows the distribution of these pole traces after appropriate background correction, which considers a random distribution of slip segments for the specific texture of the sample. The method used here to process the data was based on the stereological line segment analysis proposed by Rohrer *et al.* [5, 6]. It can be seen that the trace distribution exhibits the maximum on the [111] pole but it is quite a broad maximum extending to the [112] pole. Also in the vicinity of [110] a local maximum can be observed.



(a)



(b)

Figure 2 (a) Distribution of the normal of the planes parallel to the slip patterns obtained by the stereological method. (b) Distribution of the plane normals defined by the linear slip segments (observed on the perpendicular sections in 3D). The colorbar shows the intensity.

Alternative to the statistical method, a 3D analysis was carried out on two perpendicular planes of observation (TD and ND sections). In this method we identified slip patterns on 20 corresponding grains at the common edge of two sections. Figure 2b shows the distribution of the normals of the planes that were defined by both slip segments. It can be seen that the pole distribution of planes exhibits the maximum on the [111] pole, in the vicinity of the [112] and the [334] poles. Also in the neighborhood of the [110] pole there is a small maximum. The planar pole distribution obtained from 3D analysis (figure 2b) is in reasonable correspondence with the trace distribution produced by the statistical method (figure 2a), even though only 20 grains were considered in 3D analysis.

4. Discussion

If we compare the results of this work with the observations of Hansen (2001), we may conclude that what we have observed are cell blocks or cell block boundaries. The reason why we come to this conclusion is that our observed slip features, just as cell blocks, exhibit a linear character and in many cases they are parallel to the presumed {111} octahedral slip planes. It has to be mentioned, though, that the alignment of the planar slip features with the {111} planes is not restricted to these planes only, as also cell blocks are observed, which are aligned to other crystal planes such as {112} and ~{110}.

In an alternative interpretation, the slip patterns may be related to in-grain shear bands. However, shear bands (SB) have rather a fixed angle (*e.g.* ≈35°) with the main axis of strain, whereas the linear slip segments observed here, exhibit scattered angles with respect to the TA, ranging from 10 to 60°. Additionally, SBs would give rise to saw-tooth features when intersecting grain boundaries, which was not observed here. Moreover, it would be expected to observe shear bands in high Taylor factor grains, as they would be the most benefiting from geometric softening. In the present case, though, the linear slip segments are also observed in grains with low Taylor factor (*cf.* red grains in Figure 1). An additional argument in favor of the cell blocks hypothesis is that the slip patterns analyzed in this work have an appropriate width (≈5 μm), which very well correspond to the reported width in the literature [2, 3]. Based on these facts, it is unlikely that these patterns can be associated with shear bands, but their characteristics better correspond to cell blocks features [1-4].

5. Conclusions

To the purpose of analyzing the linear slip patterns observed in tensile elongated (25%) aluminum samples two methods were applied based on orientation contrast microscopy (EBSD): (i) a statistical analysis of stereological nature, and (ii) a 3D analysis.
The results of both methods were in reasonable agreement. It was found that the linear features are predominantly parallel to the {111} crystal planes, although the frequency of {111} planes was not exclusive; also other crystal planes such as {112} and {110} are involved. These observations give a stronger statistical basis for similar observations earlier made by TEM on much smaller fields of observation. In the discussion of the present data we argue that the observed slip segments may be related to the presence of cell blocks in the deformed structure.

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