Crystallographic aspects of nucleation and grain growth during recrystallization of high stacking fault energy metals as characterized on model Al-1%wt.Mn alloy crystals

M. Miszczyk¹,a, H. Paul¹, J.H. Driver² and C. Maurice²

¹Institute of Metallurgy and Materials Science, PAS, Krakow, Poland
²Ecole des Mines de Saint Etienne, Centre SMS, Saint Etienne, France
*a E-mail: m.miszczyk@imim.pl

Abstract. The objective of this paper is to identify the predominant crystallographic relations between deformed state and recrystallized grains during the early stages of recrystallization of the Goss{110}<001> and brass{110}<112> oriented single crystals of Al-1%Mn. The analysis was based on high resolution local orientation measurements in scanning electron microscopy. After annealing the disorientation across the recrystallization front ‘defines’ the final rotation by angles in the ranges of 35°-50° around axes located near the normals of all four {111} slip planes. Although the rotation axes approach the normal vector of the active slip planes during deformation, they only rarely coincide with the exact location of the <111> direction. For both initial orientations, preferred grain growth occurred along the {111} planes, the most active during strain.

1. Introduction

The literature on recrystallization pays a lot of attention to the role of high-angle boundaries and the conditions of their migration, e.g. [1 - 6]. Nevertheless, based on such an approach, it is unable to provide a comprehensive answer to the question of the mechanisms controlling the formation of a new grain inside the deformed structure and, in particular, its different orientation with respect to the deformed volume from which it grows. In the authors' view this results from neglecting the role of low-angle boundaries. Their thermally activated migration combined with the movement of dislocations stored inside (sub)grains and/or the diffusion of vacancies may play a key role in: (i) the 'transformation' of low-angle boundaries into high-angle ones and/or the formation of boundaries capable of fast migration [7 - 9], and (ii) the orientation change of a 'chosen area' with respect to the deformed matrix [10 - 13]. Still, the nature of these processes is not very clear at the moment. The purpose of this work is to identify and describe the preferences in the disorientation relationship appearing between a new grain and the deformed region during the early stages of recrystallization of high stacking fault energy (SFE) face centred cubic (fcc) metals. The current experimental investigations have focused on an analysis of transformations which occur in model single crystals of Al-1%Mn alloy, of brass {110}<112> and Goss {110}<001> orientations deformed in terms of plane strain compression (PSC). The deformation of stable orientation crystallites (up to large deformations) practically does not lead to the appearance of high-angle boundaries [14 - 17]. This is of paramount importance for the discussion of mechanisms.
controlling textural transformations during recrystallization. The basic research technique employed local orientation measurements based on scanning electron microscopy (SEM) equipped with electron backscattered diffraction (EBSD) facility.

2. Experimental
The material was Al-1%wt.Mn alloy. Single crystal bars were grown by directional solidification and the (110)[1-1-2] and (110)[00-1] oriented samples were carefully cut from the bars using a wire saw. The deformation was carried out in channel-die to a logarithmic strain of 0.51 at 293 K. In order to minimize friction between the sample, the punch and the walls of the channel-die, each sample was wrapped in 0.2 mm thick Teflon™ tape. Annealing was carried out in air furnace to the first stages of primary recrystallization. The microstructures were mostly analysed on the ND-ED plane (where: ND and ED are normal and extension directions, respectively) in the middle of the sample thickness by SEM using a JEOL 6500F. The SEM was equipped with electron backscattered diffraction (EBSD) facility. Post-processing analysis of the orientation maps was performed using HKL Technology Channel 5 software. The applied step size was ranged between 0.1 µm and 2 µm.

3. Results and discussion
3.1. Early stages of recrystallization in high SFE fcc crystals
After very short annealing the recrystallized phase is 'composed' of single grains of uniform orientation completely surrounded by deformed areas and the grains that typically form compact chains. In the following the orientation relationships between the adjacent regions of recrystallized grains have been ignored. The particular role of the orientations identified in the as-deformed state has been analysed by examining the orientation distribution of the new grains. A comparison of the pole figures only for the deformed and for recrystallized state shows that the <111> poles only rarely coincides. Most of new grains orientations form groups, which are symmetrically situated with respect to selected (external) axes. This symmetry results from positive and negative rotation of new grains orientations around axes grouped near the all the <111> poles of the deformed state.

![Fig. 1. Disorientation relation between recrystallized area and nearest as-deformed neighbourhood for (a) and (c) Goss (110)[00-1], (b) and (d) brass (110)[1-1-2] orientations. Distribution of disorientation angles - (a) and (b) and axes - (c) and (d).](image)

3.2. The disorientation (angles/axes) distribution at early stages of recrystallization
The 'frequency' distributions of the disorientation angles between recrystallized and deformed/recovered, regions are presented in Fig. 1a and b. The range of potential disorientation angles was binned into intervals of 1.25° into which the number of disorientations across the recrystallization front corresponding to a given angular interval...
was counted. The prevalent range of angles across the migrating recrystallization front (between recrystallized and deformed grains and for the entire set of orientation maps) was within a wide range between 25° and 50°. The [111] poles of the deformed/recovered grains, do not coincide with the [111] poles of the recrystallized grains or more precisely overlapping of the [111] rotation axes was observed only rarely (Fig. 1c and d). Basically, the majority of the disorientation axes across the recrystallization front are concentrated around (but not coincide with) the [111] poles of the two slip planes (highly privileged) during deformation. Since the disorientation axes are slightly deviated from the normals of the [111] planes they 'occupy' a wide range near the [112], [012], [123] and [122] directions. A 'grouping' of rotation axes near the two remaining poles could, however, be detected but was clearly weaker.

3.3. The directionality of grain growth

The orientation maps (on the ND-ED plane) for both initial orientations show that a considerable number of recrystallized grains are of elongated shape. These grains exhibit a well-defined lattice rotation with respect to the deformed crystal orientations. An example of the crystal lattice rotation, related to the appearance of heavily elongated grains, was carried out on Al-1%Mn single crystal of Goss (110)[00-1] orientation, as presented in Fig. 2. To a first approximation, this aspect of nucleation and grain growth leads to the following conclusions: (i) the longest grain direction runs along the traces of {111} planes, the most active planes during strain, and which are symmetrically located to the ND-TD plane. To a lesser degree some grains are elongated along the traces of two other planes. (ii) The orientations of the elongated grains are related to those of the group of the deformed crystals. The crystal lattice of each of the grain groups is rotated (positively or negatively) around diverse groups of disorientation axes. The rotation axes are preferentially situated near the poles of {111} planes, the most active planes during strain. (iii) This may suggest a mechanism for the formation of a new grain by thermally activation movement of dislocation families, 'travelling' in pairs on one of the above-mentioned planes. Although the rotation axes approach the normal vector of the preferred slip planes they only rarely coincide with the exact location of the [111] directions.

![Fig. 2. Directionality observed at early stages of recrystallization in sample of Goss (110)[00-1] initial orientation. (a) Large area SEM/EBSD orientation map on the ND-TD plane and (b) corresponding the {111} pole figure. Step size of 2.8 µm. Sample deformed up to strains of 0.51 and then recrystallized at 680 K for 70 s.](image)

An explanation of these results can be based on the thermally activated, coordinated movement of dislocations. But, many situations are possible due to screw or edge character of dislocations stored along the growth plane, as discussed in [18]. The spread of the lattice rotation angles of individual grains for a given category may result from the spread of
orientations of the deformed state and/or an 'unequal' contribution of the two dislocation families (systems) grouped on one plane.

4. Conclusions

Based on local orientation measurement in SEM the orientation relations which appear at the initial stages of recrystallization between a new grain and the as-deformed areas of stable single crystals have been statistically analyzed. The results allow us to draw the following conclusions:

- For Al-1%wt.Mn alloy of both initial orientations at the initial stages of recrystallization, the appearance of a specific number of new orientation groups of new grains was demonstrated. The orientation relation across the recrystallization front 'defines' the final rotation by angles in the range 25°-50° around axes mostly grouped about the <122>, <012>, <112>, <123> and <111> directions.
- In the case of a single isolated nucleus of uniform orientation, these rotation axes are usually grouped around, but not at, the normals of all four {111} planes.
- A large fraction of new grains is characterised by a strongly elongated shape. For both initial orientations, preferred grain growth occurred mostly along the most active planes during strain. The orientations of the elongated grains were directly related to those of the group of as-deformed orientations.
- The variations of disorientations across recrystallization front tend to follow the orientation variations in the deformed state. This facilitates 'the orientation stability' of a new grain growing into the as-deformed structure.

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