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ScienceDirect
Scripta Materialia 59 (2008) 421–423
Scripta MATERIALIA
www.elsevier.com/locate/scriptamat

Reply to comments on "Influences of crystallographic orientations on deformation mechanism and grain refinement of Al single crystals subjected to one-pass equal-channel angular pressing"

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Received 9 January 2008; revised 3 April 2008; accepted 14 April 2008
Available online 26 April 2008

We further discuss the deformation mode to clarify the possible shear mechanism during equal-channel angular pressing (ECAP). Based on the specially designed experiment, it is suggested that except for along the intersection plane (IP), shear deformation along the normal of the IP can also activate the preferential slip system of single crystals during ECAP, at least on the micro-scale, indicating a strong effect of crystallographic orientation on the microstructural evolution and refining mechanism of crystalline materials.

Keywords: Equal-channel angular pressing (ECAP); Single crystal; Shear deformation

We appreciate the interest of Tóth [1] in our previous paper about the shear deformation mechanism of Al single crystals during equal-channel angular pressing (ECAP) [2]. This gives us the opportunity to discuss further some of our results and viewpoints. We regret that the initial pole figures for the three Al single crystals before ECAP shown in Figure 6 in Ref. [2] were not illustrated correctly. However, the crystallographic orientations of the Al single crystals used in our experiment were well cut according to the design that is shown in Figure 1 in Ref. [2]. The correct pole figures of these crystals before ECAP are shown in Figure 1 in this reply. Compared to the pole figures in Ref. [2], the present diagram uses an insert direction (ID)–extrusion direction (ED) coordinate, which simply corresponds to the experimental design in Ref. [2].

ECAP is one of the major severe plastic deformation (SPD) methods and has been widely used to fabricate ultrafine-grained materials for a decade [3,4]. In general, the large shear deformation in ECAP is always considered to occur along the intersection plane (IP) between the entrance and exit channels [5–7]. Segal [7] has pointed out that there are two maximum shear stresses during ECAP, one is along the IP and another is vertical to it. However, only very limited information is available on how the two maximum shear stresses affect the microstructures during extrusion. In order to obtain a better understanding of the shear deformation mechanism during ECAP, we have designed some special experiments, including investigations using millet grains [8], polycrystalline materials [9,10] and even single crystals with special orientations [2]. In our physical modeling experiment using millet grains, it is found that shear deformation only takes place in the region of deformation zone with a fan shape, and starts and ends at the boundaries of that zone [8]. This experiment demonstrates that it is more reasonable and easier to understand the shear deformation behavior during ECAP from the view of plastic flow. It is also proved that from the view of metal flow, one can easily understand why the shear flow lines were formed along the 27° direction with respect to the ED after one-pass ECAP [10].

Subsequently, the three Al single crystals with special orientations in Ref. [2] were specifically designed to verify whether shear deformation during ECAP occurs along the IP only, or along other possible directions, such as the direction perpendicular to the IP, especially at the microscopic level. The orientation of crystal I is similar to the third group of Cu single crystals processed by Miyamoto et al. [11]. It can be seen that the orientations of the subgrains are uniformly scattered in crystal I after ECAP, as shown in Figure 1a. Crystal II has the

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doi:10.1016/j.scriptamat.2008.04.027

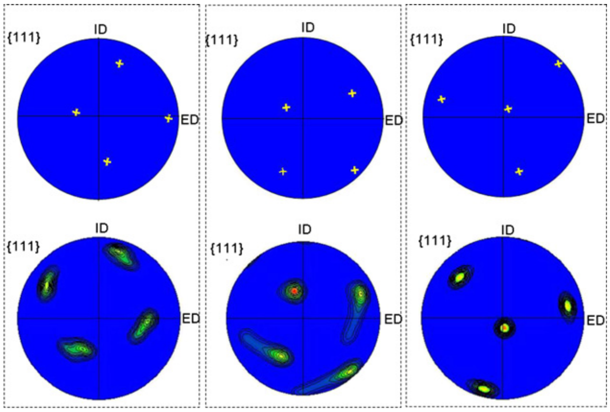

Figure 1. Pole figures for the three Al single crystals before (upper) and after (lower) one-pass ECAP in the ID–ED plane: (a) crystal I; (b) crystal II; and (c) crystal III.

same orientation as the one processed by Fukuda et al. [12], i.e. its $(\bar{1}\,1\,1)$ plane is parallel to the IP of the ECAP die and its $[1\,1\,0]$ direction is along the general shear direction on the IP. However, the microstructures of the ECAPed crystal II consist mainly of two sets of subgrains, rather than the one direction of elongated structures. The angle between the two bands is ~70°. The corresponding diffraction patterns clearly demonstrate that the two sets of ribbon grain structures are induced mainly by shear deformation along two slip planes during extrusion, as shown in Figures 8 and 13 in Ref. [2]. Its $\{1\,1\,1\}$ orientations have been scattered along certain directions with the maximum misorientation larger than 50°, indicating a kind of non-uniform deformation, as shown in Figure 1b. The $(\bar{1}\,1\,1)$ plane of crystal III is laid on the plane perpendicular to the IP of the ECAP die, and the $[1\,1\,0]$ direction is vertical to the general shear direction. It is worth pointing out that when a uniaxial loading along the ID direction is applied, the stress state and shear deformation between crystals II and III (which have the same crystallographic orientation along ID) will have no difference in nature. However, they behaved in quite a different manner during ECAP [2]. One of the most interesting findings is that the microstructure of crystal III is characterized by only one set of extended dislocation boundaries parallel to one slip plane trace. The diffraction patterns clearly show that this kind of ribbon microstructure resulted mainly from the shear deformation along one slip plane during ECAP, as shown in Figures 10 and 14 in Ref. [2]. The orientation of crystal III almost has no larger scatter, as shown in Figure 1c, which strongly indicates that crystal III has undergone a relatively homogeneous plastic deformation and still remains in essentially a single orientation.

In general, the pole figures of ECAPed crystals have an anticlockwise rotation compared with the initial pole figures. Tóth [1] thinks that the rotation during ECAP is very much orientation dependent. We agree with this. Crystals I and III undergo large-angle rigid body rotation (~80° for crystal I and ~90° for crystal III) during ECAP deformation, as shown in Figure 1. For crystal II, the present result indicates that there is no obvious rigid body rotation; however, Fukuda et al. [14] found that Al crystal with the same orientation as crystal II had been rotated about 60° around the transverse direction after ECAP, but the scatter of the $\{1\,1\,1\}$ planes in pole figures and the formed microstructures in the two experiments are basically identical. In order to investigate further the difference in rigid body rotation of crystal II between the present result and Fukuda's observation, we think it would be desirable to repeat this experiment. In addition, Tóth has conducted a simulation in Ref. [1] by considering a simple shear along the IP, and indicates that the predicted orientation position in crystal I is in good agreement with the experiment findings in Ref. [2]. However, if Tóth had considered the shear along the direction perpendicular to the IP, it is likely that the same results could also be obtained because crystal I has a very special orientation, i.e., symmetric multi-slip systems can be activated during extrusion [2]. Furthermore, if Tóth could further consider the shear deformation of the other two special crystals II and III in his simulation, this should greatly assist efforts by ECAP investigators to understand the deformation mechanism more profoundly.

In the discussion section of Ref. [2], we utilized the concept of shear factor [12] to establish a link between the formed microstructures and the deformation mode of ECAP. Given that the shear deformation occurs along the direction perpendicular to the IP, it is easy to understand the formed microstructures and orientation evolution of the three Al single crystals, especially for crystals II and III. It should be pointed out that the shear factor analysis may only predict the primary activated slip planes in crystals II and III, which were confirmed by the formed microstructures after ECAP [2]. Tóth [1] thinks that the stress state and the activated slip systems should be elucidated by performing a full crystal plasticity analysis. In Table 1 in Ref. [1], Tóth listed the activated slip systems predicted by full crystal plasticity analysis; however, these predicted slip systems do not fully explain the experimental results in Refs. [2,12]. Firstly, this prediction could not interpret (i) why the microstructures of crystal II consist mainly of two sets of subgrains corresponding to shear deformation along two slip planes [2,12]; and (ii) why the microstructure of crystal III is characterized by only one set of extended dislocation boundaries parallel to one slip plane trace [2]. Secondly, it can be found that the predicted slip systems of crystals II and III are identical in Table 1 in Ref. [1], which means that the formed microstructures in crystals II and III should be also identical. However, the experimental results clearly show that crystals II and III behave quite differently during ECAP [2,12].

There is another point in Ref. [1] that requires further discussion. Tóth considers that crystal II should not rotate at all because its slip system just meets the macroscale shear deformation of ECAP. However, the experimental results clearly indicate that crystal II has a large orientation scatter [2]. The most interesting result came from crystal III: it has the smallest orientation scatter of the three crystals, indicating that the designed primary slip systems of crystal III just meet the shear deformation to form only one set of extended dislocation boundaries parallel to one slip plane trace [2].

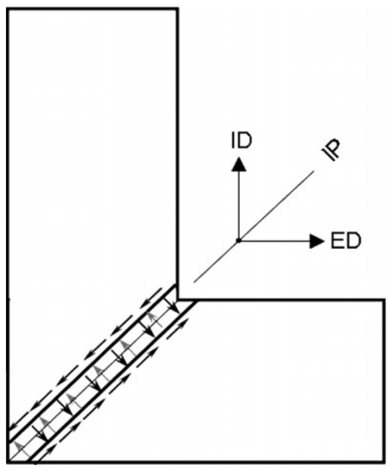

Figure 2. Schematic illustration of the shear deformation process during ECAP.

It is generally accepted that the large shear deformation in ECAP is always considered to occur along the IP between the entrance and exit channels in a right-angle die. The shear deformation should take place within a narrow region parallel to IP [8], where plastic deformation during ECAP might be realized through the cooperation of the shear deformation along the directions parallel and perpendicular to the IP, as illustrated schematically in Figure 2. Therefore, based on the experimental results reviewed above, it is suggested that, except for along the IP, shear deformation along the normal plane to the IP can also activate the preferential slip system of single crystals during ECAP at least on the microscale, indicating a strong effect of crystallographic orientation on the microstructural evolution and refining mechanism of crystalline materials. For single crystals, shear factor analysis might provide a simple method to predict their main slip systems to some extent, as is the case for crystals II and III [2]. However, the real shear deformation processes of polycrystals would be very complicated and the current experimental results in Ref. [2] offer an opportunity to deepen our understanding of the shear deformation and refinement mechanisms of crystalline materials during ECAP.

The authors thank Prof. G.Y. Li for his valuable discussion and Mr. H.J. Yang for his assistance in the EBSD experiment.

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