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Response 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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We further discuss the deformation mode to clarify the possible shear mechanism during equal-channel angular pressing (ECAP). A repeated ECAP test for crystal II was carried out and its crystallographic orientation, rigid body rotation and misorientation scatter are consistent with reports elsewhere. We believe that except for along the intersection plane (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.

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

We appreciate the interest of Li [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. Since the issues raised by Li are similar to those in the previous comment [3] on our paper, we give only a brief explanation in this reply.

The initial pole figures for the three Al single crystals before ECAP shown in Figure 6 in Ref. [2] were not illustrated correctly way because incorrect pole figures were inserted during the review process and in our haste we made a mistake. However, the crystallographic orientations of these 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 also shown in Figure 1 in Ref. [4]. Therefore, these corrections do not affect the major experimental results and the analysis using shear factors.

It is generally accepted that the plastic shear deformation during ECAP is confined in a narrow region around the intersection plane (IP), and shear deformation occurs only along the direction parallel to the IP. However, there are two maximum shear stress directions during ECAP, one is along the intersection direction and another is vertical to it. Unfortunately, only very limited information is available on the role of two maximum shear stresses during ECAP. In this case, the three Al single crystals with special orientations in Ref. [2] were designed specifically to verify whether shear deformation during ECAP occurs only along the IP, or also along other possible directions, e.g. the direction perpendicular to the IP, especially at the microscopic level. The corresponding experimental results demonstrate that shear deformation occurs not only along the direction of IP, but also along the direction normal to the IP [2]. Therefore, based on those experimental results, 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. It is worth pointing out that crystal II consists mainly of two sets of subgrains after ECAP induced by shear deformation on two primary slip planes, as shown in Figure 13 in Ref. [2]. The same experimental results were also

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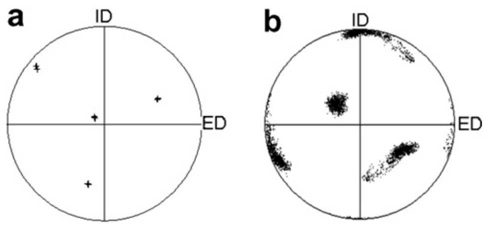

Figure 1. Pole figures for crystal II: (a) initial orientation; (b) after one-pass ECAP (ID, insertion direction; ED, extrusion direction).

presented in Figure 7 in Ref. [5], although Fukuda et al. considered that both sets of subgrains were induced by a counterclockwise rotation during deformation.

Concerning the finite element simulation of the ECAP process, we recognize that macro-shear along the IP plays an important role for isotropic materials; however, the shear deformation may also occur perpendicular to the IP, especially on the microscale. Nowadays most macro-finite element codes only adopt the isotropic constitutive relation for materials to depict plastic deformation, and therefore the shear deformation of anisotropic crystalline materials such as single crystals may not be accurately simulated. Since severe plastic deformation occurs around the IP, there is a large strain gradient there, and therefore, for better understanding, coupling strain gradient theory [6] with crystal plasticity finite element analysis may be necessary in future simulations.

In general, the pole figures of ECAPed single crystals have an anticlockwise rotation compared with the initial pole figures. However, the crystallographic orientation rotation during ECAP is very much orientation dependent. Crystals I and III underwent large-angle rigid body rotation (~80° for crystal I and ~90° for crystal III) during ECAP deformation, as shown in Figure 1 in Ref. [4]. For crystal II, the result in Ref. [4] indicates that there is no obvious rigid body rotation; however, Fukuda et al. [5] found that although an Al crystal with the same orientation as crystal II had been rotated about 60° around the transverse direction after ECAP, the scatter of the {1 1 1} planes in the pole figures and the formed microstructures in the two experiments are basically identical. In order to investigate the difference in rigid body rotation about crystal II between the result in Ref. [4] and Fukuda's observation [5], we have repeated this experiment using a die with a square cross-section channel for further confirmation. The repeated result indicates that the crystallographic orientation has been rotated about 60° around the transverse direction too, as shown in Figure 1. Our previous error concerning the rigid body rotation in crystal II might be due to the following reasons: firstly, the billet of crystal II has been bent to some extent during extrusion (hence this single crystal was not kept straight); secondly, the orientation was not directly measured from the extruded billet, but detected on a slice cut from the billet, which might have rotated a certain angle during the experiment; thirdly, the round cross-section billet used in the previous experiment might have rotated a certain angle around the insertion direction during extrusion. All the reasons listed above might account for the incorrect measurement of the exact rigid body rotation during ECAP. For the present repeated experiment, we prepared a specimen with square cross-section and measured the extruded billet directly. The repeated ECAP test for crystal II indicates that its crystallographic orientation, rigid body rotation and misorientation scatter are in accordance with Fukuda et al.'s reports [5] – in particular, there are two sets of subgrains existing in the ECAPed crystal II. Therefore, in terms of the results above and reports in Refs. [2,4], we believe that shear deformation perpendicular to IP is possible.

In summary, the real shear deformation processes of crystalline materials during ECAP appear to be very complicated and the current experimental results in Ref. [2] might offer an opportunity to deepen our understanding of the shear deformation and refinement mechanism of crystalline materials during ECAP.

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