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Effect of strain reversal on texture and grain refinement in route C equal channel angular pressed copper

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Texture development and grain refinement were studied experimentally and by simulations using a recently proposed Taylor-type grain refinement model for oxygen-free high-conductivity copper deformed by two passes of 90° equal channel angular pressing (ECAP) in route C. Route C is a deformation mode which reverses the shear deformation in ECAP, but does not completely reverse the texture. The results demonstrate better reproduction of the experimental strain reversal shear texture than the VPSC model alone, while also reproducing the grain size distribution.

Keywords: Equal channel angular pressing; Oxygen-free high-conductivity copper; Polycrystal modeling; Grain refinement

Severe plastic deformation (SPD) is an effective way to improve the yield stress of metallic polycrystalline materials. Among the various SPD techniques, equal channel angular pressing (ECAP) has received particular attention, mostly because the dimensions of the sample can be maintained during the process [1,2]. In ECAP, the main deformation mode is simple shear in the plane of intersection of the two channels [1]. It is also important to apply back pressure (BP) during ECAP to maintain the shape of the sample, which would change due to shear deformation in the absence of BP [3]. During ECAP, there are several routes (strain paths) that can be employed to a sample by applying different rotations around the sample's longitudinal axis after every pass: 0° in route A; ±90° in routes Ba and Bc; and 180° in route C. Route Bc has been found to be the most effective in terms of grain refinement—another important aspect of SPD processes that can produce grain sizes down to nano-scales (~200 nm in ECAP of copper). This route, however, is the most complex in practice, because the sample has to be removed from the die after each pass in order to apply the 90° rotation around its long axis. Route C is the easiest to realize experimentally by simply pressing the sample back and forth in the die using both the pressing and BP punches. This route, however, is distinct because the shear deformation is reversed in every second pass.

In contrast to route A, where the grain shape becomes elongated, the inversion of the strain path in route C has the consequence for the microstructure of recovering the initial grain shape every second pass. The fact that grains regain their initial shape proves that the velocity gradient is reversed for opposite shear. For this reason, in ideal conditions, the initial crystallographic texture is also expected to be recovered every second pass; experiments, however, do not confirm this effect. There is an ECAP shear texture after every even number of passes, although the texture is significantly weaker than after an odd number of passes (see Ref. [4] for route C textures in face-centered cubic (fcc) and hexagonal close packed materials). Several hypotheses have been tested to explain the origin of the strain reversal texture, but there is no entirely satisfactory explanation. Beyerlein et al. [5] and Li et al. [6] found that grain–grain interactions are not directly responsible; nor does it come from a measurement effect when deformation is heterogeneous in a rounded die [6], because the center layer—where deformation is homogeneous—still shows a strain reversal shear texture [7]. Grain shape observations in Cu [7], Be [8] and Ni [1] and in reversed torsion [9] all confirm that the grains become very much elon-

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gated in the forward shear and recover their initial shape after strain reversal. Lattice rotation, however, might not be completely reversed, as the internal microstructure of the grains has changed during forward shear. Simply using a co-rotational scheme within the VPSC model [4] (and accounting for isotropic hardening) led incorrectly to the initial random texture when the strain path was reversed. Some weak shear textures could be produced [7] in route C using latent hardening; however, these were too weak with respect to experiments. All this indicates that substructure evolution has to be taken into account to model the strain reversal textures. Taylor [10] and VPSC [11] modeling which considered substructures in the form of lamina, bands and subgrains led to some strain reversal shear textures, but again these were too weak with respect to the measured textures. The most successful simulation results were obtained using the hypothesis of imperfect reversal of the strain path [4,10]. Imperfect reversal can be due to alteration of the shape of the material flow lines due macroscopic strain hardening. For a rounded ECAP die corner, Mahesh et al. [10] showed that, by skewing the fan-type flow field in the first pass, a strain reversal shear texture can be obtained in the mid section of the sample in the second pass.

It is also believed that grain refinement should play a role in the evolution of the texture, especially when strain path is reversed [4]. Recently, a quantitative model for grain refinement due to large plastic strains was proposed [12] and was shown to predict texture, grain size distribution and next-neighbor misorientation of SPD deformed polycrystals [12–14] fairly well. This new model is based on lattice curvature developing within the grains of the polycrystal owing to the constraining effect of the grain boundaries. It will be shown in the present work that the grain refinement itself can fully explain the strain reversal texture in route C of ECAP-ed copper. Comparisons will be made with predictions of the Taylor and VPSC models in which the route C texture reverts perfectly to the initial texture, provided the strain increment is sufficiently low.

The material studied was oxygen-free high-conductivity copper in the form of a rod which was heat-treated at 650 °C for 2 h, resulting in an average grain size of ~24 μm. The texture of the rod was nearly random (Fig. 1b). The annealed copper was machined to dimensions of 20 × 20 × 120 mm and processed by ECAP to one and two passes, route C, in a 90° angle die with sharp corners. The long axis of the original rod was the extrusion axis (ED). A BP of 25 MPa was applied to the billets; the extrusion speed was 2 mm s^{-1}; and colloidal graphite was used as lubricant during ECAP. Partial pole figures were obtained from the {1 1 1}, {2 0 0} and {2 2 0} planes up to maximum tilt of 80° with a 5° interval, using a GBC-MMA texture goniometer working at 40 kV and 25 mA and equipped with a Cu Kα anode and a polycapillary beam enhancer, resulting in a collimated beam 10 × 10 mm^2. The orientation distribution functions (ODF) were calculated using commercial software developed by ResMat Corp. The deformation textures after one and two passes in route C are displayed in Figure 1c and d, respectively. The microstructure was characterized by electron backscattered

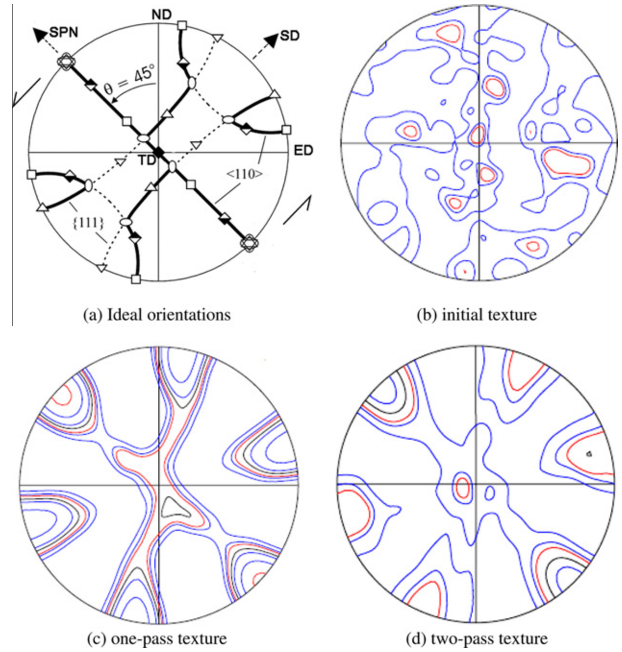

Figure 1. (a) Ideal orientations A_1^* △ A_2^* ∇ A ○ $\overline{A}$ ◊ B ◆ $\overline{B}$ ◆ C □ (after Ref. [15]) and measured {1 1 1} pole figures of the (b) as-received copper, (c) one-pass ECAP-ed copper (c) and (d) two-pass ECAP-ed copper in route C. Isolevels: 1.0, 1.2, 1.3, 1.5, 1.7, 2.2, 2.9. Pole figures are shown in the ND–ED projection plane (ND, normal or pressing direction).

diffraction (EBSD). Specimens were cut from the center of the ECAP billet along the ND–ED plane, mechanically polished to 4000 grit using SiC paper and then electro-polished for 20 s in an electrolyte of 25% orthophosphoric acid, 25% ethanol and 50% distilled water at 10 V, 20 °C, with a current of ~150 mA. EBSD measurements were performed using a JEOL 7001F FEG scanning electron microscope fitted with a HKL detector, with a step size of 0.2 μm. Boundaries were identified using a minimum misorientation angle of 5° between adjacent pixels. Grain size distributions were determined from the measured EBSD maps for the first and second passes (Fig. 2a). The average grain size decreased from the initial 24 μm to 1.04 ± 0.17 μm in the first pass, and further decreased to 0.97 ± 0.07 μm during the second pass.

The texture components of one-pass copper (Fig. 1c) are closely aligned with the ideal orientations displayed in Figure 1a (after Ref. [15]). The texture consists of a partial ⟨1 1 0⟩ fiber (where ⟨1 1 0⟩ is parallel to the shear direction) running from C to $A/\overline{A}$ through $B/\overline{B}$ and a partial {1 1 1} fiber (where {1 1 1} is parallel to the normal of the shear plane) extending from A_1^* to $A/\overline{A}$. A relatively high intensity is found for the C and A_1^* components. The texture after the second pass (Fig. 1d) is significantly weaker than after the first pass, but is clearly still a shear texture. The largest decrease was in the A_1^* and C components. These characteristics of the textures are in accordance with the observations of Li et al. [7].

Turning to the simulations which included the grain refinement model, the experimental initial texture was represented by 500 crystals. A grain size was attributed