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Investigation of texture and mechanical properties of copper processed by new route of equal channel angular pressing

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ABSTRACT

The evolution of crystallographic texture and the mechanical properties of copper subjected to severe plastic deformation (SPD) using equal channel angular pressing (ECAP) were investigated. Samples were subjected to ECAP under two different processing routes: B_{60} and B_C. As the cross sections of the samples were circular, a new route with a rotation angle of 60° in the same direction between consecutive passes was introduced. The material exhibited texture development similar to the simple shear texture in both routes and the most significant changes in texture strength in both processing routes took place after the second pass. Microstructure of ECAP processed samples were investigated using electron backscatter diffraction (EBSD) analysis. Comparison of the EBSD data with optical micrograph of the initial sample confirmed that ECAP process has led to a significant decrease in grain size. Significant increases in hardness and tensile strength were observed after the first pass of ECAP. Variations of tensile strength as a function of the number of passes were related to the dislocation densities and the average boundary spacing.

1. Introduction

Texture evolution during ECAP has received lots of attention since the process involves applying very high plastic strains in order to refine the microstructure; however, such a deformation is also likely to develop strong deformation texture [1]. ECAP is a processing procedure in which an intense plastic strain is imposed by pressing a sample in a special die. The die consists of two channels equal in cross sections, intersecting at an angle Φ (usually from 90° to 157°). There is also an additional angle Ψ, which defines the arc of curvature at the outer point of intersection of the two channels [2]. Microstructure and grain size are changed during ECAP as a result of large plastic deformation that takes place in a narrow region at the intersection of two channels [3]. In this way, since the material's cross section shape and size remain the same, ECAP process can be repeated several times. Rotation of billet (processing route) between passes is an important parameter in ECAP process [4] because when the sample is pressed through several consecutive passes, the shearing characteristics tend to be changed by rotating the sample between each pass. Thus, the route with which the sample is re-entered to the ECAP die in each pass has an influence on the microstructure achieved due to the successive change of the shear plane. The most widely used rotation schemes include; route *A*, where the billet is not rotated between consecutive passes; route B_A, where the billet is rotated 90° in alternate direction between consecutive passes; route B_C, where the bar is rotated 90° in the same direction, and route *C*, where the bar is rotated 180° between consecutive passes [2].

The close relationship of the texture evolution by ECAP and the strain path of simple shear deformation is now widely accepted [2,5,6]. Segal proposed that during ECAP simple shear deformation occurs in the shear plane laid at the intersection of the channels [3]. As for the F.C.C materials {1 1 1} planes are the slip planes, in the ECAP process, the orientation of these planes in the sample with respect to shear plane could be important [7].

In this work, as the cross section of the samples was circular a new route with rotating angle of 60° between consecutive passes in the same clockwise (CW) direction was adopted and named route B_{60}. The first part of the current study addressed the evolution of crystallographic texture using the orientation distribution function (ODF) in pure copper by routes B_{60} and B_C. The second part was concerned with the investigation of mechanical properties and fractography of the samples before and following ECAP process using both routes.

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2. Experimental procedure

Oxygen free high conductivity copper (OFHC) used for the present study was in a form of bar 20 mm in diameter. The chemical composition of the investigated material is given in Table 1.

Specimens 80 mm in length were cut from the bars. The ECAP process was carried out at room temperature using a 200 ton press and a die set with $\Phi = 120°$ and $\Psi = 20°$. Prior to ECAP deformation, the samples were annealed for 2 h at 450 °C. The samples were subjected to routes B_{60} and B_C for up to 10 passes corresponding to $\varepsilon \sim 6.3$. Fig. 1 schematically shows these two different processing routes. Disc shape specimens (5 mm in thickness) were cut from the ECAP samples perpendicular to the exit channel. The specimens were polished to a metallographic finish followed by a chemical polishing carried out by a H_3PO_4 (50%) + H_2O_2 (50%) solution.

Texture measurements were carried out by X-ray diffraction using a Siemens D-500 goniometer system (Molybdenum target) and the standard reflection technique. For each sample, texture was examined using orientation distribution functions (ODFs) which describe the crystallite orientation densities in a three-dimensional orientation space defined by the Euler angles φ_1, Φ and φ_2. For ODF calculations, three incomplete pole figures: {1 1 1}, {2 0 0} and {2 2 0} were measured in reflection on the cross section perpendicular to the axis of the samples (x–z plane). Upper center of the first exiting end of the samples was marked as the reference point for rotation of the billets in each route and also for pole figure measurements (Fig. 2). The ODFs were calculated from the pole figures data using TextTools software. The textures are presented in $0° \leqslant \varphi_1 \leqslant 360°$, Φ and $\varphi_2 \leqslant 90°$ Euler space. The microstructure of ECAP processed samples were examined by electron back scattering diffraction (EBSD) technique. The EBSD scans were carried out in areas 5 μm × 5 μm with a 0.2 μm step size.

The Vickers method was used for hardness testing. For this purpose, the tests were carried out on the cross section of the samples for 10 times and the average values were reported. The extruded samples were cut in the longitudinal direction into two equal pieces. To make samples, the tensile specimens with the gauge length of 20 mm and 4 mm in diameter in compliance with ASTM E 8 M standard [8] were machined from these half billets. Tensile tests at a strain rate of 5 mm/min were performed on a HOUNSFIELD-H50KS machine.

3. Results and discussion

3.1. Texture evolution

The ODF of the texture measured from the cross section of specimen before ECAP is shown in Fig. 3. The scale bar to the right of ODF indicates relative intensity, where 1.00 represents random orientation of grains. There is a weak texture for the initial samples that can be described as $\{1\,1\,\bar{1}\}\langle 1\,\bar{1}\,0\rangle$ ($\{1\,1\,\bar{1}\}$ is parallel to the cross section and $\langle 1\,\bar{1}\,0\rangle$ is parallel to the reference point direction) with the maximum intensity $\sim 2 \times R$ (random). The crystallographic direction, in this notation, is aligned along the direction marked on the specimen before processing and this direction is used as a reference for all ECAP passes.

As pointed out previously [9–11], during ECAP the material is deformed successively by simple shear at the intersection plane of the two channels. Simple shear textures depend on crystal structure and their ideal components are determined for F.C.C [12,13], B.C.C [12,14], and H.C.P metals [12]. The behavior of the ideal orientations of F.C.C crystals are defined by {1 1 1} || shear plane (A fiber) and ⟨1 1 0⟩ || shear direction (B fiber). The preferred orientation of the shear plane and the shear direction should be more meaningful in describing the deformation texture resulting from ECAP with different die angles. In a 120° ECAP die, the shear plane is inclined 30° from the x–z plane. Therefore, ECAP texture practice involves rotating the simple shear orientations by 30° from the shear plane into the bar axis frame (for details see [5,6]). In contrast, this study proposes to rotate experimental data obtained in the x, y and z coordinate frame by 30° to a theoretical simple shear plane (y plane in rotated coordinate frame). Because the ECAP deformation takes place by a near simple shear at the intersection plane of the two channels, the ideal ECAP texture components are the same as those for the simple shear (Table 2 and Fig. 4). As the pole figures provide semi-quantitative information about textures, and the information obtained from a limited number of pole figures is, in general, insufficient to describe the texture completely [15], we prefer to use the ODFs for evaluating the texture of each sample (Fig 5). Since the $\varphi_2 = 0°$ and 45° sections contain most of the important information about F.C.C textures, only these two sections are presented for comparison. The simple shear rotated ODF of $N = 1$ sample (Fig. 5a) is different from the ODF of the undeformed specimen. In the $\varphi_2 = 0°$ section, a strong C $(1\,0\,0)[1\,\bar{1}\,0]$ component was localized at $\Phi = 0°$ and 90° running at $\varphi_1 = 45°$, 135°, 225° and 315°. It should be noted that the C component is a special position of the B partial fiber, oriented in the ⟨1 1 0⟩ direction [16]. The same texture component was also visible in the $\varphi_2 = 45°$ section (at $\Phi = 0°$ and at $\varphi_1 = 90°$, 180° and 270°). The strongest intensity of $\sim 7 \times R$ is found in the $\varphi_2 = 45°$ section (at $\varphi_1 = 30°$, 150° and 270° at $\Phi = 55°$) and can be attributed to the A_1 $(1\,1\,\bar{1})[2\,\bar{1}\,1]$ and A_2 $(1\,1\,\bar{1})[\bar{2}\,\bar{1}\,1]$ texture components. After the second pass of route B_{60} (Fig. 5b), in the $\varphi_2 = 0°$, the texture displays no significant C component but in the $\varphi_2 = 45°$ section, a split is observed in the position of the maximum intensity of $\bar{B}$ component (relative intensity $\sim 6.6 \times R$). After four passes (Fig. 5c), the strongest texture components were $(0\,2\,1)[0\,\bar{1}\,2]$ located at $\varphi_1 = 95°$, $\Phi = 60°$, $\varphi_2 = 0°$ and $(0\,1\,2)[0\,2\,\bar{1}]$ located at $\varphi_1 = 270°$, $\Phi = 25°$, $\varphi_2 = 0°$. In the $\varphi_2 = 45°$ section, the preferred orientation was located at $\varphi_1 = 270°$, $\Phi = 70°$ with the maximum intensity of $\sim 5.6 \times R$, corresponding to $(2\,2\,1)[1\,1\,\bar{4}]$. After 10 passes (Fig. 5d), in the $\varphi_2 = 0°$ section, the maximum intensity of the components is located at $\varphi_1 = 85°$, $\Phi = 65°$; $\varphi_1 = 265°$, $\Phi = 20°$, related to $(0\,2\,1)[0\,\bar{1}\,2]$ and $(0\,1\,2)[0\,2\,\bar{1}]$ orientations. In the $\varphi_2 = 45°$, the strongest component (with the relative intensity of $\sim 5.4 \times$ R) was located at $\varphi_1 = 205°$, $\Phi = 15°$ corresponding to $(1\,1\,5)[\bar{3}\,8\,\bar{1}]$. The other active components in this section were located at $\varphi_1 = 30°$, $\Phi = 50°$, related to $(1\,1\,1)[1\,\bar{2}\,1]$ and $\varphi_1 = 270°$, $\Phi = 55°$ corresponding to $(1\,1\,1)[1\,1\,\bar{2}]$ (relative intensity $\sim 4.5 \times R$).

Table 1
Chemical composition of the Cu samples.

Element	Sn (ppm)	Pb (ppm)	Zn (ppm)	P (ppm)	Mn (ppm)	Fe (ppm)	Ni (ppm)	Si (ppm)	Cr (ppm)
Content	97.67	67.00	287.24	38.38	9.260	406.18	17.31	13.46	<4.00
Element	Te (ppm)	As (ppm)	Se (ppm)	Sb (ppm)	Bi (ppm)	Al (ppm)	S (ppm)	Cu (%)	
Content	36.36	<2.000	<2.000	6.000	<8.000	6.000	125.12	99.89	