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Textural evaluation of copper produced by equal channel angular pressing with routes A and B_{30}

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ABSTRACT

The present study investigated texture evolution and tensile properties of oxygen-free, high conductivity copper (OFHC) subjected to equal channel angular extrusion at room temperature for up to ten passes using routes A and B_{30}. As the cross sections of the specimens were circular, a new route with a rotation angle of 30° in the same direction between consecutive passes was used. Texture was weak in the initial copper specimen. Both routes exhibited texture development similar to simple shear. In route A, A_1 and C are the main components up to four passes and the $B/\bar{B}$ components strengthen in the sixth pass, but in route B_{30} the discontinuous strain path applied to the bar through rotation by 30° around its longitudinal axis between each pass results in significant changes in texture with increasing *N*. The tensile strength and ductility of the annealed and ECAP samples with routes A and B_{30} were measured using tensile tests and the relations between tensile strength and intensity of (1 1 0) textures were obtained.

1. Introduction

Severe plastic deformation (SPD) methods have been recently used for the production of metals and alloys with ultrafine grains, which are 10 to even a 100-fold finer than those observed in conventionally deformed metals [1–3]. One of the most commonly used SPD methods is the equal channel angular pressing (ECAP), that produces a homogeneous submicron grain structure in the work piece [4,5].

ECAP involves the use of a die containing two intersecting channels of equal cross sections. The strain that the sample experiences is dependent on two parameters: the inner angle of the intersection of the channels, Φ, and the outer angle of the curvature, Ψ. The geometry of ECAP experiments has been described elsewhere [6]. Like other SPD techniques, the ECAP process can be repeated several times and very high plastic strains can be applied since the material's shape and size do not change. Rotation of the bar (processing routes) between passes is a key parameter in the process [7]. In general, the deformation mechanism in the ECAP process depends on the material's properties and process parameters. For a specific material, the number of passes (amount of induced strain), die angle (Φ), and processing routes which affect the deformation process and the microstructure can be controlled [7,8]. Large plastic deformation and frequent changes in strain paths result in complex changes in both the microstructure and the crystallographic texture of the material.

Texture investigation is essential for understanding the deformation mechanism and the grain refinement process [9]. It has been shown [10–14] that the texture evolution by ECAP is very similar to simple shear texture obtained by torsion or simple shear deformation. Shear texture components that develop during simple shear deformation are described in terms of $\{h\,k\,l\}$ planes and $\langle u\,v\,w\rangle$ directions parallel to the plane and direction of shear, respectively. Thus, in fcc materials partial fibers belonging to $\{h\,k\,l\}\langle 1\,1\,1\rangle$, and $\{1\,1\,0\}\langle u\,v\,w\rangle$ types demarcate simple shear deformation.

ECAP textures have been found to be weak compared to the rolled specimens of equivalent strain. This is because no stable orientation is produced as a consequence of material rotation during simple shear [10,11,15,16]. However, it has also been experimentally demonstrated that significant differences occur in texture development under ECAP and torsion conditions [12–14,17–21]. Moreover, different possibilities of reintroducing the pre-strained bar during multiple passes also result in different "starting" textures and a discontinuous strain path, depending on the route adopted for the processing of a bar via ECAP. The deformation process is not restricted to a localized, singular plane of shear at

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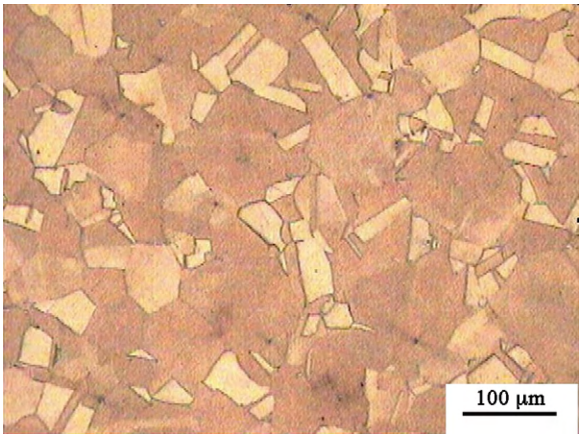

Fig. 1. Optical microstructure of initial copper annealed at 450 °C for 2 h.

the intersection of the two directions of the die, rather it is the result of progressive changes in the deformation zone (termed as the 'plastic deformation zone', or PDZ for short) which is defined by a fan-angle on either side of the die intersection plane [22]. In addition, new opportunities arise with multiple passes for different structures and textures to develop in the same material through the modification of shear planes and shear directions during the ECAP process [7,23]. That is, the bar may be rotated around the long axis for different angles between consecutive extrusions. Following Furukawa et al. [24], there are four different routes (A, B_A, B_C, and C). Route A involves no rotation; route B_A involves alternate ±90° rotations; route B_C involves 90° rotation always with the same sense, and route C involves 180° rotation. The type of ECAP route and number of passes significantly impact texture evolution. It is, therefore, expected that different textures may be developed. The textural evolution of ECAP-processed samples was investigated in a central region of pure Al, Ni, Mg, Cu, and Ag with different routes. However, as the cross-section of the specimens used in this study was circular, a new route with a rotating angle of 30° in the same direction between consecutive passes was also adopted and comparisons were made between the texture evolutions of pure copper specimens processed by ECAP up to ten passes with routes A and B_{30}. The mechanical properties of the annealed specimen and the ECAP-processed ones with routes A and B_{30} up to ten passes were investigated using tensile tests and the relation between tensile strength and texture was established for the first time.

2. Experimental procedure

2.1. ECAP process

In the present study, oxygen free high conductivity (OFHC) copper (99.9% Cu) was used as the experimental material. Bars of 20 mm in diameter and 80 mm in length were pressed using the ECAP die. Prior to ECAP deformation, the material was annealed for 2 h at 450 °C in order to obtain a fully recrystallized homogeneous microstructure with a grain size of about 50 μm. The microstructure of this specimen is shown in Fig. 1. Clearly, the texture is weak and the grain orientation is close to random with a maximum intensity of 1.6 × R (multiplied by random). ECAP deformation was carried out at room temperature up to ten passes using a die with $\Phi = 120°$ and $\Psi = 20°$ (Fig. 2), using routes A and B_{30}. The total equivalent strain after ten passes was calculated using Eq. (1), in which N is the total number of passes through the die, Φ is the angle between the channels, and Ψ is the outer arc of curvature at the intersection

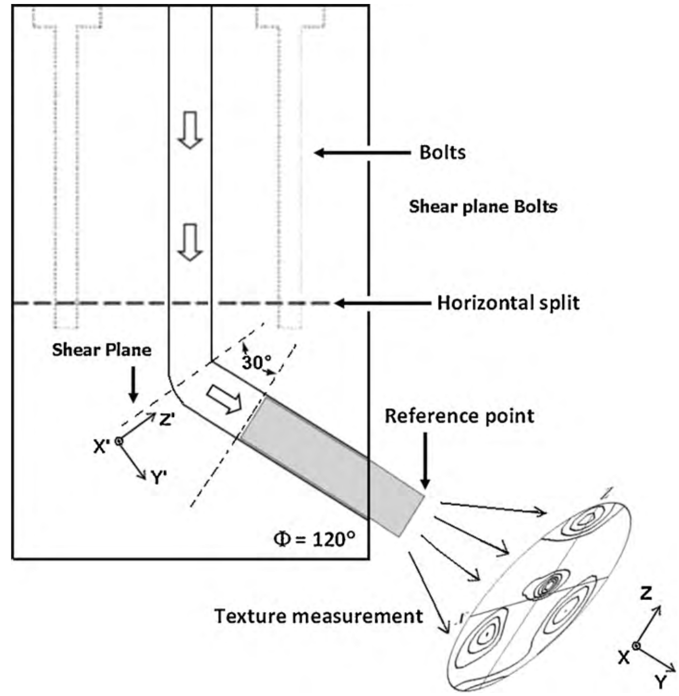

Fig. 2. The cross section of the die, texture measurement, and its reference point. Φ is the inner die angle, and Ψ is the angle of the curved portion of the die.

of the channels and equal to 6.3.

$$\varepsilon = \frac{N}{\sqrt{3}}\left(2\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi\,\mathrm{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right) \quad (1)$$

2.2. Texture analysis

Texture measurements were performed using X-ray diffraction by a Siemens D500 goniometer system (Mo tube) and the standard reflection technique. The ECAP textures were measured on the x-y-z laboratory system of die. Three incomplete pole figures ({1 1 1}, {2 0 0}, and {2 2 0}) were measured on the cross-section (x–z plane) of the samples. The upper center of the first exit end of the samples was marked as the reference point for the rotation of the bars in each route and texture measurement (Fig. 2). Specimens 5 mm thick were cut from both the initial sample and from the extruded bars after passes 1, 2, 4, 6, 8, and 10 with routes A and B_{30}. The specimens were polished to a metallographic finish and then chemically polished with a solution of H_3PO_4 (50%) + H_2O_2 (50%). The orientation distribution functions (ODF) were calculated from the pole figure data using TextTool software. The textures are presented in the $0° \le \varphi_1 \le 360°$, Φ, $\varphi_2 \le 90°$ Euler space.

2.3. Tensile test

For tensile testing, the ECAPed samples were cut in longitudinal direction to 2 pieces, and then they were machined to 20 mm gauge length and 4 mm diameter according to ASTM E 8M, to make symmetrical samples. The tensile properties of the annealed specimen and those of one, two, four, eight and ten passes ECAP of both routes A and B_{30} were tested. All the tests were carried out three times at room temperature using a HOUNSFIELD-H50KS machine at an initial strain rate of 5 mm/min.