Journal of Materials Processing Tech. 259 (2018) 305–311

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Circumferential twisting during route B equal-channel angular pressing

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ARTICLE INFO

Keywords:
Equal-channel angular pressing
Finite element method
Severe plastic deformation
Strain inhomogeneity
Circumferential twisting
Deformation behavior

ABSTRACT

Equal-channel angular pressing (ECAP) is a representative severe plastic deformation process to fabricate bulk nanostructured materials by repetitive passes. Typically, there are four basic processing routes for the repetitive passes: route B is the most beneficial for grain refinement and homogenization of microstructure. In this work, investigation on deformation during route B in ECAP was conducted using the finite element analysis. It was found that the route B could lead to the inhomogeneous equivalent strain along the longitudinal direction of the workpiece by an unusual phenomenon called "circumferential twisting". The circumferential twisting is primarily attributed to the deformation inhomogeneity for the cross-section induced during the 1 st pass of ECAP. This phenomenon occurs remarkably for the large-scale ECAP process because the twisting angle per unit length is almost constant. In addition, the higher the strain hardening exponent of the material, the greater the sample twisting during ECAP by the corner gap effect.

1. Introduction

Ultra-fine grained (UFG) metals with the average grain size less than ~1 μm exhibit not only a superior combination of strength and ductility compared to the coarse-grained counterpart, but also superior functional properties such as biocompatibility, thermal stability, and corrosion resistance as reported by Zhu et al. (2004). Severe plastic deformation (SPD), firstly introduced by Bridgman (1943), is a well-known approach to manufacture the UFG metallic materials by applying the extreme level of shear deformation and hydrostatic pressure into the workpiece materials. Because the SPD process can achieve grain refinement preserving the sample shape, fabrication of bulk nanostructured materials is possible. Furthermore, large-scale and continuous SPD processes have been recently developed, such as equal-channel angular pressing (ECAP) with billet dimensions of $50 \times 50 \times 300\,\text{mm}^3$ by Frint et al. (2011) and the ECAP-conform process invented by Raab et al. (2004), which make the application of the SPD process to the structural parts even more active.

The ECAP invented by Segal et al. (1981), which is the most developed method among the various SPD processes, is a process that imposes a large amount of shear deformation into the material by pushing the workpiece through a region where two channels with identical cross-sectional dimensions intersect each other. Because ECAP has a particular feature that the cross-sectional dimensions of the workpiece are preserved after processing, repetitive passes are possible using four different processing routes as suggested by Nakashima et al. (2000). These different processing routes activate different slip systems in the materials, which leads to the distinctive evolution of the microstructures. Therefore, the variations of the mechanical properties and crystallographic orientations in related to the processing routes have been actively investigated on various metallic materials such as Cu by Molodova et al. (2007), Al by Reihanian et al. (2008), and Mg alloy by Kim et al. (2003).

However, regardless of the kind of materials, the prevalent problem in the ECAP process is the deformation inhomogeneity of the workpiece. The deformation inhomogeneity leads to local differences in the microstructure and the mechanical properties that significantly hinder the stability of the structural material. According to the scale variation, there is no size effect on the mechanical and microstructural characteristics in the ECAP process as reported by Horita et al. (2001), so the first step for the industrialization of ECAP is to improve the deformation homogeneity.

In general, the investigation on the deformation homogeneity in ECAP is mainly focused on the cross-section rather than the

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https://doi.org/10.1016/j.jmatprotec.2018.05.001
Received 19 December 2017; Received in revised form 6 April 2018; Accepted 1 May 2018
Available online 02 May 2018
0924-0136/

longitudinal section of the workpiece because the steady state behavior appears along the longitudinal direction in the part between the front and the rear of the workpiece, as reported by Kim et al. (2001). Therefore, the previous research dealt with a trial to enhance the deformation homogeneity for the cross-section by altering the die design, such as the channel angle by Basavaraj et al. (2009) and the corner angle by Yoon et al. (2007), or using the back-pressure as reported by Xu et al. (2007). In particular, the most popular method to improve the deformation homogeneity on the cross-section is the repetitive passes by various processing routes, of which route B is most favorable for the deformation homogeneity and grain refinement as demonstrated by Stolyarov et al. (2001).

In this study, an unusual phenomenon called "circumferential twisting" is firstly introduced, which has never been studied in the previous literature as far as the authors know. The phenomenon can occur in conventional ECAP processes with a cylindrical workpiece. The objectives of this research are to clear up the cause of the phenomenon and to investigate the effect of the phenomenon on the deformation homogeneity during the repetitive passes in route B of the ECAP process, using the finite element method (FEM) and the ECAP process in the laboratory scale. Additionally, the material factor affecting the circumferential twisting in ECAP is discussed. Consequently, the present investigation revealed that the circumferential twisting is primarily attributed to deformation inhomogeneity on the cross-section of the workpiece induced in the 1 st pass of ECAP. Also, this phenomenon appeared only in route B, not routes A and C, and deteriorated the deformation homogeneity on the longitudinal section of the workpiece, even though route B is most advantageous for the grain refinement and deformation homogeneity on the cross-section. Finally, it was confirmed that the higher strain hardening exponent of the workpiece is, the more intensified the circumferential twisting is during the ECAP process.

2. Experimental procedure

2.1. Equal-channel angular pressing

An oxygen-free high-conductivity (OFHC) Cu with high purity of 99.99 wt% was subjected to the ECAP process at room temperature, and the chemical compositions of the material were shown in Table 1. For homogenizing the initial microstructure, the workpiece with the dimensions of Φ 44.6 mm × 175 mm was annealed at 900 °C for 1 h. In order to visually examine the material flow during the ECAP process, Al wires were embedded into the surfaces of the workpiece as shown in Fig. 1a, and it was confirmed that the embedment of Al wires seldom influences the deformation of OFHC Cu workpiece during ECAP (see supplementary material). A split-type ECAP die has the channel angle of 90° and the corner angle of 14°. The channel angle is the angle which the central axes of two identical channels form, and the corner angle is defined as the angle associated with the arc curvature of the outer die corner with respect to the inner die corner. The detailed dimensions of the die were illustrated in Fig. 1b. To minimize the frictional effect during the processing, the lubricant of MoS_2 was coated on the workpiece and the die, and the ECAP process was performed at a slow ram speed of 2 mm/min. After the 1 st pass of ECAP, the distorted shape near the front and the rear part of the workpiece were cut out, and then the 2nd pass was conducted in route B that the workpiece was rotated by 90° between each pass.

Table 1
Chemical compositions of OFHC Cu used in the ECAP process.

Cu (wt%)	O (ppm)	Pb (ppm)	Bi (ppm)	Fe (ppm)	P (ppm)	S (ppm)
99.99	2	1	< 1	1	< 1	3

2.2. Measurement of the mechanical properties

After initial heat treatment and 1 st pass of ECAP, the mechanical properties of the workpiece were evaluated by uniaxial tensile tests using a universal testing machine (UTM, model 1361, Instron Co., USA). Three tensile specimens were machined into the dog-bone-shape plate along the axial direction of the workpiece, and the gauge dimensions were 1 mm (thickness) × 2.5 mm (width) × 5 mm (length). The tensile tests were performed at a strain rate of $1 \times 10^{-3}\,s^{-1}$, and the strains were measured using a digital image correlation (DIC) method (ARAMIS 5 M, GOM mbH, Germany). As reported by Yoon et al. (2016), the DIC method can measure reliable true stress-strain curves for a wider range of strains by reducing the gauge length, which is useful to enhance the reliability of the FEM simulations for the SPD process imposing extremely high strain into the materials.

In order to experimentally analyze the local strain induced during ECAP, the microhardness was measured using Vickers hardness tester (FM-700, Future-Tech Co., Japan). After grinding and polishing the cross-sectional surface of the workpiece up to 1200 grit using SiC abrasive papers, the microhardness was estimated by averaging three values at each selected position from the bottom to the top region of the workpiece. The bottom region was defined as the part contacting the outer corner of the ECAP die, and the top region was the portion in contact with the inner corner. The loading force and time for measuring the microhardness were 100 gf and 10 s, respectively.

3. Finite element method

In the present work, the deformation behavior that occurs during the ECAP process with the circular cross-section was investigated using FEM. Because neither plane strain nor plane stress assumption is appropriate in the ECAP process with a circular cross-section, 3-D FEM simulations were conducted using ABAQUS/Standard Ver. 6.9. In FEM, the detailed dimensions of the workpiece and die were set identically to the experimental condition. The isotropic hardening model based on the tensile results was adapted in this simulations using the Ludwik's equation:

$$\sigma_p = \sigma_y + K\varepsilon_p^n \tag{1}$$

where σ_y, ε_p, K, and n represent the yield strength, plastic strain, material strength factor, and strain hardening exponent, respectively. The plastic stress-strain curve used in this simulation was represented in Fig. 2 and it is in good agreement between the experimental observation and Ludwik's equation with $K = 360.6$ and $n = 0.551$. Young's modulus, Poisson's ratio, and yield strength of the as-annealed OFHC Cu were 117 GPa, 0.33, and 93.9 MPa, respectively. The lubricated friction coefficient between the workpiece and die was assumed to be 0.03, which showed well matched maximum load between the experiment and FEM simulation in the work by Nagasekhar et al. (2009). Because the ram speed was very low, the effect of internal heat generated during ECAP was ignored.

In addition, the solution mapping was employed for simulating the repetitive passes in ECAP. The solution mapping is a technique to map the solutions from the deformed elements to new elements, and Wei et al. (2014) proved the computational efficiency by applying the method into the high-pressure torsion (HPT) process. In the same way, the repetitive passes of ECAP were simulated using the solution mapping method. All state variables after the 1 st pass of ECAP, including stress and strain components, were transferred to the new elements at the same coordinate in the 2nd pass ECAP simulation. Each processing condition such as the ram speed and friction coefficient was set identical to the 1 st pass. The types of elements in the workpiece and the die were fully-integrated hexahedral elements with 8 nodes (C3D8) and quadrilateral elements with 4 nodes (R3D4), respectively. The number of elements was 8000 in the workpiece and 12,142 in the die.