

The influence of ECAP geometry on the effective strain distribution

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ABSTRACT

Purpose: The present study deals with the influence of channel angle on the deformation behavior and strain homogeneity in the transverse direction of sample after two ECAP passes.

Design/methodology/approach: To increase the efficiency of ECAP method, there is necessary to design the geometry of ECAP die with focused on high degree of plastic deformation homogeneity. This analysis was carried out through finite element simulations in the Deform program. In the simulation, three main factors such as an intersecting angle of $\phi = 90^\circ, 100^\circ, 110^\circ$ a 120° , outer corner angle R (ψ) and inner corner angle (r) were being varied. The equation describing the dependence of R and r on average value of the effective plastic strain for different channel angles was established. Moreover, strain inhomogeneity index (C) in the transverse direction of sample was also calculated.

Findings: The results from simulations have indicated that if the outer corner angle increases, mean effective strain decreases. After two ECAP passes (route C), there was seen the increase in strain homogeneity of the sample's cross section.

Research limitations/implications: Equal channel angular pressing (ECAP) is one of the most well-known severe plastic deformation (SPD) method for formation the UFG structures. This method provides very high strains leading to the extreme work hardening and microstructural refinement.

Originality/value: To increase the efficiency of ECAP method, there is necessary to design the geometry of ECAP die with focused on high degree of plastic deformation homogeneity.

Keywords: ECAP; FEM; Homogeneity of deformation

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ANALYSIS AND MODELLING

1. Introduction

Ultra-fine grained materials are currently of great interesting due to their unusual mechanical and physical

properties [1-5]. The ultra-fine grained structures in metallic polycrystals is possible to develop by methods based on severe plastic deformation (SPD). This approach is referred to as a "top-down" approach [6]. Equal channel angular pressing (ECAP) is one of the most prominent and

effective procedures in SPD techniques [7-10]. The ECAP process (Fig. 1) is a method that involves large shear plastic deformation in a sample by moving through a die containing two channels with identical cross-sections that are intersected in the predetermined angle (Φ). Values of the angles Φ strongly depend on material plastic properties and can be in the range of 60° - 135° [11]. Outer corner angle ψ (or outer radius R) is a next parameter significantly affecting the distribution of plastic deformation in a sample. Theoretical calculation of the effective strain is given by the formula [12].

$$e_{eff} = \frac{1}{\sqrt{3}} \left[2 \cot\left(\frac{\Phi + \Psi}{2}\right) + \Psi \operatorname{cosec}\left(\frac{\Phi + \Psi}{2}\right) \right] \quad (1)$$

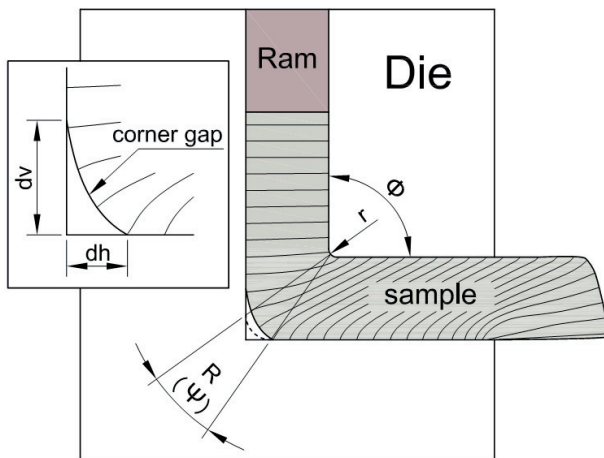


Fig. 1. The scheme of an ECAP die

This formula takes account only geometrical parameters of the ECAP die and moreover it considers the plastic deformation as an uniform in a whole process. Most of experimental works focused on the study of ECAP through FEM have clearly proved inhomogeneity in the strain distribution in the sample's cross-section [12-15]. A number of parameters as a geometry of the die, friction conditions, material properties, processing temperature, rate of the extrusion process and others have a significant impact on distribution of plastic deformation in the ECAP process. Mahallawy et al. investigated the effect of outer corner angle ψ and ECAP number of passes on inhomogeneity index in effective plastic strain [16]. Kvačakaj et al. confirmed the inhomogeneous distribution in plastic deformation after the first ECAP pass through measurements of the microhardness [17]. Oh et al.

established that the corner gap is an important index having impact on the quality of ECAP processing [18]. Lu et al. have also reported the significance of a die channel angle considering the inhomogeneity index in effective plastic strain. Bidulská et al. analyzed the material flow, strain, strain rate and temperature distribution during ECAP processing [19]. Džavanroodi et al. studied the influence of die channel angle and displacement between them on parallel ECAP channels in a multi-channels die [20].

In this paper, the effect of a die channel angle (Φ), outer (R) and inner (r) radius distance and material properties (strain hardened exponent n) are investigated by FEM analysis. Considering the results from simulations, a relation between average values of the effective strain and ECAP die geometry (Φ , R , r) was derived.

2. Finite Element Methods

The simulation of ECAP process with focus on plane strain conditions was carried out using the metal forming code DEFORMTM. To study the influence of ECAP geometry on the effective strain distribution, three main factors as an intersecting angle Φ , outer corner angle $R(\psi)$ and inner corner angle (r) were being varied. For an intersecting angle of $\Phi = 90^\circ$, there was mutual combination between $R = 0,1,2,3,4,5,6,8,10$ mm and $r = 0,1,2,3,4,5$ mm and for $\Phi = 100^\circ, 110^\circ, 120^\circ$ was $R = 0,1,2,3,4,5,6,8,10$ mm and $r = 0,2,4,6$ mm, respectively. In all simulations, there was used ECAP die with a channel diameter of 10 mm and punch speed of 1 mm/s. The sample was defined as a rigid-plastic material considering the Ludwik strain hardening model according to the following equation:

$$\sigma = \sigma_y + K \cdot e^n \quad (2)$$

where:

σ – is flow stress,

σ_y – is the yield stress,

e – is the effective plastic strain,

K – is the strength coefficient,

n – is the strain hardening exponent.

Flow stress of the materials studied is $\sigma = 210 \cdot \varepsilon^{0.28}$. The diameter and the length of samples were 10 mm and 100 mm, respectively. The friction coefficient f used for all simulations was 0.1. The samples volume was meshed to 3000 elements (were used 20 elements across the width). The surface die and punch were defined as a rigid. In all simulations, automatic remeshing was applied.

3. Results and discussion

Deformation behavior in the sample subjected to ECAP method is presented in the Fig. 2a through the distribution of effective strain contours for $\Phi = 90^\circ$ with $R5_r0$. As it has already been announced by several authors, after the 1st ECAP pass there is formed the non-uniform strain distribution in the sample [16-20]. More details about the influence of outer (R) and inner (r) corner angles is shown in the Fig. 2. Measuring points were being located across the middle plane of the sample as is shown in the Fig. 2. If $R \geq 8$ mm and $r = 0$ mm, the heterogeneity at the bottom of the sample is being increased. At the present time, scientific community is not enough involved in a study of the inner corner angle (r) in the ECAP die which could be because of wearing changed during a long-time processing. If $r = 0-3$ mm there is seen the soft fall in the heterogeneity of effective strain, however when $r \geq 4$ mm, there is an opposite progress.

The whole process of plastic deformation is influenced by materials properties which strongly depend on strain-hardening behavior and friction conditions. These parameters have an impact on the formation of a corner gap during ECAP processing. The corner gap is defined by a corner shape index λ which is suggested to calculate according to the Eq. (3), where d_v and d_h are illustrated in the Fig. 1. In the Fig. 3, there is illustrated an influence of the strain-hardening behavior and friction conditions on formation of the corner gap index during the 1st ECAP pass (for $\Phi = 90^\circ$, $R = 0$ mm and $r = 0$ mm). According to the Fig. 3, the corner gap expands if the strain-hardening index raises but on the other hand it decreases when friction conditions are being increased.

$$\lambda = d_h \left(1 + \frac{d_h}{d_v} \right) \quad (3)$$

The Fig. 4 illustrates assessment of the comprehensive impact of the ECAP die geometry (Φ , R , r) on the average value of the effective plastic strain. As is seen, when an inner radius (r) in the die with angles of $\Phi = 90^\circ$ and 100° grows, an average value of the effective plastic strain also raises. On the other hand, when $\Phi = 90^\circ$ and 100° grows, an average value of the effective plastic strain also raises. On the other hand, when an outer corner angle grows, the effective plastic strain decreases. For dies with the angles of $\Phi = 110^\circ$ and $\Phi = 120^\circ$, changes in R and r don't have a significant impact on plastic characteristics. The degree of plastic strain inhomogeneity was expressed through the index Ci [21] as:

$$Ci = \frac{e_{eff.max} - e_{eff.min}}{e_{eff.avg}} \quad (4)$$

where $e_{eff.max}$, $e_{eff.min}$. and $e_{eff.avg}$. are maximum, minimum and average values of strain value in the second cross-section of the sample respectively.

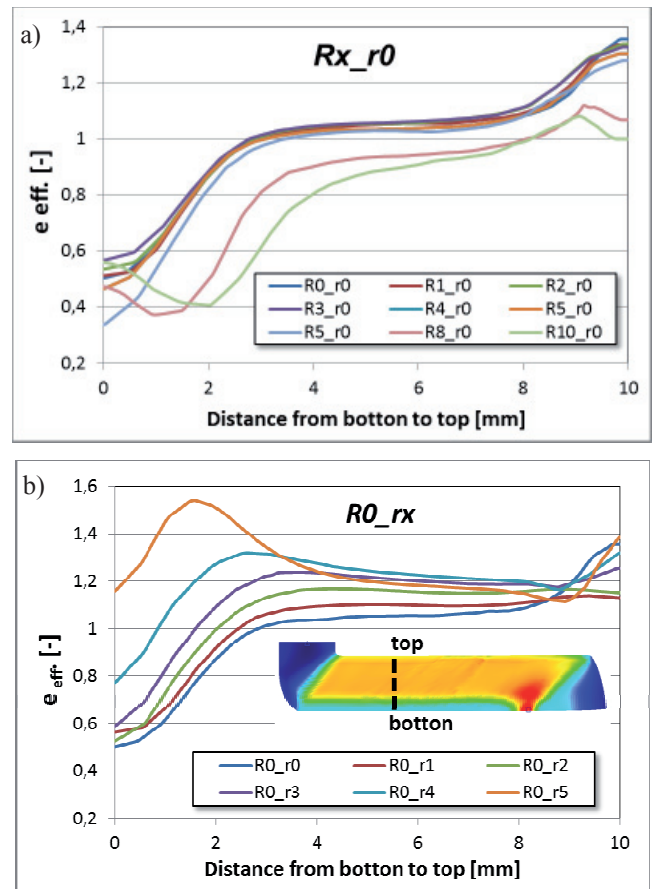


Fig. 2. Effective strain distribution in the cross-section of the sample with various parameter R and r for intersecting angle $\Phi = 90^\circ$

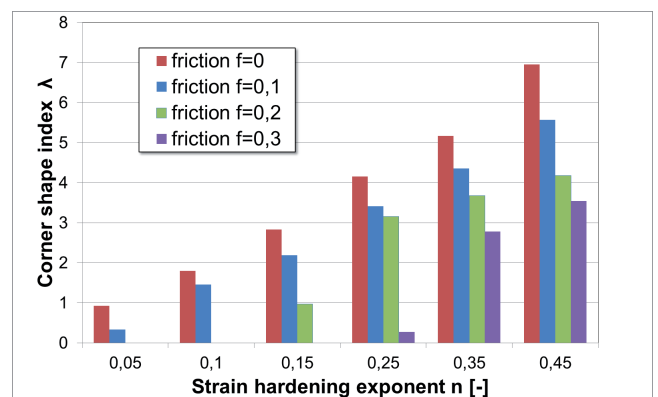


Fig. 3. The strain hardening exponent and friction effect on the corner shape index λ

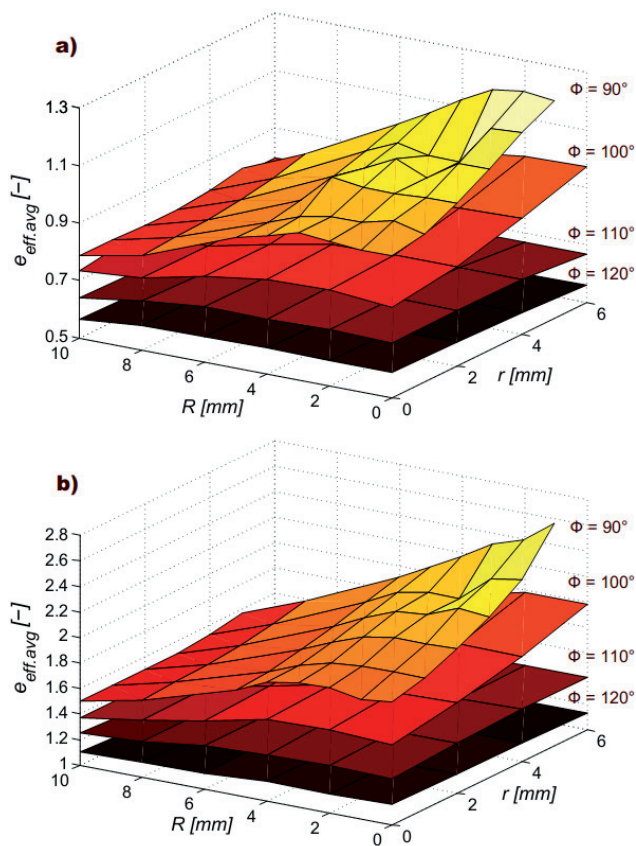


Fig. 4. Influence of the ECAP geometry on average value of the effective plastic strain $e_{eff.avg}$ after: a) the 1st ECAP pass, b) the 2nd ECAP pass

According to the index of heterogeneity C_i , the highest difference in values of the effective strain e_{eff} after the 1st

ECAP pass was seen when $\Phi = 90^\circ$, the $C_{i_{max}}$ was approximately 1.2 [-]. The value of C_i was decreased with the Φ increasing and it was 0.7 [-] when $\Phi = 120^\circ$. Throughout the 2nd ECAP pass processing (route C), there is possible to see similar situation. When Φ increases, $C_{i_{max}}$ falls down. Moreover, by using more than one ECAP pass, homogeneity is improved what was also confirmed by values in $C_{i_{max}}$, when for $\Phi = 90^\circ$, $C_{i_{max}}$ was approximately 0.55 [-] and for $\Phi = 120^\circ$, $C_{i_{max}}$ was approximately 0.45 [-].

From the FEM analyse, after the 1st ECAP pass, an average value of the effective plastic strain $e_{eff.avg}$ was determined as a function of the outer and inner radius for the die with angles of $\Phi = 90^\circ$, 100° , 110° and 120° . Function $e_{eff.avg} = f(R, r)$ is described by the Eq. (5) that is in the form of the elliptic resp. hyperbolic paraboloid.

$$\varphi_{ef.str.} = p_1 \cdot (r - p_4)^2 + p_2 \cdot (R - p_5)^2 + p_3 \quad (5)$$

where:

R – outer radius of the ECAP channel,

r – inner radius of the ECAP channel,

$p1-p5$ – parameters of the equation.

In Table 1, there are shown parameters of the Eq. (5) together with the residual sum of squares (Res) for each particular angles.

The Fig. 5 illustrates the calculated data from the equation $e_{eff.avg} = f(R, r)$ for angles of $\Phi = 90^\circ$, 100° and 120° after the 1st ECAP pass. Difference in the measured data was revealed on the surface planes are illustrated by blue and green line segments in the Fig. 5. According to the Fig. 5, there is seen a high agreement in the measured and calculated data.

Table 1.
Parameters of Eq. (5) with the residual sum of squares (Res)

	p_1	p_2	p_3	p_4	p_5	$Res.$
1 x 90°	-0.0022046	0.004912	1.0684659	-2.7342421	-0.7554524	0.0681
2 x 90°	-0.0027135	0.010474	2.3438	-9.2438	-0.9954	0.3136
1 x 100°	-0.0008	0.0021	0.8580	-3.6683	-1.0999	0.0123
2 x 100°	-0.0035	0.0047	1.7157	-1.1222	-0.7169	0.0528
1 x 110°	-0.0010	-0.0008	0.6976	2.8137	1.2559	7.2932e-004
2 x 110°	-0.0024247	0.00027001	1.3626	1.7362	-7.9968	0.0032785
1 x 120°	-0.00045794	-0.00053085	0.59116	3.2268	-1.2828	2.1545e-004
2 x 120°	-0.001	0.0003	1.1367	1.6584	7.4978	0.0011119

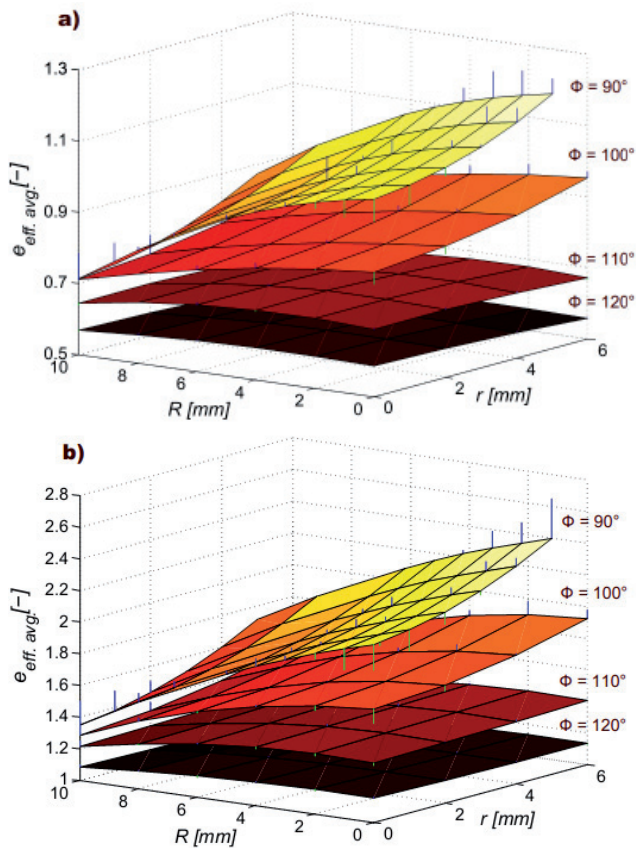


Fig. 5. Influence of the ECAP geometry on average value of the effective plastic strain $e_{eff.avg}$ after: a) the 1st ECAP pass, b) the 2nd ECAP pass

4. Conclusions

According to the numerical simulations, there is possible to formulate the following findings:

1. During ECAP processing, plastic deformation is non-uniform in the longitudinal and transverse direction.
2. The corner gap expands if the strain-hardening index raises but on the other hand it decreases when friction conditions are being increased.
3. When an inner radius in the die with angles of $\Phi = 90^\circ$ and 100° grows, an average value of the effective plastic strain $e_{eff.avg}$ also raises. On the other hand, when an outer corner angle grows, the effective plastic strain $e_{eff.avg}$ decreases.
4. From the FEM analyse, there was determined an average value of the effective plastic strain $e_{eff.avg}$ as a function of the outer and inner radius for the die with angles of $\Phi = 90^\circ, 100^\circ, 110^\circ$ and 120° after the 1st ECAP pass.

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