Theoretical analysis of ECAP process by upper bound method and its experimental investigation in condition of circular cross-section channel

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ABSTRACT

ECAP process is one of the most effective SPD processes to produce UFG metals. Also, upper bound theory is one of the reliable theoretical tools to forecast deformation strain and forming load. In this research, analysis of ECAP technique in arbitrary channel and corner angles using upper-bound theory was performed and a general and user-friendly equation for predicting the forming force is proposed according to geometry of process and elastic-plastic properties of work-piece material. By comparing amount of obtained theoretical load with experimental forming force resulted from applying process on 7075 Al alloy, has been observed very good agreement between the results. This guarantees reliability of achieved general equation for ECAP force. According to the results of present research, experimental and theoretical forming load of ECAP process on this material under conditions of channel angle 135°, corner angle 20°, billet diameter 10 mm and billet length 90 mm were obtained equal to 48 kN and 55.04 kN, respectively. Furthermore, by increasing channel angle from 60 to 150 under constant corner angle of 20°, process load is decreased equal to 41.3% from 86.4 kN to 50.7 kN. In addition, by increasing corner angle from 0° to 40° under constant channel angle of 135°, the negligible reduction of load equal to 2.5% was observed from 56 kN to 54.6 kN.

KEYWORDS

ECAP, Upper-bound theorem, Elastic-plastic properties, Forming load

1. Introduction

ECAP process is one of the most important and effective process of severe plastic deformation (SPD) processes for producing of ultrafine or nano grained structures and consequently enhancement of static and dynamic mechanical properties of pure and alloy metals. In this process, high strains are introduced to the work-piece due to existence of shear stress in deformation region [1]. In a forming process to optimization of die design, determination of required load and applied strain prior to performing of process is very essential. Nowadays, the analytical and numerical methods are generally used to predict these parameters in a forming process. Upper-bound theorem as an analytical method is one of the most conventional, accessible and reliable techniques for forecasting of load and strain [2, 3].

Literatures review shows that most researches have focused on utilize of upper bound method in ECAP process with square and circular cross-section channel and under angle of 90 degree [4, 5]. It is clear that the use of the upper bound method in investigating of deformation and forming load of ECAP with a circular cross-section with an arbitrary or general channel angle has been neglected. In this regard, the using of this method in analysis of ECAP process with a circular cross-section and at arbitrary geometric angles is innovative. Hence, there is a need to achieve the comprehensive and user-friendly equation for forecasting of forming load and this equation was obtained in this research. Furthermore, the experimental test has been performed for validation of this obtained theoretical relationship.

2. Methodology

2.1. Analysis of deformation

The understanding of geometry of deformation zone and the velocity discontinuity surfaces of material are the most important matters in analyzing the deformation in forming processes. In this research, based on these items, development and extend of relationships obtained by Paydar et al [5] were used for analysis of deformation in ECAP process with arbitrary channel angle. Hence, the required force (*F*) and pressure (*P*) were obtained according to the Eq (1) and Eq (2):

$$F = \pi a^2 \bar{k} \begin{bmatrix} \psi + 2\cot\left(\frac{\varphi+\psi}{2}\right) + \frac{4m}{\pi}\psi \csc\left(\frac{\varphi+\psi}{2}\right) + \\ 4m \cot\left(\frac{\varphi+\psi}{2}\right) + \frac{2ml}{a} \end{bmatrix} \tag{1}$$

$$P = \bar{k} \begin{bmatrix} \psi + 2\cot\left(\frac{\varphi+\psi}{2}\right) + \frac{4m}{\pi}\psi \csc\left(\frac{\varphi+\psi}{2}\right) + \\ 4m \cot\left(\frac{\varphi+\psi}{2}\right) + \frac{2ml}{a} \end{bmatrix} \tag{2}$$

2.2. Materials and experimental procedures

Al-7075 alloy was chosen as material to apply ECAP. This material was machined as a rod with a length of 90 mm and an approximate diameter of 10 mm and then for annealing was inserted into an furnace at temperature of 415 °C for one hour and then cooled in closed furnace [6]. In addition, the elastic-plastic properties of the annealed metal before and after ECAP, were obtained according to the ASTM E 8M-00.

To compare the forming load in ECAP in two methods of experimental and bound theorem, one pass of ECAP was performed on the Al-7075 billet under diameter of 10 mm, die angle of 135°, corner angle of 20° and ram speed of 9 mm/s. Fig. 1 demonstrates real views of ECAP die and setup and Also, the billet after applying one pass of ECAP under mentioned condition.

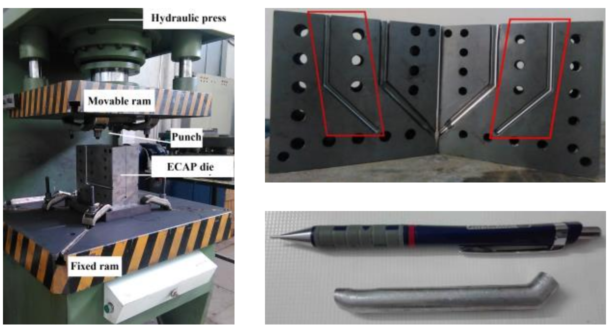

Fig. 1: The real view of (a) set-up of process and (b) ECAP die and used channel with angle of 135 degree, corner angle of 20 degree and diameter of 10 mm (shown in the red box)

3. Results and discussion

3.1. Mechanical properties

The true stress-strain diagram of annealed Al-7075 obtained from the uniaxial tensile test shows that the power equation $\sigma=592.99\ \varepsilon^{0.2133}$ has been fitted on the strain-hardening region of diagram. Amounts of strains in yield and ultimate points are 0.004108 and 0.082505, respectively. Using these values and the power relationship reported in strain-hardening region, the mean shear yield stress ($\bar{k}$) according to the Eq (3) and Eq (4) and Table 1 was obtained equal to 169.8 MPa.

Therefore, by relationship obtained from the upper bound theorem, Eq (1), and using the geometric properties of die and the mechanical properties of the billet material, the forming force can be calculated analytically and this value should be compared with results of experimental test for validation.

By fitting the Holloman power equation ($\sigma = c\varepsilon^n$) to the strain-hardening region, with coefficient (*c*) and power (*n*), the mean yield stress ($\bar{\sigma}_Y$) is obtained using Eq (3), where, ε_Y and ε_U are yield and ultimate strains, respectively. Therefore, using von-Misses criteria, the mean shear yield stress ($\bar{k}$) is determined by Eq (4) [4]:

$$\bar{\sigma}_Y = \frac{1}{\varepsilon_U - \varepsilon_Y}\int_{\varepsilon_Y}^{\varepsilon_U} c\,\varepsilon^n d\varepsilon = \frac{1}{\varepsilon_U - \varepsilon_Y}\frac{c}{n+1}\left(\varepsilon_U^{n+1} - \varepsilon_Y^{n+1}\right) \tag{3}$$

$$\bar{k} = \frac{\bar{\sigma}_Y}{\sqrt{3}} \tag{4}$$

Table 1: Strain-hardening properties of annealed Al-7075

Annealed metal	Strain hardening $\sigma = c\,\varepsilon^n$		Mean shear stress (MPa)
	c (MPa)	n	$\bar{k}$
Al-7075	592.99	0.2133	169.836
True strain		True stress (MPa)	
Yield	Ultimate	Yield	Ultimate
ε_Y	ε_U	σ_Y	σ_U
0.004108	0.082505	191.737	317.667

3.2. Forming load analysis

The experimental tests show that the required forming load for one pass ECAP of under mentioned conditions, was 48 kN. All input and output parameters and how to obtain them, were presented in Table 2. According to the amounts of geometrical characterization of setup (Table 3) and mechanical properties of material (Table 1) and also equations (1), (3) and (4), the required force will be obtained equal to 55.04 kN using upper-bound theorem.

Table 2: Input and output parameters and how to obtain them in determination of forming force

Input parameters								
φ	ψ	a	L	m	c	n	ε_Y	ε_U
Die and work-piece geometry				*	Uniaxial tensile test			

Output parameters			
l	$\bar{k}$	$\bar{\sigma}_Y$	F
$l = L - 2a$	Eq (4)	Eq (3)	Eq (1)

*1- Ring compression test, 2- Finite element simulation of ring compression test and using the calibration curve [7, 8]

Table 3: Forming force in ECAP technique in experimental and upper-bound methods

ECAP	Channel angle	Corner angle	Channel diameter
	φ (°)	ψ (°)	$2a$ (mm)
	135	20	10
Billet length	Friction factor	Maximum laod	
$L\left(mm\right)$	m	$F\left(kN\right)$	
		Analytical	Experimental
90	~ 0.1	55.04	48

As can be observed from comparing the amount of forming force obtained from analytical (55.04 kN) and experimental (48 kN) methods, there is a very good agreement between the results from the upper bound method and the real value, which means high reliability to Eq (1) to predict the forming force in ECAP process. The greater amount of analytical force than the experimental one can also be attributed to the upstream prediction in the upper limit analytical method. The amount of analytical force is more than experimental result, which can be attributed to properties of upper-bound analysis in predicting with a higher value.

4. Conclusions

The qualitative and quantitative results of the present study include the following:

- In this study, using the elastic-plastic properties of the work-piece material and the upper bound theory, a general, comprehensive and user-friendly relationship was obtained to predict the amount of required force to apply the ECAP process with circular cross-section channel and also arbitrary die and corner angles.
- Comparison of a ECAP forces obtained from upper-bound analytical method (55.04 kN) with experimental result (48 kN) on the annealed Al-7075 alloy in channel angle of 135°, corner angle of 20°, billet length of 90 mm, and diameter of 10 mm, have demonstrated that it can be trusted to the relationship obtained in this study based on the upper-bound theorem analysis.

5. References

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