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FINITE ELEMENT ANALYSIS OF EQUAL CHANNEL ANGULAR PRESSING IN DIFFERENT FRICTION CONDITIONS

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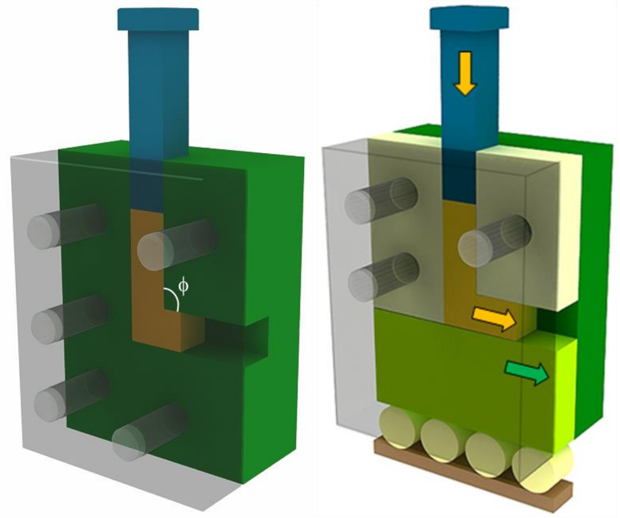
Abstract: The effects of equal channel angular pressing (ECAP) - as the most promising and effective way to produce bulk ultrafine grained metallic materials - on accumulated strain and therefore on structure refinement depend on die geometry, process conditions and material features. In this paper, a finite element analysis (FEA) of ECAP under different friction conditions was carried out. A comparison of simulated strain, stress and damage distribution corresponding to partial frictionless ECAP with dies having movable walls was conducted. Results show a decreasing in load as it was expected but similar effective strain and stress distribution within the workpiece with no favourable impact on damage factor.

Key words: Severe plastic deformation, Finite element, Strain, Stress.

1. INTRODUCTION

Bulk metallic materials having ultrafine grained structure have been intensively investigated in recent years due to their spectacular mechanical and/or physical properties such as strength and high ductility as shown Zha et al. (2013), superplasticity at high strain rate as reported Kawasaki and Langdon (2007), better corrosion resistance and biocompatibility, becoming suitable for microforming and engineering machinery. Known as the most effective structure refining method among other severe plastic deformation techniques, equal channel angular pressing (ECAP) has been extensively explored over the years due to the promising improvements in structure and therefore properties of bulk ultrafine grained/nanostructured materials.

Based on repetitive extrusion through a die containing two equal cross-sectional channels making between them an angle ϕ typically in the range of 90 - 120º (Fig.1a), ECAP can be resumed until the purposed accumulated strain is reached. Billets having symmetrical cross-sections (i.e. square or circle) are inserted in the inlet (vertical) channel, being pushed by a punch. In the inlet channel the billet moves without any plastic deformation as a rigid body. When the workpiece crosses the area around the bisector plane of the channels that defines the plastic deformation zone (PDZ), the material undergoes simple shear. The billet removal from the outlet channel (horizontal or inclined, depending of the angle ϕ) supposes a new ECAP pass in which the new sample is inserted in the vertical channel pushing out the previous deformed sample that can be thus reinserted for process resuming.



(a) (b)

Fig. 1. Schematic principle of ECAP (a) classic die (b) movable wall die

Four different processing routes (A, B_A, B_C, and C) can be approached for uniform grain refinement, depending on the twists of the reinserted billet around its longitudinal axis. Billet rotations after each pass can be 0° (in route A), alternating ±90° (in route B_A), same sense 90° (in route B_C), and 180° (in route C). Because ECAP retains unchanged the cross-section of the workpiece, the process can be resumed as often as need to get the imposed strain level. Moreover, because the cross-sectional dimensions and shapes of the two channel are the same, deformation takes place under relatively lower pressure in comparison with classical direct extrusion.

Many investigations have been devoted to study the influence of die geometry and process parameters on material flow, deformation behavior, strain inhomogeneity, and material properties (Patil Basavaraj et al. 2009). A successful ECAP supposes overcoming of at least two important obstacles: the necessary load level (that becomes essential in the case of large billets) and a favourable stress distribution, together with an appropriate formability of the material that allowing high accumulated strain without damaging the workpiece.

No matter tool design, friction stands up as a real technological factor that limits the length of the billet because of inevitable buckling of the punch. Moreover, expecially in aluminum processing, a thin layer sticking to the inner surfaces of the die channels has been reported. Over the years, some technical solutions have been developed to reduce friction: among them, the concept of converging billets (Rosochowski et al., 2013) or movable die walls (Fig.1b) have distinguished. In the first case, two horizontal punches push two opposite billets which go forward simultaneously in the vertical channel so that the contact surface between them plays the role of a movable wall. In the second case, friction is obviously reduced by moving parts of the inlet/outlet channels. But it seems the reduction in friction alone does promote neither the necessary strain homogeneity nor the lower damaging of the workpiece. Not in all cases an opposite force (some how similar to friction) becomes obstructive in plastic deformation processing. A good example is the back pressure (BP): Yoon et al. (2013) have used BP to get a uniform strain distribution and prevent cracks on the upper surface of the billet due to a more favourable stress distribution. It is shown that for homogeneous strain in BP conditions the friction has to decrease as much as possible (Yoon et al. 2013).

So, stand-alone friction may have opposite influences: Djavanroodi and Ebrahimi (2010) have showed that on the one hand it decreases the load but rises the strain inhomogeneity, and on the other hand it oppositely acts for damage reduction. Finally, one question remains standing: are the benefits of the reduction in friction on deformation load more important than those derived to failure avoiding? The present study aims to give a sustainable analyzing tool prior to the die manufacturing emphasizing the feasibility of the movable die design. A finite element analysis (FEA) of ECAP under different friction conditions was carried out. A comparison of simulated strain, stress and damage distribution corresponding to partial frictionless ECAP of AA5052 with dies having movable walls was conducted. Results show a decreasing in load as it was expected but similar effective strain and stress distribution within the workpiece with no favourable impact on damage factor.

2. FINITE ELEMENT SIMULATION

2.1 Load and effective strain

Eivani and Kamiri Taheri (2008) established the load and effective strain formulae taking into account the friction coefficient (μ) and die geometry:

$$\bar{\varepsilon} = \frac{1}{\sqrt{3}}\left[2\sqrt{\frac{1-\mu}{1+\mu}} + \left(2\mathrm{ctg}^{-1}\sqrt{\frac{1-\mu}{1+\mu}} - \phi\right)\sqrt{\frac{1+\mu}{2}}\right] \quad (1)$$

$$F = 2a^2\tau_o\left\{(1+\mu)\mathrm{ctg}\left(\frac{\phi+\psi}{2}\right) + \psi\right\} + 4\mu a l \tau_o \quad (2)$$

where τ_o is the yield stress in shear, ψ is the outer arc transition angle (corresponding to a possible outer radius transition), and *l* is the length of the workpiece remaining inside the inlet channel.

2.2 Friction model

Obviously, friction has an essential influence on deformation behaviour during ECAP and therefore on strain (in) homogeneity. Many efforts have been devoted to investigate friction during ECAP. Yang and Lee (2003) have concluded that the strain is independent of friction for a strain hardening material. They have stated that the friction has no influence on strain distribution. Dumoulin et al. (2005) have reported that the strain homogeneity increases with friction. Further, the results reported were also found to vary depending up on the friction model used to evaluate the friction effects. Because of earlier quiet contradictory results on effect of friction in ECAP processes, it becomes essential to establish which friction model are the most suitable for ECAP finite element simulations. Joun et al. (2009) have investigated the effect of Coulomb and shear friction models. In Coulomb model, the tangential (friction) stress is assumed to be dependent on coefficient of friction (μ) and normal stress to the surface ($\tau = \mu \cdot \sigma$) while shear friction model states that the tangential (friction) stress is dependent on the interface friction factor (m) and a fraction of the equivalent stress or yield stress of the material ($\tau = m \cdot \sigma_y/\sqrt{3}$). They concluded that the conventional practice is to use shear friction model for forging or extrusion and Coulomb friction model for sheet metal forming. Considering that ECAP is no doubt a friction sensitive process, Balasundar and Raghu (2010) have stated that the shear friction model is the most appropriate for ECAP simulations.

2.3 Damage factor

Damage generally relates to the likelihood of fracture in a part. The Cockcroft-Latham damage model has shown to be a good indicator of certain types of tensile ductile fracture. According to this model, a damage factor (D_f) (which is a constant corresponding to a critical condition associated with fracture) is defined by the following relationship:

$$D_f = \int_0^{\bar{\varepsilon}_f} \sigma_T d\bar{\varepsilon} \qquad (3)$$

where σ_T is the maximum principal tensile stress within the billet, $d\bar{\varepsilon}$ is the effective strain increment and the integral is evaluated from zero strain to the final effective strain, $\bar{\varepsilon}_f$.

The criterion was later normalized by incorporating the effective stress $\bar{\sigma}$ (Figuieredo et al. 2009), to give normalized damage factor D_{fN}:

$$D_{fN} = \int_0^{\bar{\varepsilon}_f} \frac{\sigma_T}{\bar{\sigma}} d\bar{\varepsilon} \qquad (4)$$

This form of the Cockcroft–Latham relationship where the maximum principal tensile stress is normalized by the equivalent stress is generally considered to provide a reasonable prediction of the fracture of metals during ECAP processing and therefore it is used in the present study.

2.4 FEA conditions

The simulations were conducted using commercial DEFORM 3D^{TM} software. The constitutive stress-strain relation of the studied material (aluminium alloy AA 5052 - 2.8%Mg; 0.2%Cr in wt.%) was experimentally found by standard tensile tests carried out according to ISO 6892-1: 2009, by using a universal testing machine Instron 3382. It was found (Fig. 2) that flow stress vs. strain follows the relation: $\sigma(\text{MPa}) = 402.29 \cdot \varepsilon^{0.30}$ and that was indicated in DEFORM 3D^{TM} software as constitutive equation of the studied material.

All developed simulations were performed at room temperature and a punch speed of 10 mm/s, using specimens with dimensions of 10 × 10 × 60 mm. Simulations were conducted taking into account a friction coefficient of 0.12 both for traditional and movable walls die. The mentioned value was experimentally obtained in a previous experiment (Chiriţă et al., 2007), being confirmed in other studies (Figueiredo et al., 2007). As a common practice for experiments which take place at room temperature, the hardening behavior of the material was accepted independent of strain rate. In simulating ECAP, the mesh that is in contact with the inner walls of the die channels does not distort as the center mesh of the sample. The material can not normally flow when coming in contact with the sharp outer corner, leading in damage of the mesh during extrusion. Because of this, in simulating metal forming, the volume loss is inevitable. There are several reasons of volume loss:

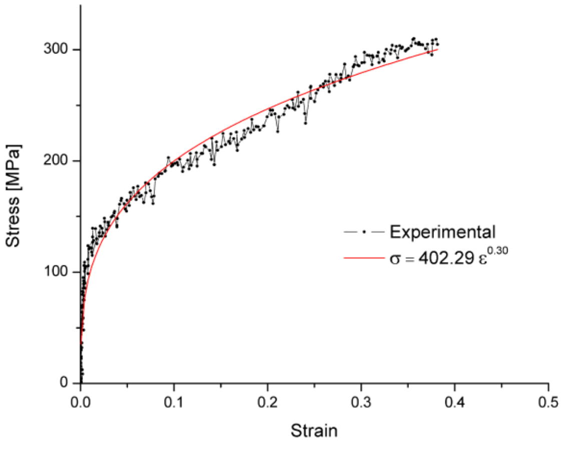


Fig. 2. Experimental stress-strain relationship for the studied material

i) if a high time step is involved and sub-stepping is unchecked, when contact occurs some nodes will penetrate slave objects, then will be repositioned at the end of the step. This repositioning can determine some small volume loss. Over the entire simulation, this can become important.

ii) as elements of slave objects/surfaces stretch around corners of master objects/surfaces, the elements will simply cut the corner of the intersected object. The corresponding volume that crosses the corner will be permanently lost on remeshing.

To enforce volume constancy of plastic objects, a volume penalty constant has to be defined. If the value is too low, unacceptably high volume loss may appear. If the value is too high, the solution can not meet the convergence.

Meshing and re-meshing is the basic reason of volume loss in simulating metal forming, which becomes invariably present. Element volume loss appears in every time-increment step although introducing the incompressibility to penalty function. If one reduces the time increment, the volume loss will decrease, but the computing time will increase accordingly. Density of mesh has similar effect as the time increment gradient.

Considering all above mentioned, the billet was discretized in 8000 elements (tetrahedral) so that give a sufficiently fine mesh to emphasize localized effects (Figueiredo et al., 2007). The volume penalty constant was set as 10^6. This value gives minimum loss of volume during remeshing due to the partial penetration of the walls of the die by finite elements, if time increment step of 0.05 s is involved. Poisson's ratio 0.33 and Young's modulus 69 GPa were designated.

3. RESULTS AND DISCUSSIONS

Figs. 3-5 show effective strain and stress distribution, and damage factor for traditional ECAP, and horizonal and vertical movable wall die ECAP, respectively (H- and V-ECAP accordingly).

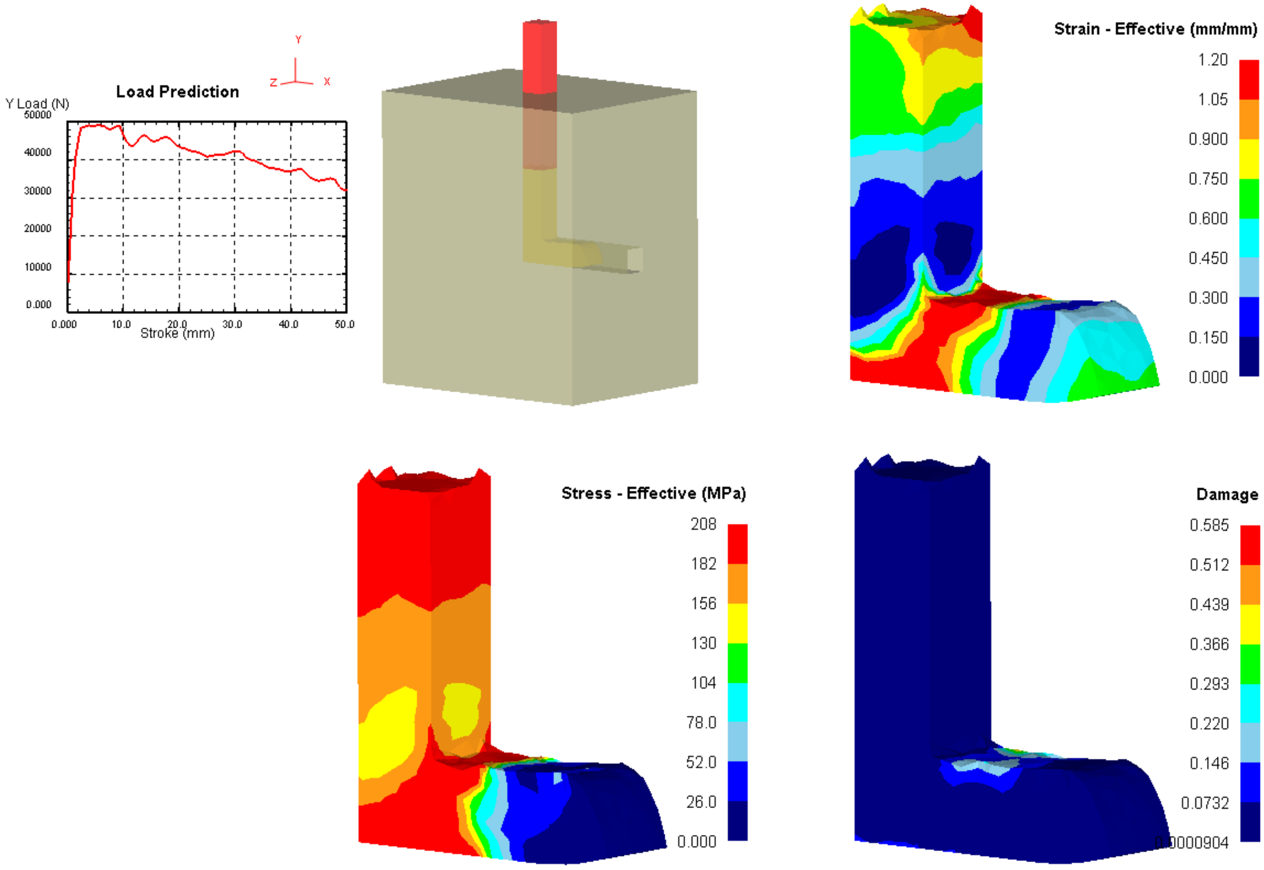


Fig. 3. Load prediction, effective strain and stress distribution, and damage factor for traditional ECAP

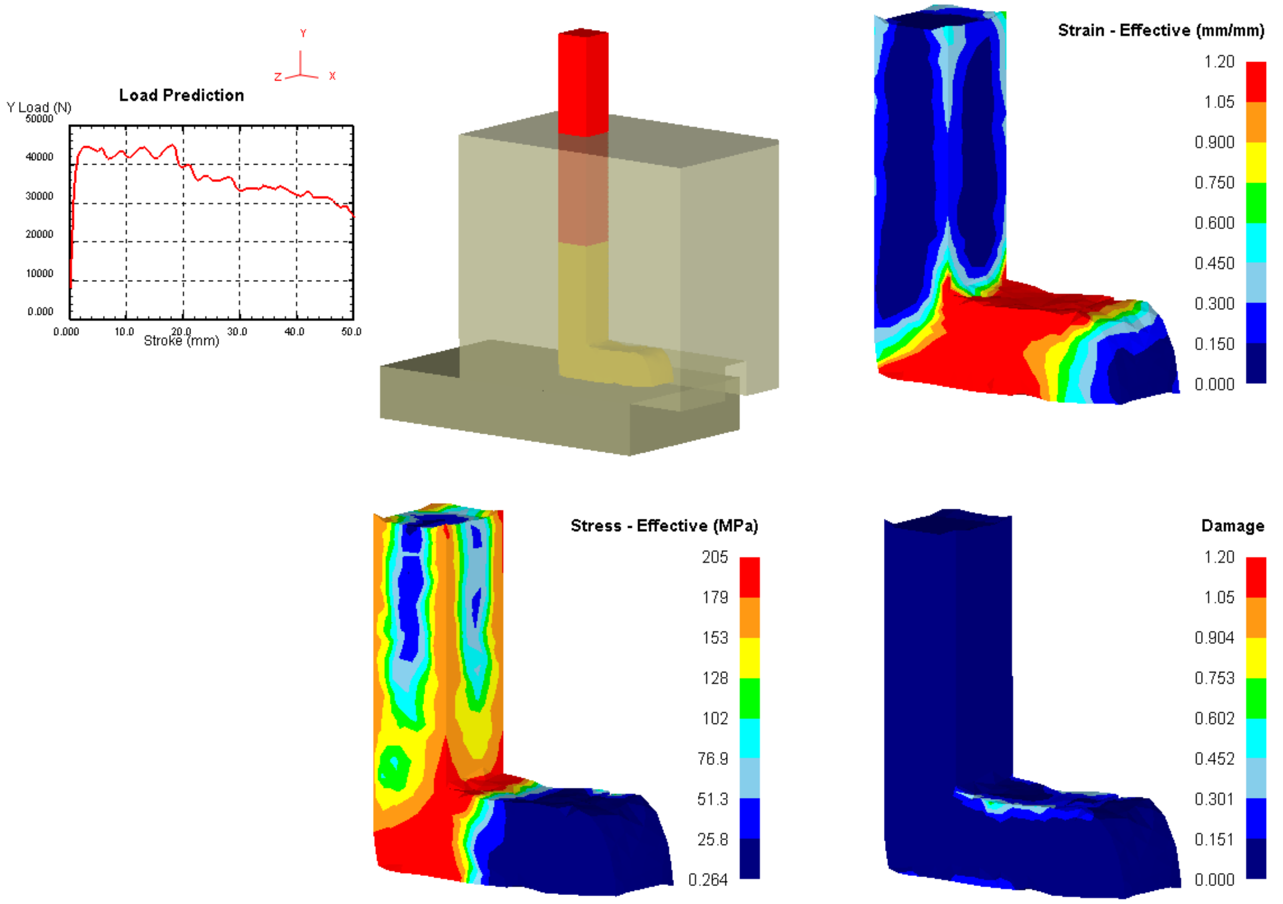


Fig. 4. Load prediction, effective strain and stress distribution, and damage factor for horizontal movable wall die ECAP

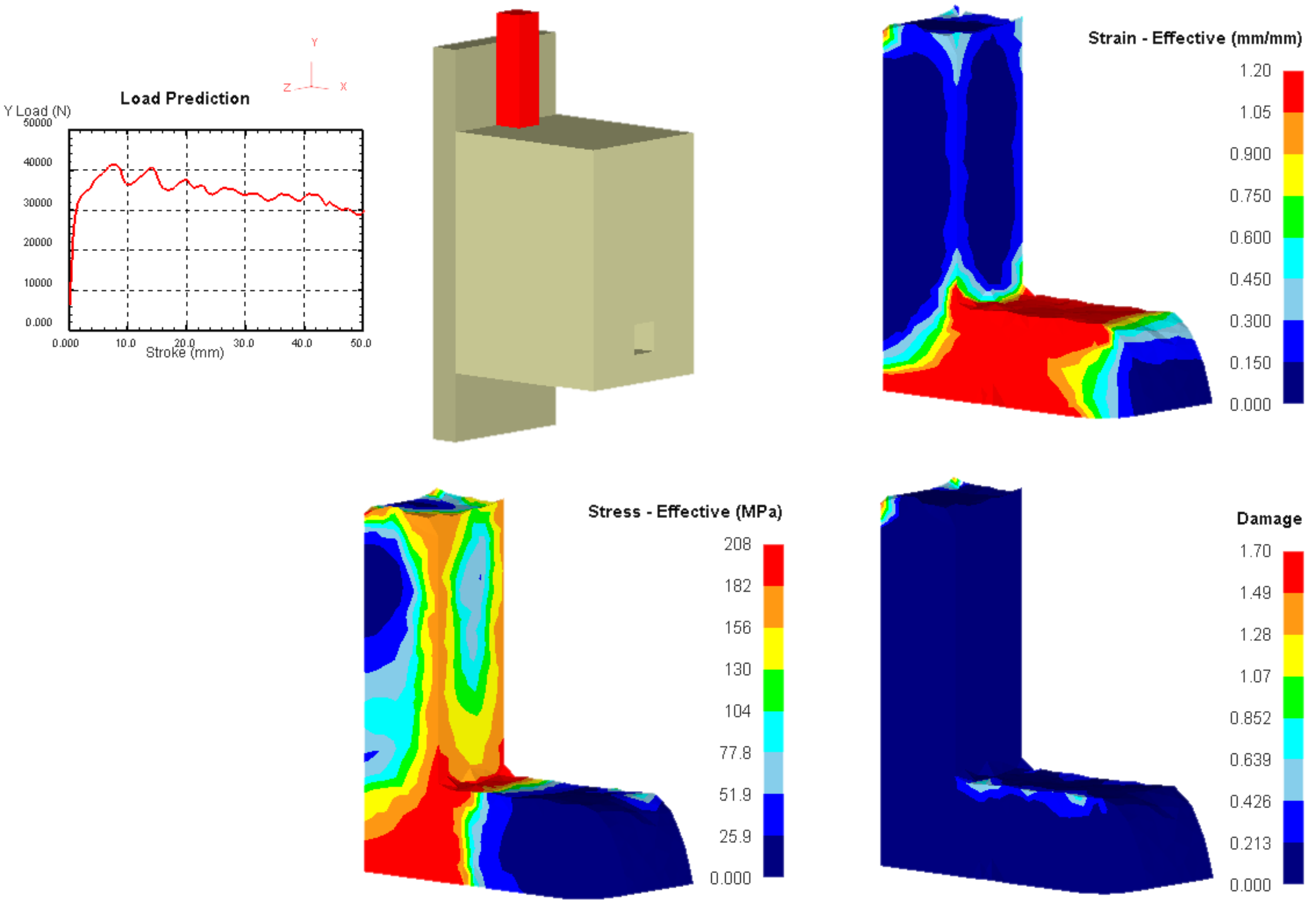


Fig. 5. Load prediction, effective strain and stress distribution, and damage factor for vertical movable wall die ECAP

As one can see, the results of FEA show that for ECAP performed with movable wall dies the strain and stress distributions are almost identical both in the vertical and horizontal channel after the material leaves the PDZ. To explain all these, cases that should be considered are minimum ($\tau \rightarrow 0$), maximum ($\tau \rightarrow k$), and intermediate friction ($\tau < k$). ECAP is schematically explained by Fig. 6.

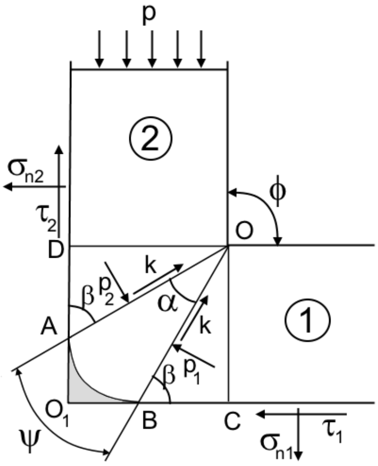


Fig. 6. ECAP with same friction in both channels

The ideal PDZ is a symmetric fan OAB on both sides of bisector plane of the two channels. The corresponding angle α between OA and OB is:

$$\alpha = 2\beta - \frac{\phi}{2};\ \beta = \frac{\pi - \mathrm{Arccos}(\tau / k)}{2} \qquad (5)$$

Eivani and Kamiri Taheri (2008) show that for $\phi = 90^\circ$, a material “dead” zone - in which there is no strain - (MDZ) AO_1B during ECAP is inevitable no matter the friction. Moreover, the edge of MDZ could be taken in as a round outer corner corresponding to an arc transition angle of ψ.

i) Constant friction in both channels

The relationship between hydrostatic pressure p_1 and p_2 corresponding to boundaries OA and OB is:

$$p_2 = p_1 + 2k\alpha \qquad (6)$$

and normal stresses along BC and AD are:

$$\begin{aligned} \sigma_{n1} &= p_1 + k\sin 2\beta\ (BC) \\ \sigma_{n2} &= p_2 - k\sin 2\beta\ (AD) \end{aligned} \qquad (7)$$

whereas σ_{n1} is always positive, σ_{n2} changes from positive to negative value depending on angle β and tangential friction stress τ.

ii) *Different friction in both channels*

In evaluating this case, one must take into account a limit case, for instance $\tau_2 = 0$ and $\tau_1 = k$ (Fig. 7). PDZ is no longer a symmetrical fan, and non-uniform strain could be achieved at the bottom of horizontal channel under the stream line *a* - *a*.

iii) *Movable walls*

This case is similar with the previous one. But because of no contact friction, MDZ can not exist, this being the difference. A stream line separating uniform and non-uniform strain is also similar. According to Segal (2003) the non-uniform strain area across the billet section is about 22%.

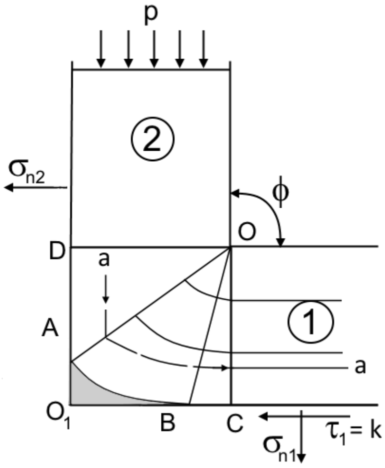


Fig. 7. ECAP with different friction in channels

4. CONCLUSIONS

In ECAP, friction and die geometry play the most important roles. PDZ can be a single line (the bisector of the two channels) or a fan - symmetrical or not, depending of friction. PDZ includes a uniform deformation area, a dead zone, and a non-uniform strain area. The high effective stress at the bottom of the channels is due to compression, but for ECAP with movable wall dies, distributions are the same.

The damage factor is higher in using movable wall dies because of increasing in tensile stress σ_t; using H-ECAP is more suitable, but building a die having a movable horizontal component is more complicated.

In movable walls die ECAP the load decreases with 10 - 18% as friction decreases accordingly that allows increasing the length of the sample and punch respectively, and that seems to be the most important reached advantage. For difficult-to-work materials classic ECAP remains more reliable.

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