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Materials Science and Engineering A

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Effect of die channel angle, friction and back pressure in the equal channel angular pressing using 3D finite element simulation

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ARTICLE INFO

Article history:
Received 20 August 2009
Received in revised form
25 September 2009
Accepted 25 September 2009

Keywords:
ECAP
FEM
Deformation behavior
Die angle
Friction
Back pressure

ABSTRACT

In this study, deformation behavior of commercial pure aluminum in the equal channel angular pressing (ECAP) is analyzed successfully using three dimensional (3D) simulation by finite element methods (FEM). The investigations include the effects of various die channel angles, low-friction and high-friction conditions and the application of the back punch pressure. It is observed that the level of the strain and homogeneity of strain distribution increase with decreasing the die channel angle or increasing the friction coefficient or imposing the back punch pressure in the outlet channel. Also, increasing the magnitude of the strain causes high punch pressure and higher press pressure for processing should be applied.

1. Introduction

Equal channel angular pressing (ECAP) is one of the most attractive processes for achieving ultra-fine grain (UFG) structures by severe plastic deformation (SPD). It is well demonstrated that the UFG structures fabricated by ECAP greatly enhance mechanical properties at room temperature and superplasticity at elevated temperatures. The process is to press a well-lubricated sample through two crossing channels and simple shear is applied to the sample at the intersection of the channels [1]. Therefore, a very high shear strain can be accumulated in the material. Several analytical studies report the magnitude of shear strain imposing to the sample is determined by the channel angle (Φ) and the angle associated with the arc of curvature (Ψ). This relationship is presented in Eq. (1) [2]:

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

Also, the equivalent strain (ε_{eq}) after number of passes (N) can be expressed in a general form by Eq. (2):

$$\varepsilon_{eq} = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\phi+\psi}{2}\right) + \psi\,\mathrm{cosec}\left(\frac{\phi+\psi}{2}\right)\right] \quad (2)$$

Eq. (2) represents the average equivalent strain developed in the sample within frictionless condition but friction between the surface of the sample and the die wall is unavoidable in the practical ECAP process. These strains imposed to the sample with a hydraulic press. The pressing pressure requirement of sample (P) using upper-bound analysis is represented in Eq. (3) [3]:

$$P = \tau_0(1+m)\left[2\cot\left(\frac{\phi+\psi}{2}\right) + \psi\right] + 4m\tau_0\left(\frac{l_i + l_o}{a}\right) \quad (3)$$

where τ_0, m, l_i, l_o and a are the shear strength, the friction coefficient, instant length of the sample in the entry channel, instant length of the sample in the exit channel and the width of the extrusion channel, respectively. Many FEM-based analyses have been performed to determine the deformation behavior of materials and to estimate the developed strain in the ECAP process [4]. Oruganti et al. investigated the influence of friction and strain rate sensitive on the effective strain for the channel angles larger than 90° [5]. They have indicated that moderate magnitude of friction coefficient provides better die corner filling and uniform strain distribution at room temperature. Also, to achieve high and homogeneous shear strain, high back pressure with reduced friction amount was needed. Zhang et al. [6] analyzed the plastic deformation zone in multi-pass ECAP at high temperature (450 °C), and pointed out that, because of reverse direction, route *C*, has develop an stable deformation zone. Figueiredo et al. explored the plastic instability and shear localization in the ECAP process to obtain distinct understanding about ECAP processing of flow-softening materials [7].

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doi:10.1016/j.msea.2009.09.052

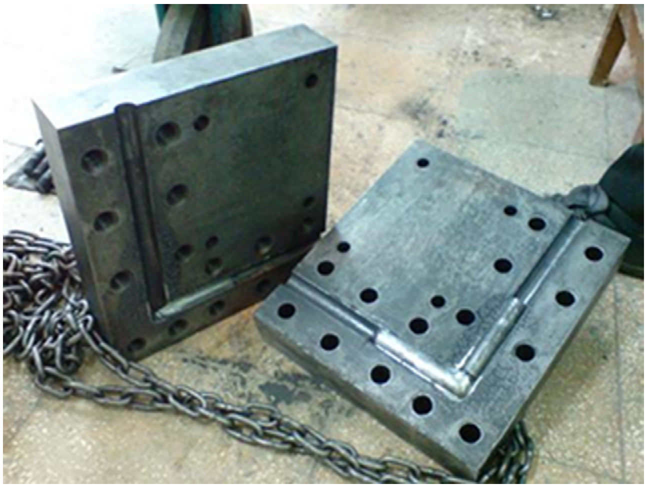

Fig. 1. ECAP die with $\Phi = 90^\circ$ and $\Psi \approx 25^\circ$.

They have concluded that, high initial flow-softening rate and lower final stress level will cause increase in the strain heterogeneities. Nagasekhar et al. considered the effect of strain hardening and friction in the pure copper by 3D FEM and experimental validation was carried out [8]. Also there are several studies about simulation of back pressure, different channel angles and friction coefficients on the homogeneity strain, magnitude of strain and punch pressure [9–11]. Suo et al. [9] reported the strain behavior of materials with various friction coefficients (0–0.15) and compared the 3D simulation results with experimental outcomes. Luis-Pérez's et al. [11], has shown that die channel angle and friction condition are critical factors in the effective strain. Nagasekhar et al. Investigated the effect of acute die channel angles ($\Phi \leq 90^\circ$) on the deformation behavior of material with 2D FEM in low-friction condition and revealed that the deformation occurred in three steps for die channel angles of 60° and 75°, in comparison to only two steps for $\phi = 90^\circ$ and decrease in the die channel angle resulted in an increase in the punch pressure [12]. Son et al. used a 2D FEM simulation for equal channel angular pressing with back pressure. Three types of die tooling which can produce the back pressure to the sample in low frictionless condition were studied. It was reported that route *C* is better than route A for achieving more uniform strain distribution [13]. Karpuz et al. [14] investigated the effect of material properties (strength coefficient and strain hardening exponent) on the corner gap angle and expressed any increase in the magnitude of these material parameters will cause increase in value of this angle.

For this study, an ECAP die was designed and manufactured with the channel angle of 90° and the outer corner angle of 25°. Commercial pure aluminums were ECAPed one pass and the obtained data were used for validating simulations. To study the different channel angles and the application of back punch pressure, FEM were simulated in the low and high-friction conditions and the effect of above parameters have been investigated in the deformation behavior and magnitude of the punch pressing pressure.

2. Experimental procedure

The material used in this study was commercial pure Al (composition wt.%: 0.212 Fe, 0.100 Si, 0.015 Cu, 0.013 Zr, 0.009 Ti, 0.007 Mg, Al balance) which was homogenized at 670 °C for 0.5 h and cooled slowly. Samples with diameter of 20 mm and 80 mm in length were pressed via ECAP process at room temperature with the ram speed of 1 mm s^{-1} and lubricated by MoS_2 [15]. The ECAP die and the Al sample after one pass pressing are shown in Figs. 1 and 2 respectively.

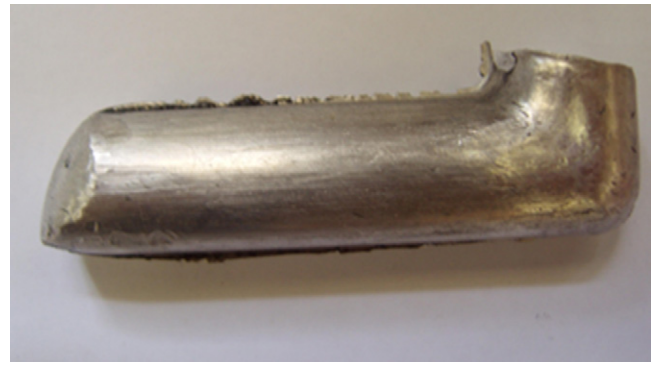

Fig. 2. The deformation shape of sample after 1 pass ECAPed.

3. Finite element methods

Finite element simulations were carried by using Deform-3D™ V5.0 for this study. The sample model has the same geometry with the experimental work. The true stress–true strain relationship were determined by fitting the data to the equation $\bar{\sigma} = C\bar{\varepsilon}^n$, where $\bar{\sigma}$ is the effective von-misses stress, $\bar{\varepsilon}$ is the effective plastic strain, *C* is the strength coefficient (*C* = 52 MPa) and *n* is strain hardening exponent (*n* = 0.14) respectively (tensile tests were performed to determine *C* and *n*, according to ASTM B557M (2006) for pure Al). The number of elements after solid mesh generation was 50,000 and automatic re-meshing was used to accommodate large deformation during all of the analyses. The die, punch and back punch were assumed to be rigid so that there is no deformation. The punch speed was 1 mm s^{-1} and all of the simulations were performed at room temperature. Since the model is symmetrical about the middle plane of the ECAP, half of the sample, die and punch were analyzed and the symmetrical boundary conditions were applied. The ECAP die with a back punch and a simulated deformed sample after 1 pass with the effective strain contour for a die channel angle of 90° are shown in Figs. 3 and 4.

The various channel angles of 60°, 75°, 110° and 120° were simulated in low (*m* = 0.001) and high (*m* = 0.3) friction conditions to investigate deformation behavior and pressing pressure requirement. These results were compared with the theoretical values given by Eqs. (2) and (3) and experimental results. Then various back pressure were imposed to the die with the channel angle of

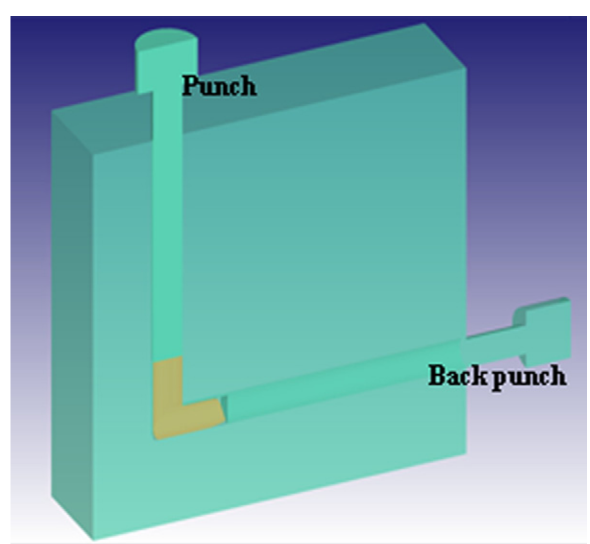

Fig. 3. The ECAP die with the die channel angle of 90° and the outer corner angle of 25°.

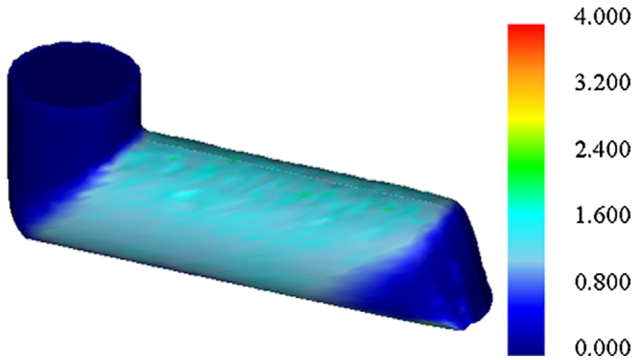

Fig. 4. The ECAPed sample after 1 pass with an effective strain contour.

90° to investigate the homogeneity of strain distribution in the length and width of the sample and its magnitude. A total number of 12 simulations were done and in all studies, the outer corner angle was 25° and the running time was about 9 h for each simulation.

4. Result and discussion

4.1. Effect of die channel angle and friction coefficient on the deformation behavior

Fig. 5 displays the effective strain contours of deformed samples with four die channel angles in two friction conditions. Using these contours the deformation behavior of the samples were studied. As can be observed, under low-friction condition ($m = 0.001$) gaps can be formed between the sample and the outer corner of the die. Increasing friction tends to decrease the gap size, so high-friction condition in all die channel angles assure a complete filling of the outer corner by providing a concentrated shear in a very narrow zone, so that the deformation is larger. On the other hand, low-friction condition leads to a partial filling, creating a dead zone at the outer corner and the deformation results in an arc which is bent rather than sheared. These results are in good agreement with the result of Kumar [16]. Therefore, by comparing same die channel angle with two friction conditions, the influence of friction on the deformation behavior is apparent. First, friction reduces the size of corner gaps, which can be attributed to the increased con-

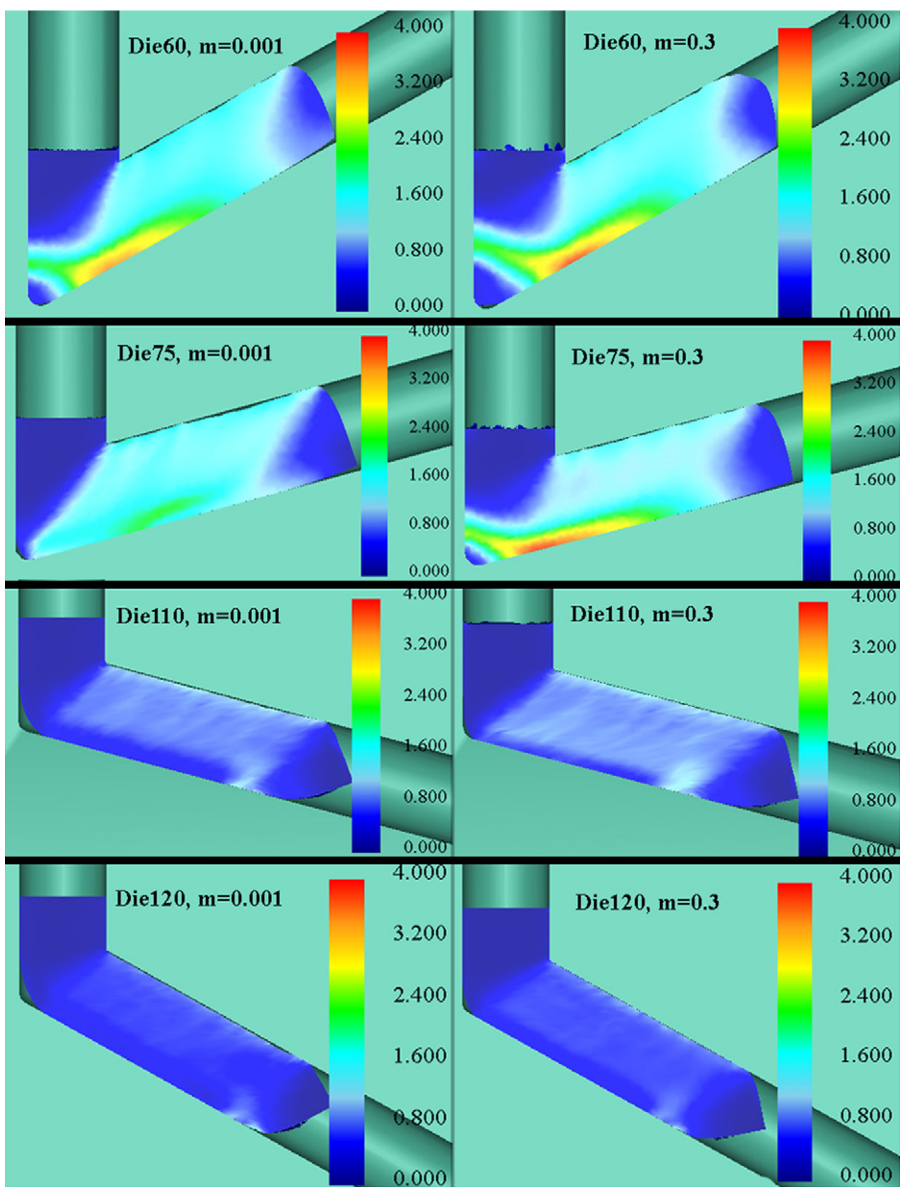

Fig. 5. Effective strain contours of samples simulated with four die channel angles in two friction condition.

straint force at the sample surface. Secondly, friction reduces the upward bending of the sample and causes smaller gap in the outlet channel. On the other hand, increasing the die channel angle in the low-friction condition, results in an increase on the size of corner gap. Therefore increasing the magnitude of friction coefficient, approximately cancels the effect of the die channel angle on the corner gap. So, to eliminate the corner gap and produce uniform strain behavior in the sample, use of either acute die channel angle or high-friction coefficient is suggested. Absence of dead zone in the outer corner part of ECAP die has also been reported for acute die channel angle by Nagasekhar et al. [12] which coincide with achieved results.

In addition, the deformation length is greater with die channel angles of 60° and 75° compared to 110° and 120°. This shows that a longer length of sample underwent deformation. Basically, the deformed sample has been divided to three district regions: head, steady-state and tail. The length of the non-uniformly deformed head and tail regions are similar for the different conditions. Between the unavoidable non-uniformly deformed head and tail regions, there is clearly a steady-state region where the strain distribution is uniform along the deformation axis but deformation in-homogeneity still exists along the transverse direction. For better realization of strain in-homogeneity, Fig. 6 represents the distribution of effective strains through the cross-section of samples for above conditions. Also, the effective strain contours in the cross-section of samples for the die channel angles of 60° and 110° with two fiction coefficient conditions are shown in Fig. 7.

From Fig. 6, it is obvious that the strain distributions were uniform in only 75% of the cross-section, while the remaining 25% of the cross-section experienced non-uniformed strain. For the cases of $\Phi = 60°$ and 75°, because of high-deformed zone in the outer corner of the ECAP die, higher effective strain are produced in the bottom of the sample, therefore moving from the bottom to the top of the sample's cross-section, the effective strains decrease. For $\Phi = 110°$ and 120° material in the outer corner region suffers a combination of bending and shear instead of pure shear, resulting in an increase in the effective strains. Chung et al. [17] reported a similar finding, hardness measurement on the Al5083 sample with the die channel angle of 90° showed lower effective strain in the vicinity of the lower part of the sample than the upper part. On the other hand, as can be seen in Fig. 6, although lower magnitude of effective strain achieves for larger die channel angle, but a better strain homogeneity distribution has been obtained. Similar finding was also reported by Patil Basavaraj et al. [16]. The effective strains obtained accord-

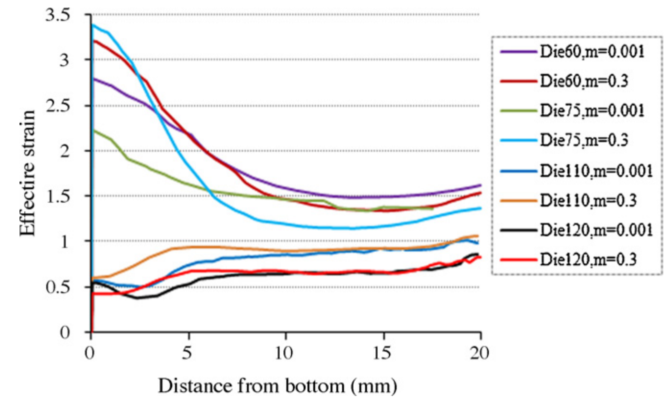

Fig. 6. Distribution of effective strains in the cross-section of samples after ECAP in four die channel angles with two friction condition.

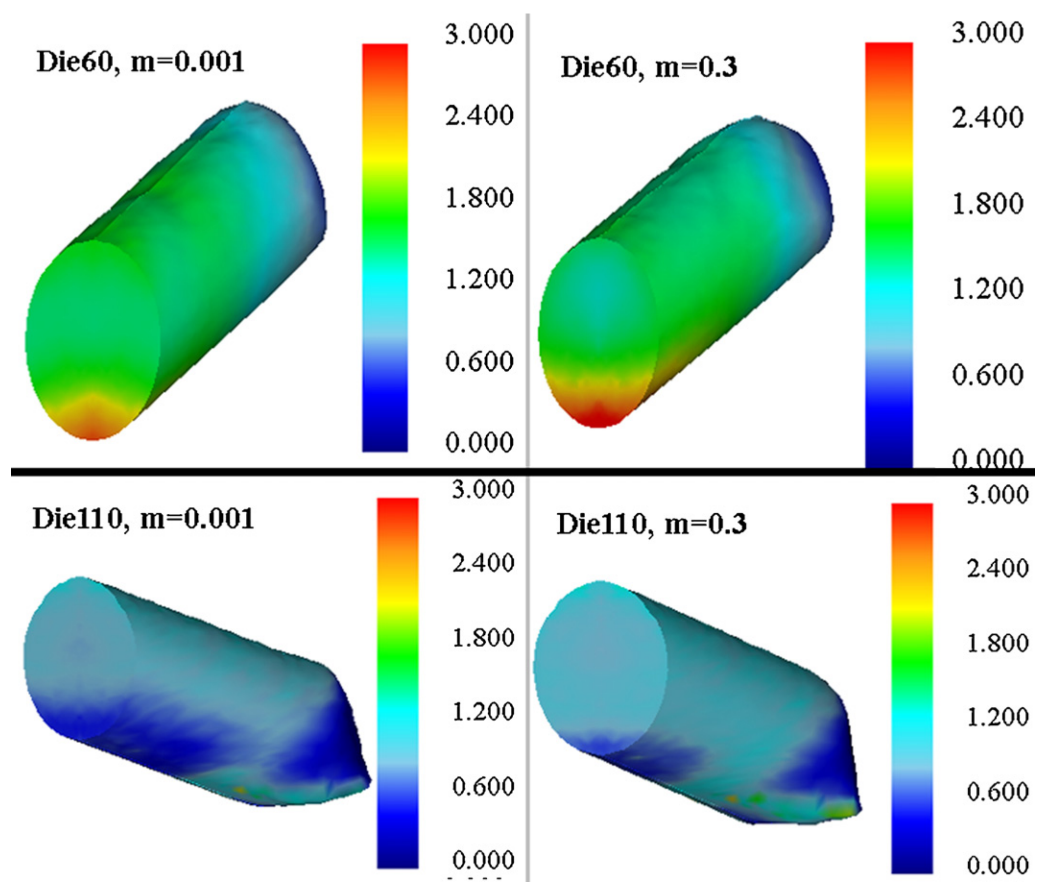

Fig. 7. Effective strain contours in the cross-section of samples for the die channel angles of 60° and 110° with low-friction and high-friction conditions.

Table 1
Comparison of effective strain values obtained by simulation with the theoretical values.

	$\Phi=60^\circ$, Ψ 25°	$\Phi=75^\circ$, Ψ 25°	$\Phi=110^\circ$, Ψ 25°	$\Phi=120^\circ$, Ψ 25°
Theoretical	1.633	1.297	0.751	0.628
FEM ($m=0.001$)	1.531	1.108	0.683	0.555

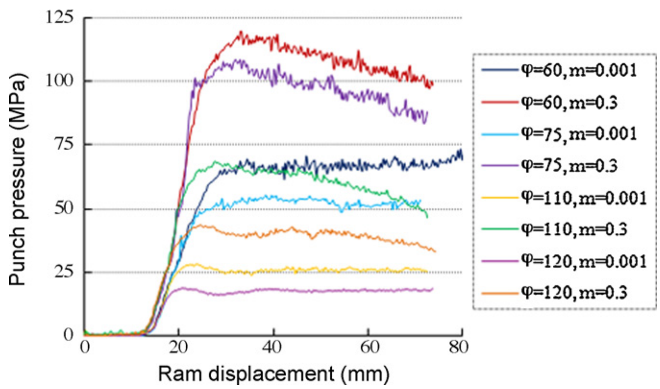

Fig. 8. Predicted of punch pressure versus ram movement for four die channel angles in two friction conditions.

ing to Eq. (2) are also shown in Table 1 for comparison with the simulated results and a good agreement is observed.

Various die channel angles, also impose different strain values. According to Eq. (2), it is obvious that the effective strain decreases when the die channel angle increases. As an example, when the die channel angle increases from 60° to 120° with the friction coefficient of 0.001, the magnitude of effective strain decreases by 63%. Similarly, increasing friction coefficient from 0.001 to 0.3 with the die channel angle of 60°, this magnitude increases by 6%. Therefore, using a die with low-friction coefficient (well-lubricated) and high die channel angle are beneficial for pressing low ductility materials.

4.2. Effect of die channel angle and friction coefficient on the pressing pressure

Punch pressure requirement versus ram displacement is shown in Fig. 8 for four die channel angles in two friction conditions. Referring to these plots, the pressing pressure increases with the ram movement until shear strain imposed to the sample. From this point (maximum punch pressure), the pressing pressure decreases with a very slow rate which continuous to the end of the process.

The magnitude of punch pressure is a major factor to be considered for selecting the suitable hydraulic press in designing the ECAP die. It can be observed that the punch pressure of the sample increases with reducing the die channel angle, For example, the 300% increase in the punch pressure observed when the die channel angle down to 60° from 120° in low-friction condition. The observed high pressure is due to the higher strains generated along the outer corner side of the sample in low die channel angles. So, the existence of the high pressure assures complete filling of the gap and reduces the dead zone. Also, friction coefficient has a noticeable effect on the magnitude of the punch pressure requirement and this pressure increases with increasing the friction coefficient. For example, when friction coefficient decreases from 0.3 to 0.001 in

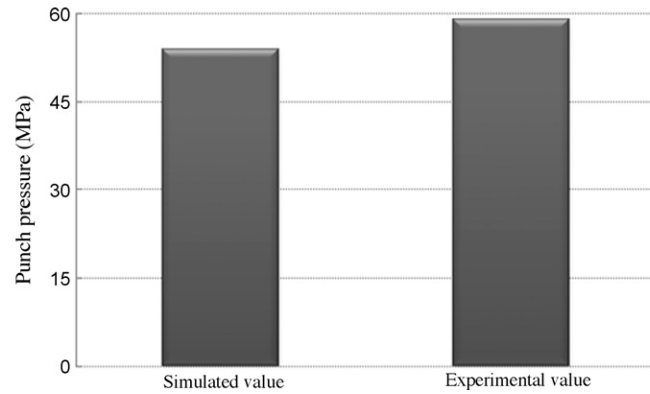

Fig. 9. Comparison of punch pressure values between the simulated and experimental results with a die channel angle of 90° in ECAPed process.

Table 3
Comparison of effective strain and punch pressure for four die conditions in ECAP process.

	Φ°	Ψ°	m	Bp (Mpa)	ε (tot)	P (Mpa)
Die1	90	25	0.12	0	0.882	54
Die2	90	25	0.12	10	0.886	66
Die3	90	25	0.12	14	0.891	73
Die4	90	25	0.12	20	0.896	79

the die channel angle of 110°, the magnitude of the punch pressure reduces by 60%.

Table 2 represents the magnitude of punch pressures for two ECAP die conditions that were calculated with the theoretical values from Eq. (3) and simulated results for verifying the values of FEM simulations. As can be seen, there is a good agreement between them. Also, the punch pressure requirement for a die channel angle of 90° obtained in the experimental work has good conformity with a simulation outcome. The results are shown in Fig. 9. In this case, the friction coefficient assumes 0.12 (MoS_2 is used as a lubricant).

4.3. Effect of back pressure

To investigate the effect of back punch on the strain behavior and punch pressure requirement, four FEM analyses were carried out for an ECAP with a die channel angle of 90° with and without back pressure and friction coefficient of 0.12, as in the experimental work. Details of simulations and their results are shown in Table 3. As can be viewed, use of back punch does not have obvious effect on the magnitude of the effective strain but increase the punch pressure requirement.

To consider the strain uniformity distribution, the effective strains versus cross-section of the deformed sample are shown in Fig. 10. The uniformity of the effective strain increases at the outer corner (lower part of the sample) but it does not have any effects at the top (upper part) of the sample. During ECAP, there is an underfilling of the outer corner of the die due to the formation of the dead zone, especially in the vicinity of the lower part of the deformed sample. Back pressure will prevent dead zone formation by filling in the outer corner region, hence the homogeneity of the strain distribution in the vicinity of the lower surface of the sample increases. Magnitudes of back pressure, has no influence on the magnitude of

Table 2
Theoretical values for punch pressure requirement in two conditions.

Conditions	Φ	Ψ	m	l_i+l_o (mm)	a (mm)	ε (tot)	τ_0 (Mpa)	$P_{theoretical}$ (MPa)	$P_{simulated}$ (MPa)
Die 1	60	25	0.001	62.5	17.5	1.531	27.9	73	69
Die 2	110	25	0.001	62.5	17.5	0.683	24.9	32	29

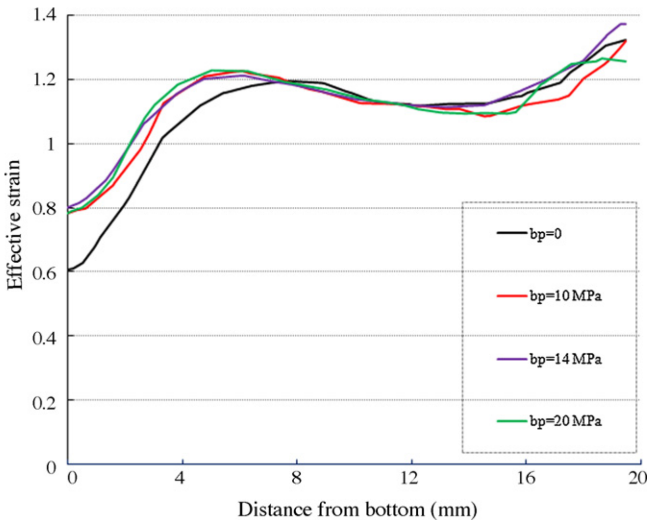

Fig. 10. Distribution of effective strains in the cross-section of samples with four different back pressures.

strain, but it has effect on the uniformity of strain distribution as long as there is sufficient back pressure to fill the outer corner. In other words, the sample does not undergo shear via back pressure. The strain in-homogeneity in the lower part of the deformed sample without back pressure has been verified by Wei et al. [18]. The result obtained by Oruganti et al. [5] and Xu et al. [19] regarding effects of back pressure on the strain distribution has good agreement with above outcomes. As already noted, especially in larger die channel angles, during ECAP back pressure leads to filling of this outer corner and gradually removes the dead zone, thus the uniformly strain distribution can form and surface cracking can be prevented. Therefore, imposing a back punch causes a smaller dead zone, a higher magnitude for strain, a more uniform strain distribution on the cross-section of the sample, prevent surface cracking and a higher pressing pressure requirement.

5. Conclusion

The deformation behavior of a commercial pure aluminum processed by ECAP was investigated by using 3D FEM and experimental method. Several conclusions were drawn:

1. Great increases in the level of the strains were made with decreasing the die channel angle or increasing the magnitude of the friction coefficient. Also, lower die channel angle or higher friction coefficient causes complete filling the outer corner of the die, thus the dead zone was decreased or removed. Lower magnitude of effective strain has been achieved for larger die channel angle; on the other hand a better strain homogeneity distribution has been obtained.
2. For eliminating the corner gap and producing uniform strain behavior in the sample, use of either acute die channel angle or high-friction coefficient is suggested.
3. A higher amount of punch pressure was needed with decreasing the die channel angle or increasing the magnitude of the friction coefficient. This result is because of higher level of the friction force that was imposed to the sample during deformation.
4. Application of the back pressure, however, increases the volume of the punch pressure but does not have any noticeable effect on the magnitude of the strain imposing to the sample. Also, due to decrease or removal of the dead zone, the homogeneity of the strain does increases in the cross-section of the sample.

For validating purposes, FEM analysis results were compared with theoretical and experimental values and there was a good agreement between them.

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