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EFFECT OF CHANNEL ANGLE AND FRICTION IN MODIFIED ECAP-CONFORM PROCESS OF Al-6061: A NUMERICAL STUDY

J. Gholami, M. Pourbashiri* and M. Sedighi

* *mpourbashiri@iust.ac.ir*

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School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.

Abstract: *Equal-channel angular pressing (ECAP) combined with the Conform process provides a solution for the continuous production of ultrafine-grained materials. In the present study finite element method was executed to investigate the effects of die channel angle and friction on the strain homogeneity and the required torque in ECAP-Conform process. Deformation behavior of Al 6061 wires was analyzed using the ABAQUS/Explicit software. A number of Finite element simulations considering different channel angles (90°, 100° and 110°) and various friction conditions of 0.2, 0.3 and 0.4 were surveyed. The results revealed two distinct trends in which by increasing the channel angle among 90° to 110°, the amount of induced plastic strain into the initial wire is reduced about 40% and required processing torque is decreased about 50%. In addition, more homogeneity was observed in higher angle values. The results regarding to equivalent strain, obtained from FE analyses, show a good agreement with previous studies. Eventually, the FE results indicate that plastic strains and required torque for a successful processing increased about 8% and 12% when the friction coefficient raises between (0.2-0.4).*

Keywords: *SPD, ECAP-Conform, Numerical Study, Al 6061*

1. INTRODUCTION

Fine grained materials with the grain size of about 1μm or less, have unique properties in terms of mechanical and physical and can be produced by severe plastic deformation processes [1]. Equal channel angular pressing (ECAP) as a popular severe plastic deformation (SPD) method [2] is an effective way to impose high shear stresses and strains to bulk materials. However, there are some obstacles for commercialization of SPD methods. Most of these processes suffer from some disadvantages such as the limited length of the initial samples, high cost of production and the large number of steps required to achieve the desired properties. To overcome these disadvantages continuous methods should be developed. To achieve this goal, various SPD processes are presented such as Equal Channel Angular Drawing (ECAD) [3], Accumulative Roll Bonding (ARB) [4], Equal Channel Angular Rolling (ECAR) [5], Con-shearing process [6], Continuous Frictional Angular Extrusion (CFAE) [7] and ECAP-Conform [8]. Among them, ECAD method is not able to produce a product with the required dimensional accuracy [9]. Other processes are conventionally used for continuous grain refinement of sheets or plates. But samples with different cross-sections such as sheets, bars, rods and wires could be processed by ECAP-Conform [1]. In this process, initial sample is guided to ECAP die by friction force. Fig. 1 schematically shows the ECAP-Conform process.

From Fig. 1, it can be seen that the channel angle (∅) plays a crucial role in this process. Lee et al. [10] shown that Ø can be adjusted from 100° to 140° for producing ultrafine grains with high angles of misorientation. On the contrary, Nakashima et al. [11] have found that ECAP with Ø=135° was not capable to produce UFG structure. Through experiments for the pure aluminum strip, it is shown that the optimal value for the ∅ in the Con-shearing process is about 115° [12].

In the present study three different channel angles of 90°, 100° and 110° has been analyzed in order to investigate the distribution of plastic strains at the wire cross section. Based on the ASM standard, the friction coefficient between the steel and aluminum-6061 is about 0.38 to 0.47 [13]. In this paper, three friction coefficients of 0.2, 0.3 and 0.4 have been considered. Finally, distribution of equivalent plastic strain at the cross section of wire and the amount of required torque for different cases are compared with each other.

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2. FINITE ELEMENT ANALYSIS

The ECAP-Conform process is simulated by commercial FEM software Abaqus/Explicit. The Initial length of the wire is considered to be equal to 100 mm. Initial wire diameter is reduced from 4.1 mm to 4 mm during the early stage of the process. Roller diameter is equal to 200 mm. The FEM model is presented in Fig. 2.

True stress-strain curve of Al 6061 wire is illustrated in Fig. 3. The other parameters for FEM simulations are shown in table 1. The roller and the dies are defined as discrete rigid parts. The proper element's size has been obtained by mesh sensitivity analysis.

In order to study the effect of outlet channel angle, three different angles (90º, 100º and 110º) have been considered. In these simulations the friction coefficient between the roller and wire is considered to be constant and equal to 0.4. Friction type in all FE simulations is modelled using the penalty formulation. Correct definition of friction in FEM simulations is so important because the friction force is the main factor to drive the wire into the die channel. The rotational speed of roller for FEM Simulations is 0.05 rad/s and it is constant during the process.

The ECAP-Conform process is performed at low speed relative to other SPD processes. Because the slipping of wire on the roller surface should be avoided and as a result the friction force could be applied to the wire completely.

For studying the effect of friction coefficient on the induced plastic strain and reaction forces and torques, three different friction coefficients (0.2, 0.3 and 0.4) are considered. In these simulations, the channel angle of the die is considered to be constant and equal to 110º. Other simulation parameters are as before.

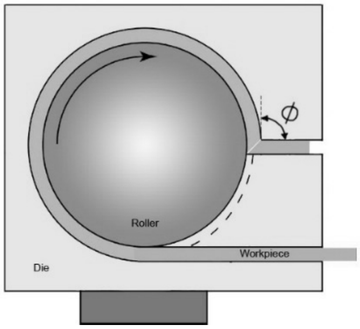

Fig. 1. Schematic view of the ECAP-Conform process

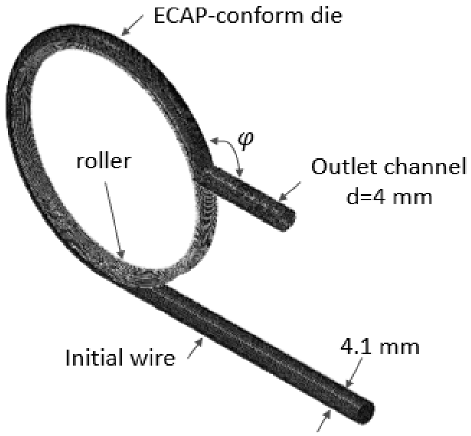

Fig. 2. FE model

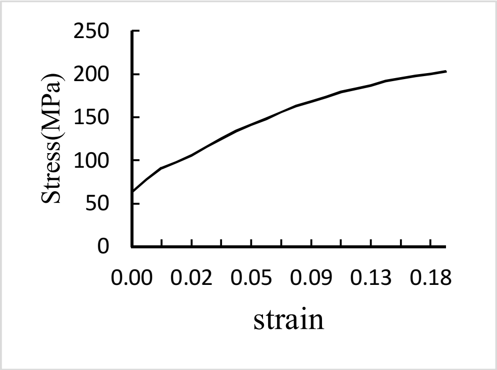

Fig. 3. True Stress–strain curve of Al-6061[14]

3. RESULTS AND DISCUSSIONS

3. 1. Effect of the Outlet Channel Angle

Fig. 4 shows the distribution of equivalent plastic strain in the longitudinal cross-section of wire for different outlet channel angles. It can be seen that the amount of equivalent plastic strain at the bottom of outlet channel is greater than the upper part. Also Fig. 4 shows that the amount of induced plastic strain for outlet channel angle of

Table 1. FEM simulation parameters

Rotational velocity, $\omega(rad/s)$	0.05
Friction coefficient, (μ)(wire and roller)	0.2, 0.3, 0.4
Friction coefficient, (μ)(wire and die)	0.05
Material	Al 6061
Element Type	C3D8
Approximate Global Size (m)	0.0011
Young's modulus (GPa)	68.9
Poisson's ratio, ε	0.33
Density, ρ (kg/m3)	2700
Die channel angle ($\emptyset$)	90, 100, 110

90° is greater than 100° and 110°. Comparison of the average amount of equivalent plastic strain for three cases is shown in Fig. 5.

This conclusion could be considered based on the analytical relationship Presented by Lee and colleagues [10] too. The effective plastic strain in the outlet channel can be calculated by the following equation:

$$\boldsymbol{\varepsilon_e = \frac{2N}{\sqrt{3}} K^2 cot\frac{\phi}{2}} \tag{1}$$

where K is the ratio of changing the diameter of the input state to output state, N is the number of passes and Ø is the angle of the outlet channel.

With replacement angles of 90°, 100° and 110° in the equation (1), approximate value of induced strain would be equal to 1.15, 0.97 and 0.81 respectively. From Fig. 4 it can be seen that the results of analytical and numerical simulations are in good agreement.

Evaluation of the forces and torques acting on the axis of rotation for outlet channel angles of 90°, 100° and 110° is shown in Fig. 6. The maximum amount of force and torque required for ECAP-Conform process happens at an angle of 90 degree. The results indicate that the amount of required force and torque are reduced by increasing the channel angle.

3. 2. Effect of Friction Coefficient

Fig. 7 shows the distribution of equivalent plastic strain in the longitudinal cross-section of wire or the outlet angle of 110 ° and three friction

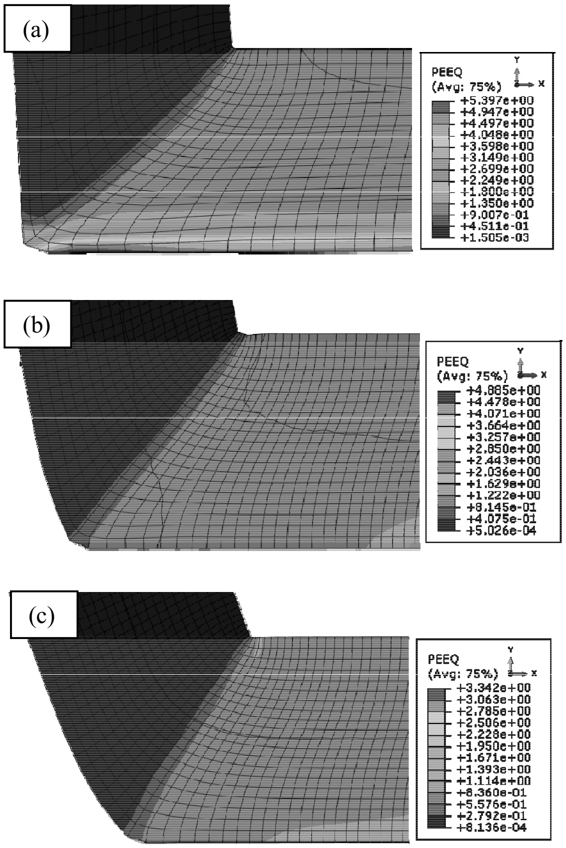

Fig. 4. Distribution of equivalent plastic strain in the longitudinal cross-section of wire for different output channel angles. a) Ø=90°, b) Ø=100°, c) Ø=110

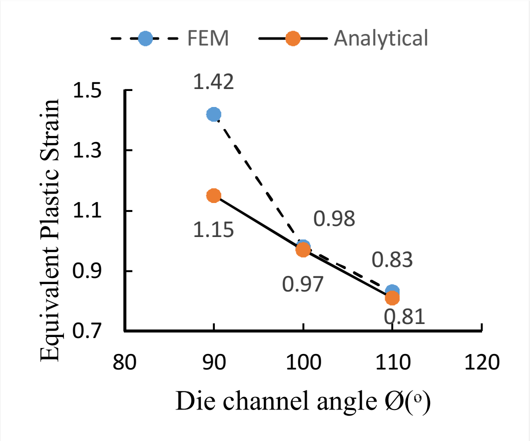

Fig. 5. Comparing the analytical and FE results for equivalent plastic strain (PEEQ) and different channel angle of 90°, 100°, 110°.

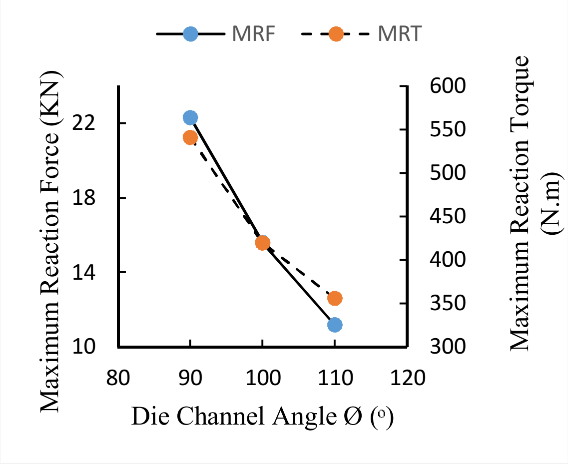

Fig. 6. Comparing the forces and torques acting on the axis of rotation for angles of 90°, 100° and 110°.

coefficient of 0.2, 0.3 and 0.4. The results show that for friction coefficient of 0.4 higher degree of plastic strain could be achieved. It can be concluded that if the amount of friction and the resulting friction force increases, the amount of induced plastic strain will also increase. The distribution of equivalent plastic strains for different friction coefficients obtained from analytical equation and FE simulations are presented in Fig. 8. As is shown, analytical and simulation results are in good agreement. According to equation (1), plastic strain for angle of 110° and 1 pass is calculated equal to 0.81. There is a little difference between the analytical and simulation results. The maximum difference is about 19% for the die with 90° angle and is about 3% for the dies with 100° and 110° angle. This difference is caused due to lack of consideration of the frictional conditions in equation (1). Also the amount of required force and torque are investigated for different frictional conditions.

From Fig. 9, it can be seen that by increasing the coefficient of friction, the amount of required force and torque are increased. Further friction coefficient causes the increase of friction force between the wire and the roller. Therefore, more torque is needed to drive the wire into the die channel. It should be noted that in reality the friction between the wire and the roller should be

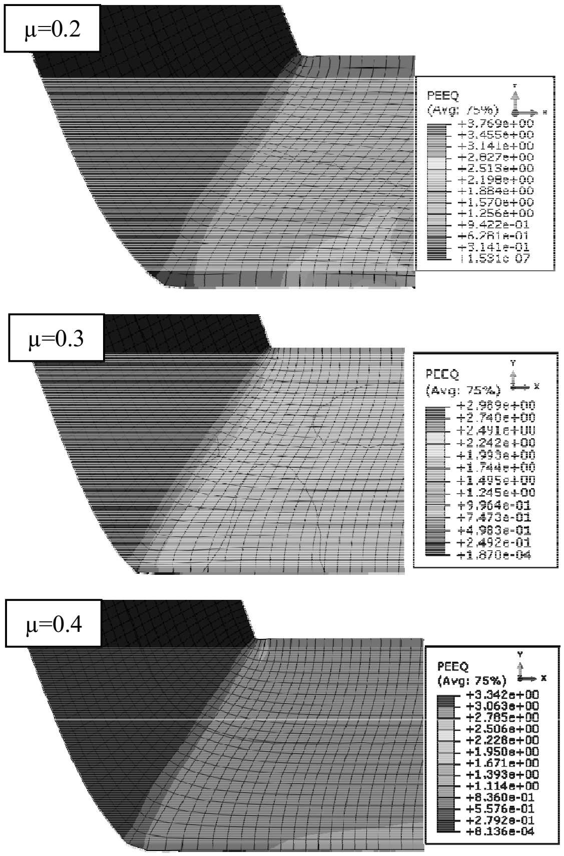

Fig. 7. Distribution of equivalent plastic strain in the longitudinal cross-section of wire for channel angle of 110 ° and friction coefficient of 0.2, 0.3 and 0.4.

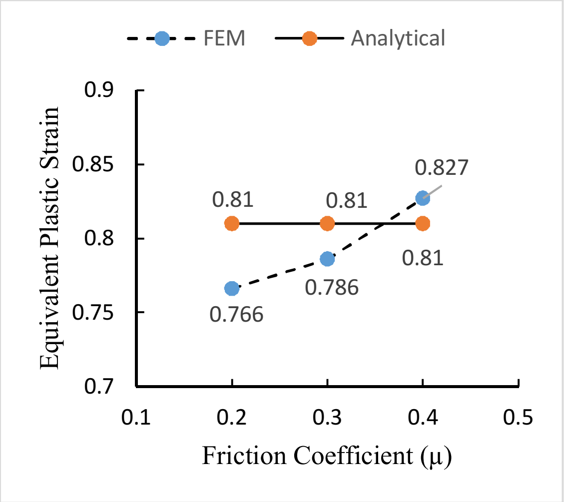

Fig. 8. Comparing the analytical and FE results for equivalent plastic strain (PEEQ) and friction coefficients of 0.2, 0.3, and 0.4.

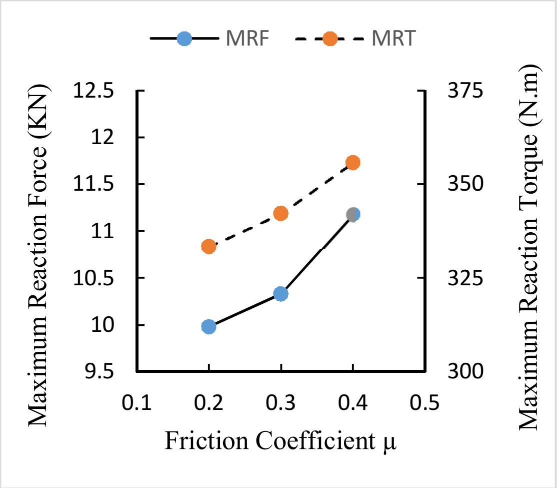

Fig. 9. Comparing the forces and torques acting on the axis of rotation for friction coefficients of μ=0.2, 0.3, 0.4

increased as much as possible. In this case, the slipping between the wire and the roller would be minimized and the amount of achievable plastic strain will increase. More plastic strain caused more grain refinement leaded to enhanced mechanical properties of the wire.

4. CONCLUSIONS

In this paper, ECAP-Conform process has been studied by FE simulations. Plastic strain distribution in the cross-section of the wire, the required force and torque for different cases were examined and the following results were obtained:

1. With increasing the angle of the outlet channel from 90° to 110°, the amount of plastic strain at the wire cross-section is reduced from 1.42 to 0.83. The amount of required force and torque to carry out the process is also reduced about 50%.
2. For the channel angle of 90°, the distribution of plastic strain at the wire cross section is non-uniform. The amount of induced plastic strain is changed from a maximum value at the bottom of the wire to a minimum value at the upper part of the wire. The strain homogeneity improves by increasing the outlet channel angle.
3. By increasing the coefficient of friction between (0.2-0.4), the amount of plastic strain at the cross section of the wire is increased from 0.76 to 0.83. Also, the required force and torque in the process increased about 12%.

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