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Research Paper

Different Die Designs for Processing of Al Alloy Using Equal Channel Angular Pressing: A FEM Study

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Severe Plastic Deformation (SPD) has become an exciting prospect as it provides the potential for refining the grain size of polycrystalline bulk metals to the submicrometer or even the nanometer level. It allows stable deformation to larger strains than most conventional metal forming techniques, thereby increasing the degree of strengthening possible. Equal channel angular pressing (ECAP) is one such technique for producing ultra-fine grain structures by introducing a large amount of shear strain into the materials without changing the billet shape or dimensions. FE modeling of metal forming processes has become an important tool for designing feasible production processes, because of its unique capability to describe the complex geometry and boundary conditions. The present paper is an effort to study the effect of different die designs in evolution of equivalent strain during Equal Channel Angular Pressing of Al6061 using finite element modelling done in FORGE. The simulation results clearly depict the change in equivalent strain in the entire specimen on account of this process and a comparison is made between FE results of different die designs. Also, the study is extended to analyse the effect of friction on forging force and equivalent strain using current FE model. This study is expected to contribute in forming ultra-fine grained (UFG) materials that are useful for automobile, aerospace industries.

Key Words: Severe Plastic Deformation; Equal Channel Angular Pressing; Finite Element Modelling; Ultra Fined Grains

1. Introduction

Pure aluminium and aluminium alloys play a key role in modern engineering since they are the most commonly used non-ferrous materials. They are widely used in automotive, aerospace, and construction engineering due to their good corrosion resistance, superior mechanical properties along with good machinability, weldability, and relatively low cost [1, 2]. One of the key factors in changing the mechanical properties of polycrystalline materials is by controlling the grain size. At low temperatures, the yield strength is related to the grain size by the well known Hall-Petch relationship [3, 4], where the yield strength of material increases with decreasing grain size. A reduction in grain size can also lead to low temperature and/or high strain rate supeplasticity [5].

Since last decade many deformation processes are under investigation to obtain metals and alloys with ultra-fine microstructures and consequently high strength. Hence, materials with nanometer or sub micrometer grain sizes are receiving greater interest because of their unique mechanical and physical properties and high performance [6-9]. The production of materials with ultra-fine grain sizes can be achieved by subjecting coarse grained metal to severe plastic deformation to improve their mechanical and physical properties [10-14]. SPD technology has become the focus of attention of many research groups and

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individual researchers and an analysis was conducted by Langdon [15] to evaluate the impact of the broad publications appearing over the last decade within the discipline of material science indicating it to be the most popular research area. Many SPD techniques like equal channel angular pressing (ECAP) [8-11], high pressure torsion (HPT) [16], twist extrusion (TE) [17], etc., have been developed and analysed. ECAP is a promising process because it can produce bulk, fully dense, and contamination-free UFG materials. Moreover, one can design and predict the microstructural evolution by using different routes (route A, B_A, B_C and C). In recent years, numerous theoretical and experimental investigations on the ECAP process [9-15] have been conducted to demonstrate the effect of process parameters on material behaviour. Recently, Valiev *et al*. [18] discussed new concepts and principles in application of SPD processing to fabricate bulk nanostructured Al alloys with advanced properties. Many researchers are also working on Finite Element Modelling (FEM) [19-26] to understand the deformation behaviour of materials and to estimate the developed strain in the ECAP process. FE simulations help to understand and critically assess the existing ECAP process with a better insight into influence of different process parameters. Recently, Suo *et al*. [19] and Basavaraj *et al*. [20] have done some 3D analyses to trace the homogeneity during the ECAP processes after the first pass Xu *et al*. [22] and Jiang *et al*. [23] studied the distribution of strain in the cross-section of the sample of pure Al and CP-Ti, respectively, during the 3D FEM simulations for the multiple passes. Hans Raj, *et al*. [21, 24] has analysed the influence of friction and channel angle in ECAP using FE analysis. Nagasekhar *et al*. [25] considered the effect of strain hardening and friction in the pure copper by 3D FEM. Recently, Balasundar *et al*. [26] analysed the effect of friction models on deformation behaviour of pure aluminium.

In this paper, finite element modelling of ECAP is attempted with different die designs to study the evolution of equivalent strain in Al6061 alloy in different friction conditions.

2. Equal Channel Angular Pressing (ECAP)

The process of Equal Channel Angular Pressing (ECAP), also known as Equal Channel Angular Extrusion (ECAE), was first introduced by Segal and his co-workers in the 1970s and 1980s at an institute in Minsk in the former Soviet Union [27]. The principle of ECAP is schematically illustrated in Fig. 1. This technique involves pressing a billet through a die with the billet constrained within a channel which is bent through an abrupt angle within the die, where 'Φ' and 'Ψ' are the channel intersection angle and the arc curvature angle respectively. The nature of the imposed deformation is simple shear which occurs as the billet passes through the die. Despite the introduction of a very intense strain as the billet passes through the shear plane, it ultimately emerges from the die without experiencing any change in the cross-sectional dimensions.

The retention of the same cross-sectional area when processing by ECAP, despite the introduction of very large strains, is the important characteristic of this type of SPD processing and it is a characteristic which distinguishes this type of processing from conventional metal-working operations such as rolling, extrusion and drawing. Another important characteristic of this process is its ability to continuously produce long metal bars and strips which makes it suitable for mass production.

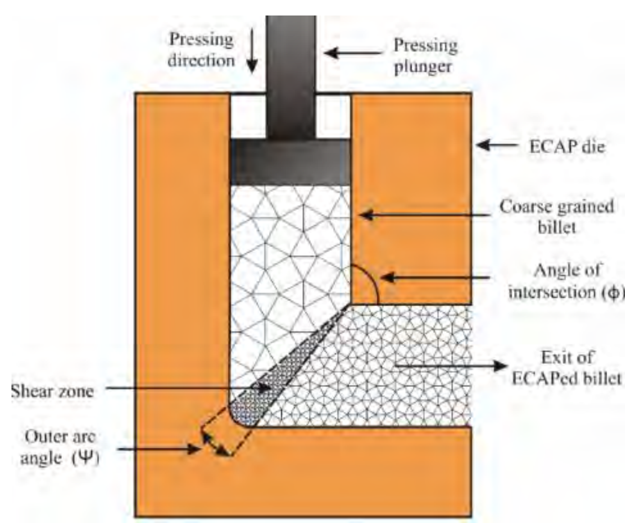

Fig. 1: Schematics of ECAP process

ECAP is an attractive processing technique for several reasons listed below:

- It can be applied to fairly large billets and has the potential for producing materials that may be used in a wide range of structural applications.
- It is a relatively simple procedure that is easily performed on a wide range of alloys
- It may be developed and applied to materials with different crystal structures and to many materials ranging from precipitation-hardened alloys to intermetallics and metal–matrix composites.
- Reasonable homogeneity is attained, provided the pressings are continued to a sufficiently high strain.

The magnitude of channel and corner angles along with the number of passes determines the shear strain induced into the sample.

Shear strain in general condition is given by Eq. 1:

$$\gamma = 2\cot(\Phi/2 + \psi/2) + \Psi \operatorname{cosec}(\Phi/2 + \psi/2) \quad (1)$$

Finally, the equivalent strain after N passes, ε_N, may be expressed in a general form by the relationship given by Eq. 2:

$$\varepsilon_N = N/1.732\,[2\cot(\Phi/2+\psi/2) + \psi \operatorname{cosec}(\Phi/2+\psi/2)] \quad (2)$$

Die design is also an important aspect in ECAP process. The following different die designs are used for the present study, Fig. 2. Conventional ECAP die is similar to the one shown in Fig. 1, while in modified die, conventional die is modified by tilting the upper surface of the exit channel by 2-6°. Finally, the 3rd die design is the combination of two SPD processes namely ECAP and Twist Extrusion (TE). In this design, the specimen is subjected to both ECAP and TE in the same die setup resulting in the generation of higher equivalent strains in the specimen.

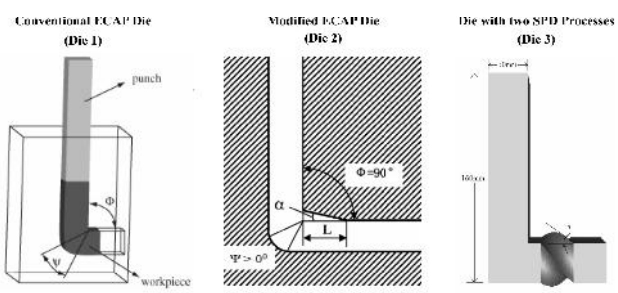

Fig. 2: Different die designs

3. Finite Element Modelling of ECAP

Finite Element Method (FEM) is one of the important approaches to understand the deformation occurring in the Equal Channel Angular Pressing (ECAP) process

In this work, the FE modelling of ECAP is done in FORGE environment, a finite element code developed by CEMEF laboratory at France [28], which is capable of modelling 3-D situations of metal forming (including thermal and friction effects) with automatic mesh regeneration. The billet is meshed with 7426 tetrahedron elements having 1773 nodes (Fig. 3). Also, an automatic re-meshing is done when initial mesh degenerates. The user has to provide various inputs while making project in FORGE related to different friction files, selection of press during the pressing operation, co-ordinates of the plunger movement, etc. Different types of data are already available in the FE software and user has to select it according to the needs. In present study we have selected high, medium and low friction files based on coulomb friction law, hydraulic press for pressing the plunger (defined its movement in Y direction from initial to final coordinates). The material is assumed to be homogeneous, isotropic and incompressible. The dies are assumed to be rigid. The dimension of the plunger is 20mm (width) x 20mm (breadth). The three dimensional work piece (billet) considered has the dimensions of 20 mm (width) x 20mm (breadth) and 105 mm (height). The material of the billet is Al6061. FE simulations are carried out for ECAP ($\Phi = 90°$ and $\psi = 0°$) having high friction conditions ($\mu = 0.2$) and value of Tresca coefficient *m*, is 0.4, refer Eq. 9), medium friction conditions ($\mu = 0.05$ and value of Tresca coefficient *m*, is kept constant at 0.1, refer Eq. 9) and low friction conditions ($\mu = 0.02$ and value of Tresca coefficient, $\bar{m}$ is kept constant at 0.05). For all the dies, Φ and ψ value remains same. In addition to it, die 2 has $\alpha = 4^o$, while for die 3, TE (twist angle, $\beta = 90^o$).

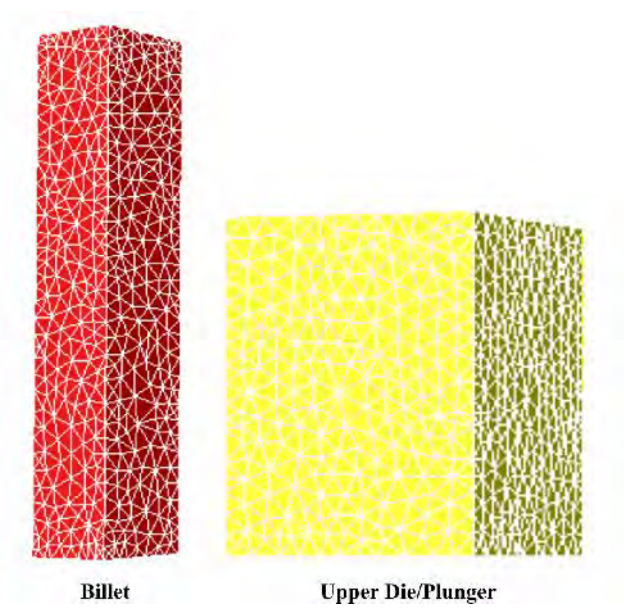

Fig. 3: Meshing Contours of Billet and Upper Die/Plunger

All the simulations are done at 20°C under constant pressing velocity of 10 mm/s and the material rheological behaviour is assumed to be elastoplastic. At every moment, it is possible to separate the instantaneous deformation of elastic reversible part and plastic irreversible part. In tensorial form the hypothesis can be written as :

$$\bar{\varepsilon} = \bar{\varepsilon}_p + \bar{\varepsilon}_e \tag{3}$$

where,

The linear elasticity law for purely small strains can be written in the following form:

$$\Delta\varepsilon = \frac{1+\nu}{E}\sigma + \frac{3\nu}{E}p \tag{4}$$

where, $\Delta\varepsilon$ represents the elastic small strain tensor, σ is the stress tensor, p is sensitivity to sliding velocity and ν is poisson's ratio. Von Mises criterion defines the plastic part of the deformation, which can be defined in a simplified way as:

if $\sigma_{eq} = \sigma_0$: plastic deformation occurs

if $\sigma_{eq} < \sigma_0$: elastic deformation occurs

if $\sigma_{eq} = \sigma_0$: impossible configuration

where, σ_{eq} is equivalent stress and is defined as one of the stress tensor invariant with the following expression:

$$\sigma_{eq}^2 = \frac{1}{2}[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2] + 3(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2) \tag{5}$$

and σ_{eq} is called the yield stress and is defined as follows:

$$\sigma_0 = \sqrt{3}K(T, \dot{\bar{\varepsilon}}, ...) \tag{6}$$

The description of the rheology values of the material in FORGE is based on the NORTON-HOFF behaviour law written in the following tensorial form:

$$S = 2K(T, \bar{\varepsilon}, ...)(\sqrt{3} * \dot{\bar{\varepsilon}})^{m-1}\dot{\varepsilon} \tag{7}$$

This formulation represents that the material plastic behaviour is exactly equivalent to the viscoplastic behaviour when m coefficient (sensibility of the strain rate) becomes close to zero. The thermo mechanical conditions are governed by the Hansel et Spittel rheology [29] which can be defined by the following eqation:

$$\sigma_f = A \exp^{m_1 T} T^{m_9} \varepsilon^{m_2} \exp^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5 T} \exp^{m_7 \varepsilon} \varepsilon^{m_3} \varepsilon^{m_8 T} \tag{8}$$

where, ε is total strain, ε is total strain rate, T is temperature and A, m_1, m_2, m_3, m_4, m_5, m_7, m_8, m_9 are regression coefficients.

The friction on the interface of the die and billet is modelled using the modified Coulomb friction law [30] written in the following general form:

$$\tau = \mu\sigma_n \frac{\Delta\bar{V}}{\Delta V} \text{ if } \mu\sigma_n < \frac{\sigma_0}{\sqrt{3}} \text{ and}$$

$$\tau = \bar{m}\frac{\sigma_0}{\sqrt{3}}\frac{\Delta\bar{V}}{\Delta V} \text{ if } \mu\sigma_n > \bar{m}\frac{\sigma_0}{\sqrt{3}} \tag{9}$$

where, τ is the shear stress, $\bar{m}$ is coefficient of tresca friction, μ is coefficient of coulomb friction and σ_n is the normal stress.

The viscoplastic equations can be transformed into an integral mixed formulation; for any virtual velocity field v*:

$$\begin{aligned} r^v(x,\bar{\varepsilon},v,p) &= \int_\Omega 2K(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\dot{\varepsilon} : \dot{\varepsilon}^* \, dV \\ &+ \int_{\partial\Omega_c} \alpha_f K|v_s|^{p-1} v_s v^* \, dS \\ &- \int_\Omega p\,div(v^*)\, dV = 0 \end{aligned} \tag{10}$$

and for any virtual pressure field p*:

$$r^p(x, v, p) = \int_\Omega p^* div(v)\, dV = 0 \tag{11}$$

Corresponding integral formulations, in term of the velocity field, can be derived for elastoplastic or elastic viscoplastic behaviour. But most often a displacement formulation is preferred for simplicity. From Eq. 10 and Eq. 11, the discretized mixed formulation for viscoplastic material gives the following set of non linear equations :

$$\begin{aligned} R_n^V &= \int_\Omega 2K(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\dot{\varepsilon} : B_n dV \\ &- \int_{\partial\Omega_c} \alpha_f K|v_s|^{p-1} v_s N_n dS \\ &- \int_\Omega p\,tr(B_n)\, dV = 0 \end{aligned} \tag{12}$$

$$R_m^P = \int_\Omega M_m div(v)\, dV = 0 \tag{13}$$

which takes the symbolic form:

$$R(X, \bar{\varepsilon}, V, P) = 0 \tag{14}$$

The time evolution strain is governed by:

$$\frac{d\bar{\varepsilon}}{dt} = \dot{\bar{\varepsilon}} \tag{15}$$

and co-ordinate vectors by:

$$\frac{dX}{dt} = V \tag{16}$$

For an elastoplastic or elastic viscoplastic material, the general form of the discretized integral equation is:

$$R(X, \bar{\varepsilon}, V, P) = 0$$

The equations of evolution being Eq. 13 and Eq. 15 and the stress evolution equation is given by:

$$\frac{d\sigma}{dt} = \dot{\sigma} \tag{18}$$

The variation of energy required and equivalent strain in the end product after 1st pass for different die designs having channel intersection angle (Φ = 90°) and different friction conditions are obtained in Table 1.

4. Results and Discussion

4.1 Evolution of Equivalent Strain

During ECAP, billet experiences severe plastic deformation by simple shear at the region where two channels intersect. Die 1 and Die 2 undergoes similar deformation process while in Die 3 deformation occurs twice, first during ECAP and secondly during twist extrusion where the billet is twisted with an angle β about its longitudinal axis. The equivalent strain contours during the deformation process for different dies are shown below:

From Fig. 4 it can be concluded that almost little deformation is obtained in the front and end part of the billet, so it exhibits minimum equivalent strain whereas intensive shear deformation is obtained in the centre part of the billet, thereby exhibiting higher values of equivalent strain. The schematic representation of end billet in ECAP after 1st pass with representative cross-sections is depicted in

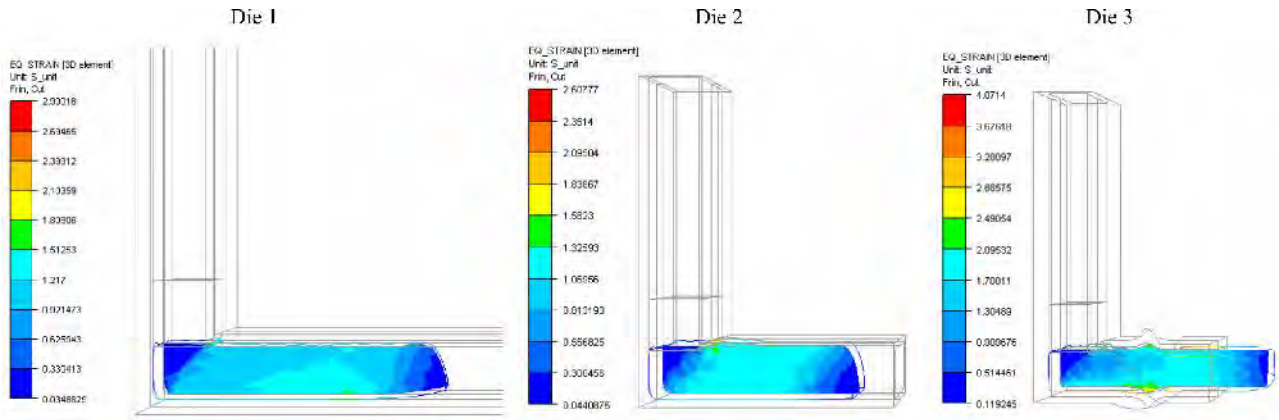

Fig. 4: Equivalent Strain Contours of ECAP for different dies under low friction conditions

Table 1: The FE evaluation of equivalent strain, forging force and energy during ECAP for die 1, die 2 and die 3

Die design	Friction condition	Average equivalent train	Forging force (tonnes)	Energy (KJ)
Die 1	High	1.6	35.3	23.41
	Medium	1.4	17.14	12.33
	Low	1.35	14.38	10.27
Die 2	High	1.57	31	16.75
	Medium	1.42	15	8.5
	Low	1.38	12.4	7
Die 3	High	2.73	45.89	31.54
	Medium	2.29	25.18	17.34
	Low	2.1	21.49	14.92

Fig. 5. The variation of equivalent strain along the billet length at the middle (A-B) is also evaluated and shown in Fig. 6.

The variation of strain along the middle surface of the billet in ECAP for the cases under study can be seen from Fig. 6 and it is indicated that for die 1 and die 2, strain increases initially, remains steady for certain length and thereafter decreases again towards the trailing end of the billet while in die 3 (combined SPD processes) strain increases with increase in billet length and attains a peak value almost in the middle and then starts decreasing till the end of the billet.

4.2 Effect of Friction on Equivalent Strain and Forging Force

The effect of friction on evolution of equivalent strain and forging force can be seen from Fig. 7. It clearly

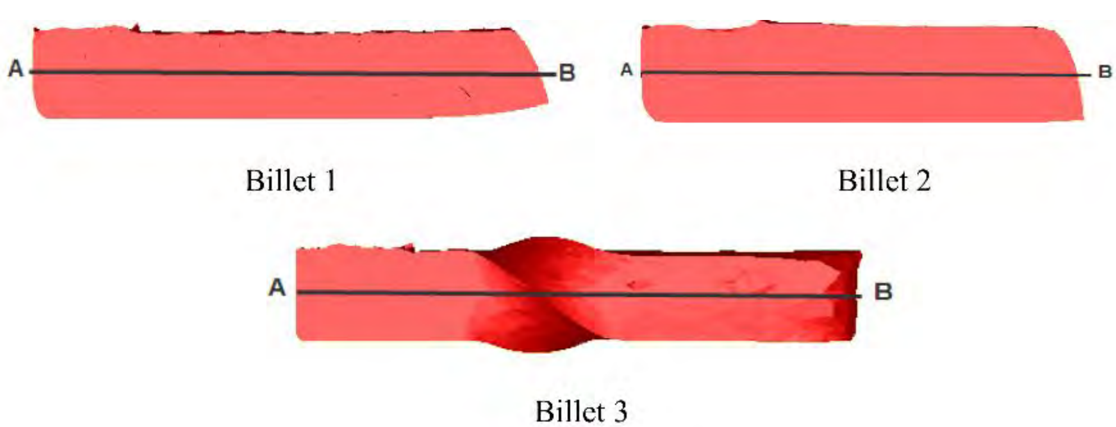

Fig. 5: Schematic representations of end billet for different dies after ECAP process

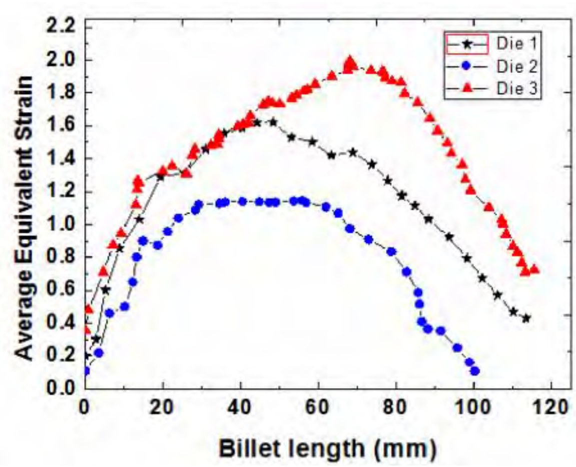

Fig. 6: Strain distribution in billet for the middle surface in ECAP

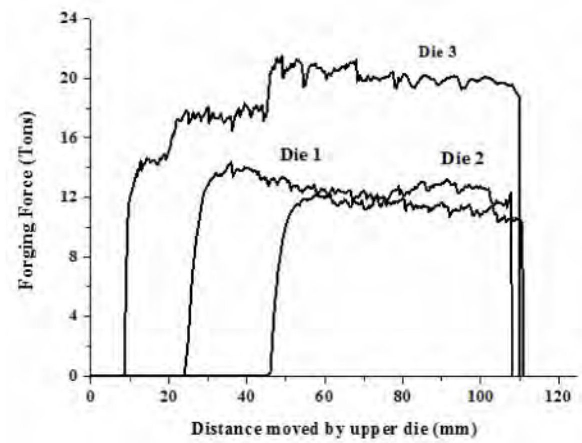

Fig. 8: Forging Force variations during pressing of specimen in die 1, die 2 and die 3

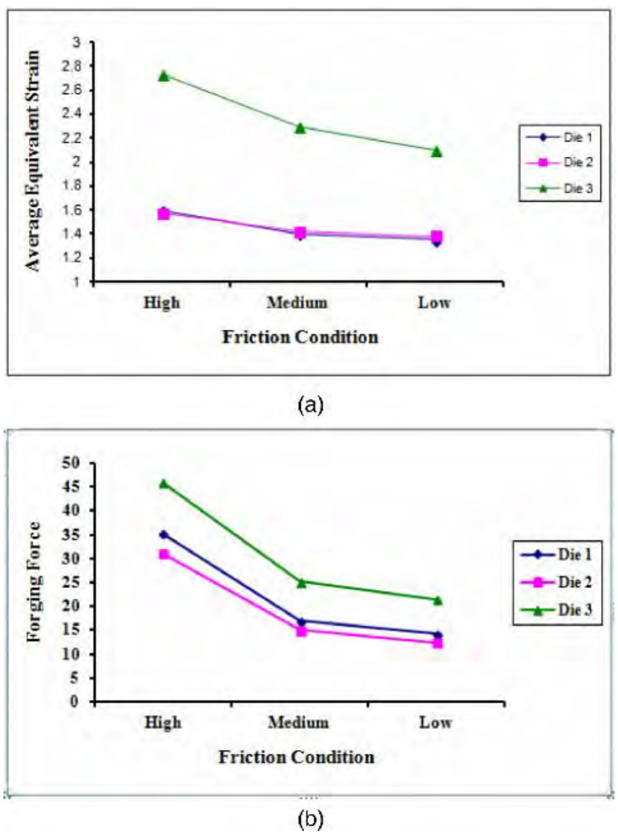

Fig. 7: Effect of friction on (a) equivalent strain (b) forging force during ECAP process for different dies

indicates that die 3 generates higher values of equivalent strain as compared to other dies. Moreover, in die 1 and die 2 the evolution of equivalent strain is almost same for all the friction conditions. Fig. 7 (b) indicates that die 3 requires high values of forging force as compared to other dies because billet is severely deformed during ECAP and then in TE in the same die setup. Further, die 2 requires less forging

4.3 Variation of forging force for different dies

Fig. 8 depicts the variation of forging force during 1st pass for $\phi = 90^0$ at low friction condition. During the initial stages of deformation, the billet enters the main deformation zone or shear zone (Fig. 1). For die 3, as the punch moves in the downward direction, the billet is compressed in the shear zone and hence the forging force increases to a certain limit. During further deformation, the billet again enters the twisted channel where force attains its peak value. On further pressing, billet slides on the die surface which causes shear deformation and hence the forging force drops. In die 1 and die 2, main deformation or shear zone occurs only once therefore as force attains its peak value, it starts decreasing till the end of the process.

5. Conclusions

Three different die designs have been investigated during ECAP process and modelled using FEM for producing ultra-fined grained materials. The simulation study illustrated the role of friction on evolution of strain, forging force and energy (Table 1). The following conclusions are drawn:

- Die 3 enables to generate higher equivalent strain in a single pass ~ 2.73 as compared to die 1 (conventional ECAP), 1.6 and die 2 (modified ECAP), 1.57.

- Die 3 requires high amount of forging force as compared to other dies. It is up to the designer to decide whether high equivalent strain is the priority or low forging force. For high equivalent strain, die 3 is the best option but deformation is complex as it includes two SPD processes in same die set up. While for low forging force die 2 is a better option.
- Forging force and energy increase with increase in friction condition for all the considered dies.

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