INFLUENCE OF FRICTION IN EQUAL CHANNEL ANGULAR PRESSING – A STUDY WITH SIMULATION

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Abstract:
Severe Plastic Deformation (SPD) processes like Equal Channel Angular Pressing (ECAP) are currently being widely investigated because of their potential to produce ultra fine-grained microstructures in metals and alloys. Ultra-fine materials exhibit superior mechanical properties such as high strength and ductility. The die for ECAP consists of two channels of equal cross sectional area intersecting at a specified angle that usually varies between 90 and 120 degree. The work-piece undergoes intense plastic deformation within a region in the intersection corner of the two channels. A sound knowledge of the plastic deformation and the load is necessary for understanding the relationships between plastic deformation, grain size and mechanical properties. The friction between the die and the work-piece has great influence on the extrusion pressure and flow in the process. This influence can be studied by Finite Element Modeling.

In the present work Finite Element Modeling of ECAP process is carried out using the ABAQUS/Standard software. Channel intersection angle of 105 degree was considered for the study. A cylindrical work-piece of diameter 20 mm and length 105 mm was considered for analysis. Coefficient of friction between the die and billet was varied form 0 to 0.1 in steps of 0.02. The pressure required for deformation v/s the stroke length were obtained and compared with experimental data. The results presented are very useful for understanding the effect of coefficient of friction on extrusion pressure, material flow and strain distribution in the work-piece.

Keywords: Equal Channel Angular Pressing, Finite Element Analysis, strain inhomogeneity, plastic equivalent strain, ABAQUS.

1. INTRODUCTION

Equal channel angular pressing (ECAP) is severe plastic deformation process used for producing bulk ultra-fine grained materials. It was first developed by SEGAL (1977, 1995, 1999). The main advantage of the process is work-piece can be subjected to uniform and high shear strain without major change in the shape and size of the work-piece. The general principle of ECAP is illustrated in Fig. 1. The work-piece is pressed through a die with two channels of equal cross section, intersecting at an angle (channel angle, 2\(\phi\)) ranging between 90\(^{\circ}\) and 120\(^{\circ}\), having corner angle of \(\psi\). The work-piece under deformation can be divided into four zones namely (a) head (the front of the work-piece) (b) body (c) plastic deformation zone and (d) tail (the un-deformed portion at the end of the work-piece). As the work-piece undergoes deformation without change in shape, it can be pressed several times to obtain desired accumulation of plastic strain. During plastic deformation of metals by this process the grain size reduce to sub-micron level and mechanical properties improve; this can be controlled by proper selection channel angle and corner radius.
SEGAL et al. (1995) have shown that the theoretical equivalent plastic strain $\bar{\varepsilon}_p$ after $N$ passes is given by

$$\bar{\varepsilon}_p = \frac{2N}{\sqrt{3}} \cot(\phi)$$

Eqn - (1)

A modified form was proposed by IWAHASI et al (1996) to consider the die with rounded corner. According to their model, the strain per pass can be obtained by

$$\bar{\varepsilon}_p = \frac{1}{\sqrt{3}} \left[ 2\cot\left(\phi + \frac{\psi}{2}\right) + \psi \cos ec\left(\phi + \frac{\psi}{2}\right) \right]$$

Eqn - (2)

Common assumptions in deriving these equations were frictionless condition, uniform plastic deformations, complete filling of corner gap and ideal perfectly plastic behavior of material. In reality there is always some friction between any two mating surfaces and usually metals exhibit strain-hardening behavior. Distribution of strain depends upon these parameters in addition to the die geometry. Eqn 1 and Eqn 2 are closed equations with parameters $\psi$ and $\phi$ to predict $\bar{\varepsilon}_p$ for a given die geometry and these equations cannot be used to obtained strain distribution in the work-piece. Soft computing tools help to look into the details of strain distribution.

Fig. 1: Schematic of ECAP process and zones of work-piece under deformation (a) head (b) body (c) plastic deformation zone (d) tail

Finite element method is one of the approaches to understand the deformation behavior of materials and to estimate the developed strain in the ECAP process. Many FEM-based analysis have been reported. These include the effect of channel angle and outer corner for frictionless condition by RAGHAVAN (2001), plastic deformation analysis for 90° die by KIM et al. (2001), the effect of outer corner on inhomogeneity for 90° die for frictionless condition by JIN-YOO et al. (2001), the corner gap formation and its effect by KIM et al. (2002), the effect of channel angle and corner angle on material flow by YI-LANG and SHYONG (2003), the study of deformation behavior, corner gap and strain inhomogeneity by
NAGASEKHAR and YIP (2004), the extensive work on different material models, outer corner angle and coefficient of friction by LI et al. (2004), the work on the origin of inhomogeneous behavior of metal by WEI et al. (2006), the effect of backpressure by ILHEON et al. (2006), the optimum die design for homogeneous plastic deformation by YOON et al. (2007). All these reports are based on 2D approximation of plane-strain condition. Recently KIM and KIM (2006), TAO et al. (2006) and SU et al. (2007) have done some 3D analysis but no extensive work is reported.

Friction plays very important role on distribution of strain in ECAP. Researches have used coefficient of friction of $\mu = 0$ to 0.3 for various materials. Generally coefficient of friction for metals operating with a good lubrication conditions is between 0.05 and 0.1 (NEALE, 1995). A range of 0.03 to 0.08 was used by ALTAN et. al. (1983) for cold extrusion of alluminium under lubricated condition. It is difficult to determine the exact coefficient of friction in ECAP by experimental methods. In the present study, to understand the influence of friction on extrusion pressure, material flow and strain inhomogeneity, finite element analysis was carried out for different coefficient of friction ranging between 0 and 0.1. The general-purpose finite element software ABAQUS/Standard, which has the capability to model non-linear engineering simulations accurately and reliably, was used. Simulation results were compared with the experimentally obtained peak pressure to estimate the actual friction.

2. FINITE ELEMENT SIMULATION

Researchers have been using 2D approximation to model ECAP process. 2D approximation of the type plane-strain can be used when the thickness of the work-piece is very large and plane-stress can be used when thickness of the work-piece is very small. Both plane-strain and plane-stress are not suitable for the cylindrical work-piece used in ECAP. Another 2D approximation, axi-symmetric is also not suitable because the axis of the channel intersect at an angle. Results obtained by 2D analysis give limited information in addition to the inherent 2D approximation errors. Thus 3D model is most suitable, which gives clear idea of metal follow, distribution of strain at different zones.

Only half portion of work-piece and die was considered for modeling because of the symmetry about the parting surface. A cylindrical work-piece of diameter 20 mm and length 105 mm, made of aluminum alloy was used. At the front side, filleting of 1 mm x 1 mm was done. Material used for work-piece was Aluminum alloy AA 6101 with flow stress given by $\sigma_0 = 208 e^{0.25}$, obtained experimentally by NAGARAJAN (2005) using compression test. Yield stress 75.8 MPa, Poisson’s ratio 0.33 and Young’s modulus 69 GPa were assumed. The work-piece was modeled with 7600 nodes and 6320 elements using 8 node linear hexahedral elements (C3D8) (Ref. Abaqus users Manual). It was assumed that the hardening behavior is isotropic and independent of strain rate at room temperature. Heat generated due to deformation and friction was neglected.

The die considered for analysis was made of high strength steel. The channel angle was 105° and outer corner was 4 mm (corner angle, $\psi = 6.5^\circ$). As the strength and rigidity of steel die were very high compared to aluminium, the die was modeled as rigid surface with linear quadrilateral elements (R3D4) (Ref. Abaqus users Manual). Because of the symmetry only half portion was considered for analysis. Numbers of elements and nodes used were 2300 and 2700 respectively.
The coefficient of friction between the die and the work-piece was varied from 0.0 to 0.1 in steps of 0.02.

The boundary conditions applied to the model were as follows:
- Displacement and rotation in x, y and z direction for all nodes in the die were arrested.
- As the conditions were symmetric about the parting plane of the work-piece, only half portion was modeled and all the nodes of the work-piece on this plane were given symmetry condition. The symmetry boundary condition arrests the displacement in the direction perpendicular to the plane and rotation about other two directions.
- The top surface of the work-piece was in contact with the punch and was taking load resulting in the movement of the work-piece. All nodes on the top surface of the work-piece were given displacement in the direction of movement of the punch.

2.1. Quantification of average strain and strain inhomogeneity:

The average strain in the body of the work-piece can be obtained by

$$Avg\bar{\varepsilon}_p = \frac{\sum_{i=1}^{n} \varepsilon^i_p}{n}$$  \hspace{1cm} (3)

where $n$ is number of nodes in the body of the work-piece and $\varepsilon^i_p$ is equivalent plastic strain at the node $i$. Degree of inhomogeneity can be quantified as coefficient of variance of equivalent plastic strain

$$CV\bar{\varepsilon}_p = \frac{Stdev\bar{\varepsilon}_p}{Avg\bar{\varepsilon}_p}$$  \hspace{1cm} (4)

where $Stdev\bar{\varepsilon}_p$ is standard deviation of equivalent plastic strain.

3. RESULTS AND DISCUSSION

The influence of the friction on material flow, distribution of the strain, strain inhomogeneity and the pressure required for extrusion are discussed in this section based on the results obtained from the simulation.

3.1. Material flow:

Figure 2 shows the material flow for different values of coefficient of friction. It can be observed from the figure that as the friction increases the corner gap decreases. Initially corner gap is present for all cases and as the process continues the corner gap fills completely for high friction conditions but only partially for others. For frictionless condition the initial corner gap remains unchanged. This is because of the continuous increase in the contact between work-piece and die in exit channel, which leads to a frictional drag in the exit channel. This acts like a back pressure leading to filling of the corner gap. It can be observed from the figure that the plastic deformation zone is wide for frictionless condition and as the friction increases it becomes narrow.

3.2. Average strain and strain inhomogeneity:

Figure 3 shows the average equivalent plastic strain obtained using Eqn. 3. As per the Eqn. 2 the analytical strain is constant with a value of 0.87 for the die geometry considered.
But the calculated strain linearly increases with friction. The calculated strain is nearly equal to analytical strain when $\mu = 0.08$. The increase in calculated strain with friction is due to the presence of an initial corner gap and its partial filling as the process continues.

The Fig. 4 shows the variation of inhomogeneity in terms of $CV\overline{\varepsilon}_p$ obtained by Eqn. 4 for different friction conditions. For the cases studied the inhomogeneity decreases up to 0.08 where the corner gap is nearly filled (Fig. 3: $\mu = 0.08$) but increases on further increase in friction. It can be concluded that the inhomogeneity decreases with increase in friction until the backpressure (exerted by frictional drag in the exit channel) is just sufficient to fill the corner gap. Further increase in friction leads to increase in inhomogeneity.

![Fig. 2: Equivalent plastic strain along the longitudinal section various friction values.](image-url)
3.3. Extrusion Pressure:

The calculated extrusion pressure v/s the stroke is shown in Fig 5. The curves follow the pattern explained by LI et al. (2004).

In ECAP friction can be reduced by applying coating of graphite or molybdenum disulphide which are strong in compression and weak in shearing. Though lubricants are used metal-to-metal contact can occur at the intersection of channels. Metal surfaces are rough on an atomic scale and when placed in contact touch only at the tips of their asperities. The real area of contact is generally much smaller than the apparent. At these regions of real contact
the atoms of one surface attract atoms of other leading to a strong adhesion termed as cold welding. When sliding occurs the adhesion are sheared. The force to shear the adhesion is primary cause of friction. Since die is harder than work-piece, asperities of die plough out grooves on work-piece. Total force due to friction is the sum of force to shear the adhesion and force to plough the asperities on the work-piece. At entry and exit channels a lubricating layer is present. Since force required to shear the lubricating layer is very less compared to force required to shear the adhesion of metals friction is lesser at the entry and exit channels than at the intersection of the two channels. It is very difficult to determine the exact value of coefficient of friction ($\mu$) by experimental techniques like ring compression test. But it can be estimated with the help of peak pressure.

The peak pressure required for the process v/s friction is shown in Fig 6. It is clear from the figure that peak pressure increases exponentialy with friction. A third order polynomial can be fit to the relation between the friction and peak pressure as

$$P_{\text{max}} = 661270 \mu^3 - 35866 \mu^2 + 2952.8 \mu + 119.46$$

- (5)

which can be used to predict the peak pressure. Experimental results have shown that the peak pressure required is 320 MPa for the die-workpiece combination considered in the present study (Nagarajan, 2005). Using the Eqn. 5 the friction can be estimated as 0.062 for the present condition. This estimated value of friction lies within the range given by ALTAN et al. (1983) and NEALE (1995).
4. CONCLUSIONS

Three-dimensional finite element analysis was carried out for different values of coefficient of friction to understand its influence on material flow, pressure and strain inhomogeneity in equal channel angular pressing for isotropic strain hardening aluminium alloy AA6101. It was found that the friction has very important role in the process.

As the friction increases the corner gap decreases due to back pressure. The average strain increases with friction due to the corner gap. The inhomogeneity in strain distribution decreases with increase in friction until the backpressure is just sufficient to fill the corner gap; further increase in friction leads to increase in inhomogeneity. The peak pressure required for the process increases exponentially with friction. Based on the polynomial developed for peak pressure and friction, coefficient of friction can be estimated as 0.062 for the conditions assumed.

5. REFERENCES

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