Effect of friction in Dual Equal Channel Lateral Extrusion using finite element simulation

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Abstract: Dual equal channel lateral extrusion (DECLE) is a type of equal channel angular pressing which employs T-shaped die instead of L-shaped die. In the present work, deformation behavior in the DECLE process is analyzed by using DEFOEM-2D. The effect of friction between the die channels and the specimen on the effective strain distribution homogeneity and load were investigated. The friction induces inhomogeneous deformation in the head, top and bottom regions of the work piece. As friction increases, the top gap becomes smaller and the strain distribution becomes more homogenous, but the maximum load value increases. These results can serve as a design for reasonably technological parameters for DECLE processing.

Keywords: ECAP; FEM; Severe plastic deformation; Deformation homogeneity

1. Introduction

Severe plastic deformation (SPD) is well known as a method to obtain ultrafine-grained materials with unique mechanical and physical properties. Different techniques for applying SPD have been introduced and developed\textsuperscript{[1, 2]}. Among these techniques, equal channel angular pressing (ECAP) is the most capable and attractive technique which may be used in industrial applications\textsuperscript{[3-6]}. The conventional L-shaped consists of two channels equal in cross section and intersecting at an angle near the center of the die. The material is made to enter one of the channels and exit through other channel without any change in cross-sectional area. So the sample can be repeatedly pressed to attain exceptionally high strains.

Due to different geometrical shape of the ECAP die, a lot of techniques have been generated and developed. Such as, Multi-Pass ECAP\textsuperscript{[7]}, Rotary-die ECAP\textsuperscript{[8]}, ECAP-Conform\textsuperscript{[9]}, T-shaped equal-channel angular pressing or dual equal channel lateral extrusion (DECLE)\textsuperscript{[10]}, et al. Now, the pressing was carried out using T-shaped die, where the material was placed in one channel of the T-shape and made to exit from the aligned horizontal channels. The advantages of this process with respect to ECAE are\textsuperscript{[11]}: (i) more intensive strains attainable per pass, and (ii) less extruding power needed for a given sample.
size. Nonetheless, less homogeneous strain per pass is seen in case of DECLE. Talebanpour.B\(^{[12]}\) calculated effective strain and d effective strain by Upper-bound method. However, there is a limited data report about the deformation characteristics of materials during DECLE. Therefore, in this paper, finite element simulation was used to investigate the plastic deformation characteristics of the process and study the effect of friction on the stress and strain distribution homogeneity and load value.

The principle of DECLE is illustrated schematically in Fig.1. Samples are placed in a vertical channel of rectangular cross section of equal size as that of the sample. A proper punch intrudes into the channel and forces the sample to extrude laterally into a dual channel of the same cross section lying horizontally below the vertical channel, while being subjected to simple shear. Since there is no change in cross-sectional area, the sample can be repeatedly pressed to obtain a large cumulative strain. To satisfy the volume constancy the flow velocity of the material in the horizontal channels are half of that in the vertical channel. The material at the channels intersections sees two paths to flow and escape the exerted force. Thus, Generally speaking, less pressure is required for this process relative to ECAE. The shear strain per pass is given by Lee\(^{[13]}\):

\[
\gamma = \cot\alpha \csc\beta
\]

Where \(\alpha = \tan^{-1}\frac{1}{2}\), \(\beta = \tan^{-1}2\), giving \(\gamma\) to be 2.5.

Fig.1. Schematic diagram of dual equal channel lateral extrusion.

2. Finite element analysis procedure

Isothermal FEM simulations of the DECLE process were carried out using the commercial finite element code DEFORM-2D (Version 9.1). The sample material was selected 6062 Al alloy. Sample with initial dimensions of 10mm\(\times\)10mm\(\times\)50mm with 1000 four-node plane strain elements. A constant ram speed of 0.1mm/s was employed. The friction coefficient values between sample and die wall were assessed: \(\mu=0,0.2,0.4,0.7\) respectively. In all simulations, an automatic remeshing scheme was used to accommodate large strains and to take into account the occurrence of flow localization, which prevents further calculation during the simulation.
3. Results and discussion

Fig. 2 is the calculated pressing load versus the ram displacement curves, showing the deformation steps during DECLE. Three stages of the DECLE load can be distinguished. Step I, the load increases rapidly from zero because the initial undeformed head part of the sample which mainly occurs upsetting and shear deformation, as shown in Fig. 3(a-b). The volume of the deformation part of sample increases as well and goes through the main deformation zone. Step II, the front part of the sample exits the main deformation zone with two horizontally direction and starts bending toward to the upper surface of the exit channel, see Fig.3(b-c). The load increases slowly to the peak load point. Since the two front part of the sample touch the upper side of the exit channel die during bending, as shown Fig. 3(d). The load suddenly decreases. Step III starts when sufficient interactions are established between the sample and the exit channel, where the load decreases gradually due to a decrement in the contact area within the entry channel. As the friction factor increases, the maximum pressing load increases form 410 N to 1486 N. Fig. 3(e) shows the end part of the sample exiting the main deformation zone and the loads drops.

![Fig.2. Predicted pressing load versus ram displacement curves during DECLE with various friction conditions.](image)

![Fig.3. Deformed geometry changes for the DECLE process with zero friction.](image)

Fig.4 shows the final deformed geometry after one pass DECLE process with vary friction factor. The flow net (not the FEM mesh) indicates that the deformation homogeneity is not
uniform. The flow net is unformed at tail end regions. In the upper areas, a gap between the upper of the deforming sample and the DECLE die is observed with $\mu=0$ and $\mu=0.4$, but the gap is disappeared with $\mu=0.7$. As is seen, corner gap formed after conventional ECAP is not observed. The geometrical shape are obviously different at the head region, the angle between the DECLE die and the upper region at the head is $35.2^\circ$, $17.7^\circ$, $6.7^\circ$, corresponding to friction value of 0, 0.4, 0.7, respectively. The angle between the DECLE die and the bottom region at the head is $19.7^\circ$, $13.7^\circ$ with friction value of 0 and 0.4. The bottom folding defects also are found during DECLE process. Specifically, surface regions on the back part of the heads penetrate into the sample inside. It is important to note that the predictions of the FEM simulation in Fig. 4(c) are in excellent agreement with the experimental result shown in Fig. 3(d).

**Fig. 4.** The final deformed geometry after one pass DECLE process: (a) $\mu=0$; (b) $\mu=0.4$; (c) $\mu=0.7$; (d) Experimental sample.

**Fig. 5.** Effective strain distributions $y$ after one pass DECLE process: (a) $\mu=0$; (b) $\mu=0.4$; (c) $\mu=0.7$.

Fig. 5 shows the effective strain distribution of the DECLE deformation process. The effective strain distribution is inhomogeneous in the inner region of the sample. The effective strain in
the two front and the end parts of the sample is smaller than the one in the center part of the sample. Little deformation is obtained in those regions, the effective strain is limited, so the effective strain is the minimum. Intensive deformation is obtained in the center of the bottom regions, so the effective strain is the maximum. The amount of effective strain increase form top side toward to the bottom side. As friction coefficient increases, deformation becomes more homogeneous and the effective increases.

As a whole, it can be seen from Fig. 4 and 5 that flow net and the effective strain distribution during the deformation process. And there is a steady and uniform region in the sample, although there is certain inhomogeneous deformation in the local regions of the sample.

4. Conclusions

Finite element analysis of deformation behavior during DECLE process has been carried out and the effect of friction on the deformation behavior was also studied. The deformed geometry was predicted to be relatively homogeneous. However, friction coefficient induces highly inhomogeneous deformation in the head, tail, top and bottom regions of the sample. As friction coefficient increases, the pressing load and the effective increase.

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