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The effect of deformations passes on the extrusion pressure in axi-symmetric equal channel angular extrusion

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ABSTRACT

The most applicable configuration of the equal channel angular extrusion (ECAE) dies is the axi-symmetric one. However, most of the previous analytical solutions are focused on the plane strain conditions. In this research, an upper bound model is used to investigate the deformation of the material during axi-symmetric ECAE. The analysis considers the effect of die angle, friction between the sample and the die walls, and the angle of the outer curved corner of the die, on the extrusion pressure. It is found that increasing the die angle and outer curved corner angle and decreasing the friction coefficient results in decreasing extrusion pressure. The proposed model is verified using two dies of the same die angle and different outer curved corner angles. The applicability of the solution in the ECAE process with more than one pass is investigated and the difference between the theoretical and experimental results are discussed.

1. Introduction

Equal channel angular extrusion (ECAE) is a processing method in which the material is subjected to an intense plastic straining through simple shear without any corresponding change in the cross-sectional dimension of the sample [1]. During the ECAE process, the grain refinement occurs together with significant strain hardening resulting in remarkable enhancement of strength in many engineering materials [2–6]. This process could be performed in two different designs; plane strain and axi-symmetric. However, referring to the literature [7–13] it will be appreciated that in contrast to numerous publications on deformation mode, extrusion force, and strain of plain strain ECAE, few papers has been published on the mechanics of axi-symmetric ECAE especially using the upper bound method. For example Lee [7] has analyzed the stresses and strains in channel angular deformation (CAD), in which two channels are not equal in cross-section. He has considered ECAE as a special form of CAD in his upper bound analysis. Alkorta and Sevillano [8] have analyzed the pressure needed for non-friction ECAE of perfectly plastic and strain hardening materials using an upper bound and a FEM solution. They have compared the results achieved from these solutions. Luis Perez [9] has analyzed a configuration of ECAE dies called equal fillet radii angular extrusion (EFRAE) being slightly different from the general ECAE dies. Altan et al. [10] have analyzed the deformation of the material in a 90° ECAE die using the upper bound theorem. Their model includes the effect of friction between the sample and the die walls, the radius of inner corner of the die, and the dead metal zone on the deformation pattern during ECAE. Moreover, the same authors [11] have performed a comprehensive study on the ECAE process using upper bound method considering the effects of die geometry and friction coefficient on the total strain and extrusion pressure. A deep study has also been performed by the same authors on the total strain using a new method dividing the outer curved corner of the die to infinite number of sub-dies [12], based on shear and principal strains [13] and considering the formation of dead metal zone [14]. However, all of the mentioned studies are in the case of plane strain or rectangular cross-section while the axi-symmetric one is more applicable from the practical aspects for producing nano-structured materials [15–17]. Therefore, further investigations are of interest to assess the effect of process parameters on the mechanics of axi-symmetric ECAE. Moreover, there has

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been no study considering the second pass of ECAE process regarding to extrusion force. However, as ECAE is a sever plastic deformation method which is generally used in more than one pass, the extension and verifying of the solutions to the second and the third passes of ECAE is very important.

In the present study, an upper bound solution is presented to consider the effects of die geometry such as die angle, outer curved corner angle, sample dimensions and also friction coefficient on the extrusion pressure in axi-symmetric ECAE. Geometrical differences between plane strain and axi-symmetric dies result in some mathematical complications in the solution and some differences in results which are challenged and solved in this study. To verify the reliability of the model, extrusion force is measured in two dies of the same angle but of different outer curved corner angles and the results are compared with the results of the theoretical model. Moreover, the application of the model in the second and third pass of ECAE is compared with experimental results.

2. Analysis

In this research, in order to develop an upper bound solution, a simple deformation model considering the effect of outer curved corner angle, introduced by Alkorta and Sivillano [8] and then used by Altan et al. [10], and Eivani and Karimi Taheri [11], in square cross-section ECAE dies is extended, and utilized in the case of axi-symmetric ECAE dies. In this deformation model, the ECAE die is divided into three regions as shown in Fig. 1. In Region I, the material moves rigidly downward with a velocity of V_0. Region II, called the "deformation zone", is where the material undergoes continuous plastic deformation.

It is assumed that in this region the material moves along the concentric circles with center at *O*. Considering that in any part of the die, the cross-section should not be smaller than the initial cross-section of the die, one can conclude that $\phi + \psi \leqslant \pi$, where ϕ is the die angle and ψ is the outer curved corner angle of the die (deformation zone). In Region III the material moves outward the die without any further deformation. Region II is separated from Region I by the entry surface of the deformation zone, Γ_i, and from Region III by the exit surface of the deformation zone, Γ_o. The origin of the rectangular coordinate system is taken as point *O* shown in Fig. 1. The *x*-axis is taken positive to the left, and the *y*-axis is positive down. Cylindrical coordinates (r,θ), defined with the origin at *O*, are also utilized when it is needed. The angle between the entry surface and the velocity in Region I, and between the exit surface and the velocity in Region III are assumed to be the same and presented by φ.

The material in Region II, the deformation zone, is moving with a constant velocity of $V_0\cos\varphi$. Using the cylindrical coordinates, the velocity field in this region can be expressed as

$$\upsilon_r = 0, \quad \upsilon_\theta = V_0 \cos\varphi, \quad \upsilon_z = 0 \tag{1}$$

where $\upsilon_i (i = r,\theta,z)$ is the velocity field components in the deformation zone (Region III) and *z* is the axis of the cylindrical coordinate system.

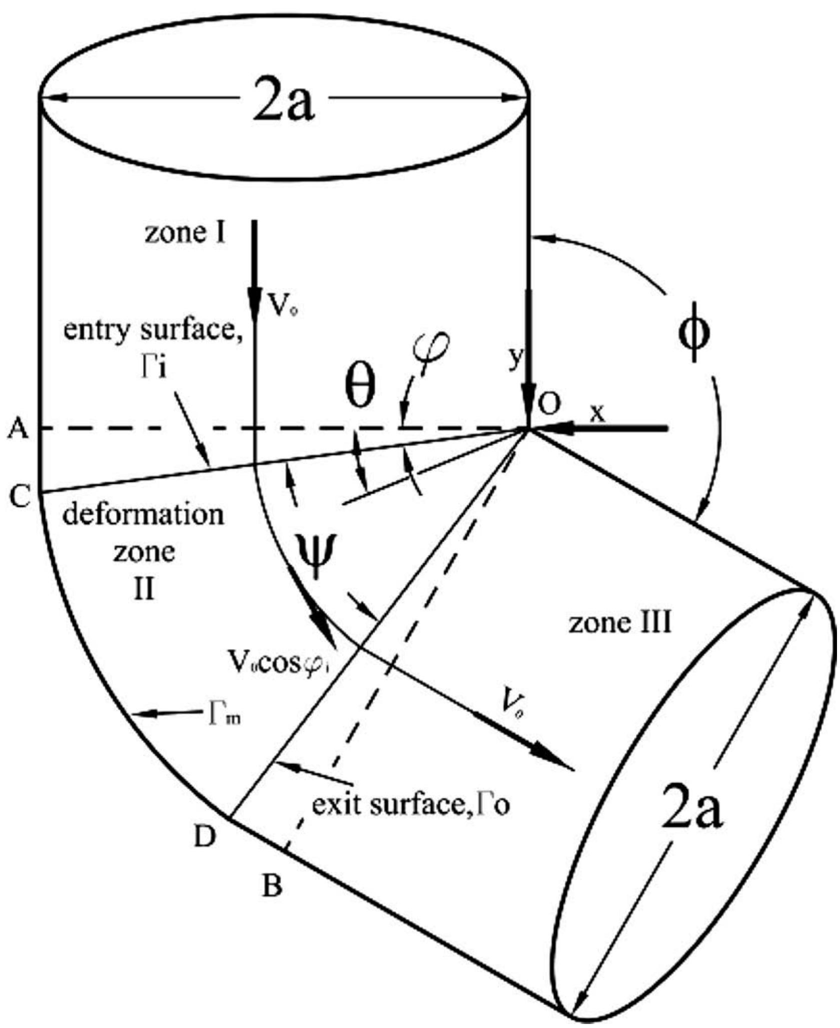

Fig. 1. The deformation model used for ECAE process in this study.