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The effect of dead metal zone formation on strain and extrusion force during equal channel angular extrusion

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Abstract

In this research, deformation of material during equal channel angular extrusion (ECAE) is analyzed using an upper bound model. The model considers the effect of die angle and friction between the sample and the die walls on the geometry of dead metal zone and total strain. The relationship between the friction coefficient, the extent of dead metal zone and total strain is derived. It is found that strain decreases with increasing die angle and friction coefficient. Moreover, a critical value for friction coefficient is determined that when the friction coefficient is more than the critical, deformation zone and therefore, the dead metal zone forms which consequently total strain decreases. The theoretical results are compared with previously published theoretical and experimental calculations by the same authors. It is concluded that considering the effect of friction coefficient on total strain and extrusion force results in closer accord between the theoretical and experimental results. Using this method, the difference between the theoretical and experimental results has decreased from 8.9% to 5.6% when compared with the previous study.

Keywords: ECAE; Upper bound; Dead metal zone; Friction coefficient; Strain; Extrusion force

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]. Attaining favorite properties and microstructure requires a good knowledge of the mechanics and deformation pattern of the process. However, referring to the literature, it will be appreciated that in contrast to numerous publications on structure characterization of ECAE products, few papers have been published on the mechanics of ECAE. Moreover, regarding to the previous works on ECAE [2–8], not enough attempts has been made on the upper bound analysis of the process. Considering the previous publications on ECAE using upper bound method, only the effect of certain parameters on extrusion force has been assessed.

In other works by the same authors [8,9] strain is calculated using two different methods; 1 – upper bound solution [8], and 2 – extending multi-stage ECAE dies to the dies with outer curved corner [9]. However, in both of them and also in studies by other investigators [2,4–6,11] the effect of friction coefficient and dead metal zone formation on total strain is not considered. Therefore, further investigation is needed to comprehensively assess the effect of processing parameters such as die angle and friction coefficient on dead metal zone formation, total strain and extrusion force of the process.

Avitzur, in his text [10] has studied the effect of die angle and friction coefficient on the dead metal zone formation in general deformation processes such as extrusion and wire drawing using upper bound method. What makes this study interesting is that in the case of ECAE total strain is directly dependent on the formation of dead metal zone. Moreover, in one of the works by the authors [8] the

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extrusion force is calculated using upper bound theorem and the results are compared with experimental results. In this work, the authors have added the effect of dead metal zone formation on the extrusion force and have compared the obtained theoretical results with the previously published theoretical and experimental results in [8].

2. Deformation analysis

The deformation model used in this study is based on the model proposed by Alkorta and Sevillano [2], Altan et al. [3], and used by Eivani and Karimi Taheri [8] which its convenience is studied and compared comprehensively with FEM simulation [2] and experimental results [3,8]. In the deformation model considered, the ECAE die is divided into four 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 concentric circles of center O. Region III is called the "*dead metal zone*" where the material is stationary. Regions II and III are not always existed. In this case, shear deformation occurs on one shear surface which its cross-section is OO' shown in Fig. 1. The existence of regions II and III depends on some parameters that their determination is one of the aims of this study. In region IV the material moves to the exit of the die without any further deformation.

Region II is separated from region I by the entry surface Γ_i and from region IV by the exit surface Γ_o. The origin of the rectangular coordinate system is 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

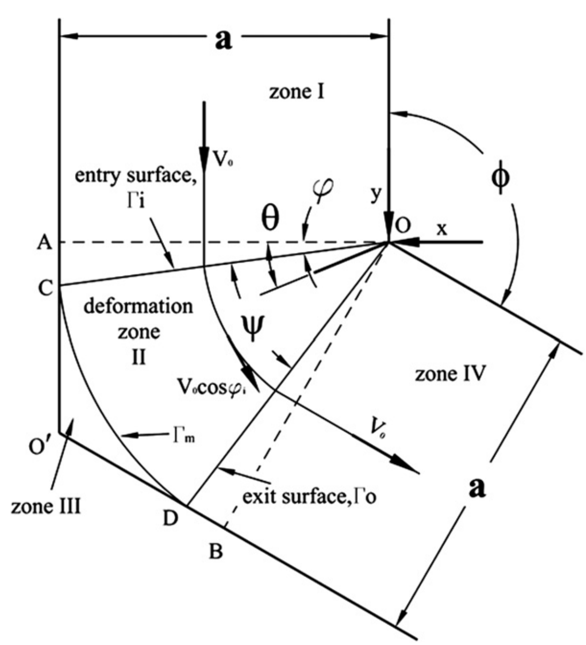

Fig. 1. The deformation model used in this study.

the origin at O, are also utilized when they are needed. The angle between the entry surface and the velocity in region I, and the exit surface and the velocity in region IV is chosen to be the same and is denoted by φ.

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

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

where $\upsilon_i\ (i = r, \theta, z)$ are the velocity field components in the deformation zone (region III). At the entry and exit surfaces the velocity undergoes a sudden change. The kinematical relations based on the principle of conservation of mass results in the velocity discontinuity on these surfaces as

$$|\upsilon_i| = |\upsilon_o| = V_0 \sin\varphi \tag{2}$$

where $|\upsilon_i|$ and $|\upsilon_o|$ are velocity discontinuities on the entry and exit surfaces of the deformation zone, respectively. The kinematical relations on the entry (Γ_i) and the exit (Γ_o) surfaces are shown in Fig. 2(a) and (b), respectively. The friction force along the surfaces AC and BD where the material is in contact with the die is modeled by $m\tau_0$ where τ_0 is the yield stress in shear and m, the friction coefficient, varies between 0 and 1.

2.1. Solution for the deformation zone

2.1.1. Deformation zone angle, dead metal zone formation and extrusion force

The components of strain rate in the deformation zone are obtained from the velocity field given in Eq. (1) as

$$\dot{\varepsilon}_{r\theta} = -\frac{1}{2}\frac{V_0 \cos\theta}{r} \tag{3}$$

In this equation $\dot{\varepsilon}_{r\theta}$ is the none-zero strain rate component in the deformation zone (Region III). The other components are equal to zero. Hence, it can easily be verified that this velocity field satisfies the incompressibility conditions given by

$$\dot{\varepsilon}_{rr} + \dot{\varepsilon}_{\theta\theta} + \dot{\varepsilon}_{zz} = 0 \tag{4}$$

where in this equation $\dot{\varepsilon}_{ii}\ (i = r, \theta, z)$ are the principal strain rate components. The power supplied to deform the material in the ECAE process is given by

$$J = FV_0 \tag{5}$$

where F is the force applied by the ram and V_0 the speed of the ram. The power dissipated during ECAE can be expressed as

$$\dot{W}_{\text{tot}} = \dot{W}_d + \dot{W}_i + \dot{W}_o + \dot{W}_m + \dot{W}_{W(AC)} + \dot{W}_{W(BD)} + \dot{W}_{l(i)} + \dot{W}_{l(o)} \tag{6}$$

In this equation $\dot{W}_{\text{tot}}$, $\dot{W}_d$, $\dot{W}_i$, $\dot{W}_o$, $\dot{W}_m$, $\dot{W}_{W(AC)}$, $\dot{W}_{W(BD)}$, $\dot{W}_{l(i)}$, and $\dot{W}_{l(o)}$ are the total power dissipated during ECAE, power dissipated in the deformation zone, power