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International Journal of Mechanical Sciences 50 (2008) 589–602
International Journal of MECHANICAL SCIENCES
www.elsevier.com/locate/ijmecsci

A computational study of die geometry and processing conditions effects on equal channel angular extrusion of a polymer

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Received 28 July 2006; received in revised form 18 July 2007; accepted 24 July 2007
Available online 1 August 2007

Abstract

Equal channel angular extrusion (ECAE) is an efficient process to obtain enhanced microstructures via super-plastic deformation. In view of its optimisation, it is of prime importance to assess the relationships between processing conditions and material flow. More precisely, detailed knowledge of the plastic strain distribution in the extruded material in relation to the ECAE processing variables is required. The key parameters of the ECAE process are primarily die geometry, ram speed, extrusion temperature, use of back-pressure, number of extrusion sequences and processing route (e.g. rotation of the sample between successive passes). A numerical investigation was achieved to check out the influence of these parameters on the homogeneity of plastic strain distribution in the case of a conventional thermoplastic polymer. Material parameters of a phenomenological elastic viscoplastic model were deduced from compressive deformation tests at different temperatures and strain rates on high-density polyethylene (HDPE). Recommendations on tool geometry and processing conditions can then be provided, according to the numerical results.

It was found that optimum ECAE die geometry is strongly material dependent. The application of a back-pressure significantly contributes to reduce the corner gap and consequently promotes the homogeneity of the plastic strain field. A slight sensitivity of plastic strain to ram speed and friction conditions was pointed out. The extrusion temperature strongly influences the magnitude of the plastic strain and has a slight effect on its homogeneity. The number of passes has a significant effect on the magnitude of the plastic strain but has a negligible influence beyond a certain temperature. The extruded material reaches a stationary strain state after few passes. The homogeneity of the plastic strain field is strongly affected by the processing route.

Keywords: ECAE; Polymers; Finite element analysis; Back-pressure; Multi-pass

1. Introduction

Equal channel angular extrusion (ECAE) is an innovative forming process to extrude materials without substantial change to their geometrical shape. The ECAE process, first developed by Segal [1,2], is shown schematically in Fig. 1. A key advantage of this process is that the sample cross-section is not modified after extrusion. So, it can be repeated to induce large cumulative plastic strains in the material. Moreover, by changing the orientation of the sample between successive extrusions, different microstructures can be generated in the material. Depending on the orientation for each pass, four fundamental ECAE routes are defined and used to achieve different objectives [3]: route A (no rotation between passes), route B_A (alternate 90° rotation), route B_C (consecutive 90° rotation) and route C (180° rotation). The equivalent plastic strain assigned to a sample as it passes through an ECAE die can be estimated using the analytical model developed by Iwahashi et al. [4]. In this relationship, the plastic strain depends upon the two angles Φ and Ψ defined in Fig. 1, as follows:

$$\varepsilon^p = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)+\Psi\,\mathrm{cosec}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right]. \qquad (1)$$

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doi:10.1016/j.ijmecsci.2007.07.012

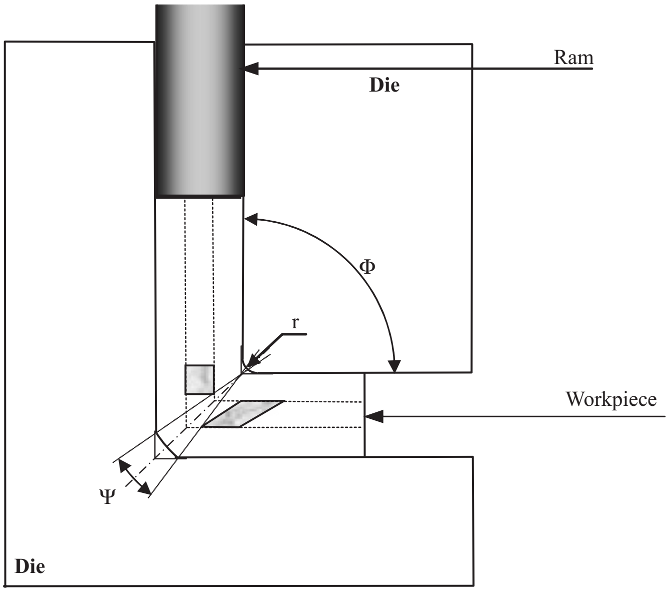

Fig. 1. Schematic illustration of the ECAE process showing the channel angle Φ, the outer corner angle Ψ and the inner radius *r*.

In order to optimise the process conditions, the knowledge of the plastic strain distribution in a given material is fundamental. Several analyses of ECAE process were made to investigate the plastic strain in the extruded material. These include geometric analysis [2,4,5], slip lines method [6–8], upper bound theory [9–11], visio-plasticity modelling [12,13] and finite element (FE) analysis [14–21]. These experimental, theoretical and numerical investigations were carried out for a large number of metallic materials. However, for polymeric materials, little work is available to address the mechanical behaviour during the ECAE process [22–31]. It is interesting to note that the ability of a polymer to achieve high toughness and ductility is linked to its microstructure [22]. In this respect, the ECAE process is a potential way to trigger significant morphological changes and hence induce profound modifications of the mechanical properties of the extruded materials. Complementary to the experimental work devoted to ECAE processing of polymers, further numerical work is required to optimise process parameters. In a previous paper [32], the present authors assumed elastic perfectly-plastic (PP) behaviour of the material in the ECAE process. In the present paper, the respective influences of die geometry and process conditions on plastic strain distribution are evaluated, using FE modelling. The effects of processing variables including die geometry, strain rate, friction, temperature, back-pressure and multi-pass extrusion are thoroughly analysed. The simulations were performed on the basis of the real behaviour of a typical semicrystalline polymer (high-density polyethylene: HDPE). For this purpose, experimental data obtained by compressive testing of this polymer at different temperatures and strain rates were used to identify the parameters of a constitutive elastic viscoplastic (VP) model. The experimental application of ECAE to HDPE was reported by Campbell and Edward [23]. They found that bending plays a significant role in the angular extrusion of this polymer in 135° die. In what follows, we shall rather emphasize on the evolution of plastic strain distribution when the polymer workpiece is extruded in 90° die in order to point out the effects of the die geometry and processing conditions during ECAE of polymers.

2. Material modelling

2.1. Constitutive law

The large strain behaviour of the polymer under study (HDPE) is characterized by a strain rate dependent yield followed by a strain hardening. Various VP models, based on physical [33–35] or purely phenomenological [36–38] considerations, were developed to intend to describe the particular mechanical behaviour of polymers. In this paper, a phenomenological constitutive model, detailed in this section, is used to describe specific behaviour of the studied material.

The strain rate tensor $\mathbf{d}$ is decomposed into an elastic part $\mathbf{d}^e$ and a VP part $\mathbf{d}^{vp}$ as

$$\mathbf{d} = \mathbf{d}^e + \mathbf{d}^{vp}. \tag{2}$$

The elastic strain rate tensor $\mathbf{d}^e$ is given by the hypo-elastic law:

$$\mathbf{d}^e = \mathbf{C}^{-1}\tilde{\boldsymbol{\sigma}}, \tag{3}$$

where $\tilde{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}} - \mathbf{W}\boldsymbol{\sigma} + \boldsymbol{\sigma}\mathbf{W}$ is the Jaumann derivative of the Cauchy stress tensor $\boldsymbol{\sigma}$ based upon the spin tensor $\mathbf{W}$ and $\mathbf{C}$ is the fourth-order isotropic elastic modulus tensor

$$C_{ijkl} = \frac{E}{2(1+\nu)}\left[\left(\delta_{ik}\,\delta_{jl} + \delta_{il}\,\delta_{jk}\right) + \frac{2\nu}{1-2\nu}\delta_{ij}\,\delta_{kl}\right]. \tag{4}$$

In Eq. (4), E, ν and δ are, respectively, Young's modulus, Poisson's ratio and Kronecker-delta symbol.

The VP strain rate tensor $\mathbf{d}^{vp}$ can be given by the following Norton-type power law equation:

$$\mathbf{d}^{vp} = \frac{3}{2}\left\langle\frac{\sigma_e - R}{K}\right\rangle^n \frac{\boldsymbol{\sigma}'}{\sigma_e}, \tag{5}$$

where $\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \mathrm{tr}(\boldsymbol{\sigma})/3\mathbf{I}$ is the deviatoric stress tensor, $\sigma_e = \sqrt{3/2\boldsymbol{\sigma}'\boldsymbol{\sigma}'}$ is the equivalent stress, K and n are the viscosity parameters and R is the isotropic hardening defined by a simple phenomenological evolution law:

$$R = h\left(1 + \frac{\varepsilon^p}{\varepsilon_0}\right)^m. \tag{6}$$

In relation (6), $\varepsilon^p = \int_0^t \dot{\varepsilon}^p d\tau = \int_0^t \sqrt{2/3\mathbf{d}^{vp}\mathbf{d}^{vp}}d\tau$ is the equivalent VP strain, ε_0 is the initial yield strain, m and h are the hardening parameters.

2.2. Fitting of experimental observations

Compressive tests were performed on an electromechanical Instron© testing machine under various strain rates