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ANALYSIS OF PLASTIC DEFORMATION OF SEMI-CRYSTALLINE POLYMERS DURING ECAE PROCESS USING 135° DIE

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In this paper, analysis of plastic deformation of high density polyethylene (HDPE) and polypropylene (PP) during an equal channel angular extrusion (ECAE) process is investigated. The effects of ram speed, number of passes, processing route and temperature are tested experimentally using a 135° die. The results show that the pressing force decreases with an increase in the number of passes and reaches a saturation state rapidly for routes A and C compared to routes B_A and B_C. Furthermore, it is found that the reduced curvature of the extruded samples is obtained by route C, however, the maximum warping is obtained by route A. A slight influence of temperature on the reduction of the warping is observed on the extruded samples. In order to predict the plastic strain inside the extruded samples, an elastic viscoplastic model is identified using compressive tests at different strain rates and coupled with the finite element method (FEM). A good correlation is found between the numerical modeling and experimental findings. FEM results show that the PP samples display a higher level of plastic strain compared to HDPE samples. However, almost the same degree of strain heterogeneity is obtained for both polymers. Finally, in order to reduce the warping and improve the strain homogeneity, a controlled back-pressure with small corner angle is expected to be an adequate solution.

Keywords: ECAE, polymers, finite element analysis, plastic strain, back-pressure

1. Introduction

Equal channel angular extrusion (ECAE) is an innovative process to improve physical and mechanical properties of materials by severe plastic deformation (SPD) without alteration of the geometric shape of workpiece. Moreover, since the cross-section of the workpiece is not modified after extrusion, the process can be repeated several times, and by changing the orientation of the workpiece between consecutive extrusions, stylish microstructures can be developed in the extruded materials. Up to now, the majority of research and development on ECAE have been conducted on metallic materials (Segal, 1995; Iwahashi *et al.*, 1996; Valiev and Langdon, 2006). However, for polymeric materials, little work is available to address the mechanical behaviour during ECAE process (Sue and Li, 1998; Campbell and Edward, 1999; Li *et al.*, 2000; Weon *et al.*, 2005; Wang *et al.*, 2006).

According to our knowledge, this process was first applied to polymers by Sue and Li (1998). They showed that the ECAE process is effective in altering the morphology of a linear low density polyethylene (LLDP). Sue *et al.* (1999) reported that for ECAE to be effective, it is necessary that the extrusion be held at temperatures slightly below the glassy transition in the case of polycarbonate (PC). For the same polymer, Li *et al.* (2000) confirmed that the mechanical properties can be tailored by extruding the material via various processing routes and a different number of passes.

The effect of molecular anisotropy on the impact strength of polycarbonate (PC) was examined by Xia *et al.* (2001a). They found that the enhancement of the impact resistance is directly related to the changes in molecular orientation induced by the ECAE process. According to Xia *et al.* (2001b), the crystallinity and molecular orientation were identified as two important factors affecting the dynamic mechanical properties of the ECAE-oriented semicrystalline polyethylene terephthalate (PET). An improvement of the bending and torsional storage modulus was found. Creasy and Kang (2005) studied fibre fracture during the ECAE process of short fibre-reinforced thermoplastics. They found that the fibre length can be controlled and oriented by setting the process temperature below the melting point of the polymer crystallites. On the other hand, the effect of different ECAE routes on the tensile, fracture toughness, flexural, and ballistic impact properties of polymethylmethacrylate (PMMA) was investigated by Weon *et al.* (2005). A fruitful discussion was reported by Wang *et al.* (2006) on lamellar formation and relaxation in simple sheared polyethylene terephthalate (PET) using the in-situ time resolved synchrotron Small-Angle X-ray Scattering (SAXS) technique. Recently, numerical and experimental investigations were achieved to highlight the effects of the main geometrical and processing parameters on the viscoplastic behaviour of polymers during the ECAE process (Zaïri *et al.*, 2008; Aour *et al.*, 2009; Bouaksa *et al.*, 2014).

The findings presented above show that the ECAE process is an effective tool for the improvement of mechanical properties of polymers by inducing molecular orientation in bulk polymers. This feature enables ECAE to have useful applications for the fabrication of many anti-impact components, such as fighter-jet canopies, vehicle structures, windshields, and anti-theft transparencies (Xia *et al.*, 2001a). Furthermore, the ECAE technique can be easily incorporated into the conventional polymer processing setup without much capital investment by attaching, for example, a conventional injection unit to the entrance channel, which can potentially be used for extruding pipes, tubes, rods, sheets, plates and other profiles with significantly improved physical and mechanical properties (Sue *et al.*, 1999).

In this paper, an experimental and numerical investigation of plastic deformation of two semicrystalline polymers (HDPE and PP) during the ECAE process using 135° die is presented. In order to achieve this objective, the paper is organised as follows. The experimental procedure is discussed in Section 2. Section 3 is focused on the presentation of the experimental results obtained for the effects of processing routes, number of passes and temperature. Section 4 is devoted to describe the elastic viscoplastic constitutive law and its identification using compressive tests at different strain rates. Section 5 is reserved for the presentation of the FEM results. A particular attention is made on the effect of the back-pressure on the homogeneity and the level of the plastic strain distribution into the extruded samples. Finally, some concluding remarks are given in Section 6.

2. Experimental procedure

2.1. ECAE device

After an optimization study of various geometrical parameters (Aour *et al.*, 2008), an ECAE device with a channel angle $\Phi = 135°$ and a corner angle $\theta = 34°$ has been designed and manufactured (Fig. 1a). The die consists of two square channels of cross-sectional area 10.1 mm×10.1 mm, which allows one to apply four routes (A, B_A, B_C and C) as shown in Fig. 1c. The lengths of the entrance and exit channels are respectively 75 mm and 50 mm. An electromechanical Istron 5800 testing machine has been used to extrude the samples through the angular die.

2.2. Processing routes

Figure 1b shows a set of material axes referred to the sample, which is useful in describing the different routes. The X-direction is the zero strain direction (transverse direction: TD), the

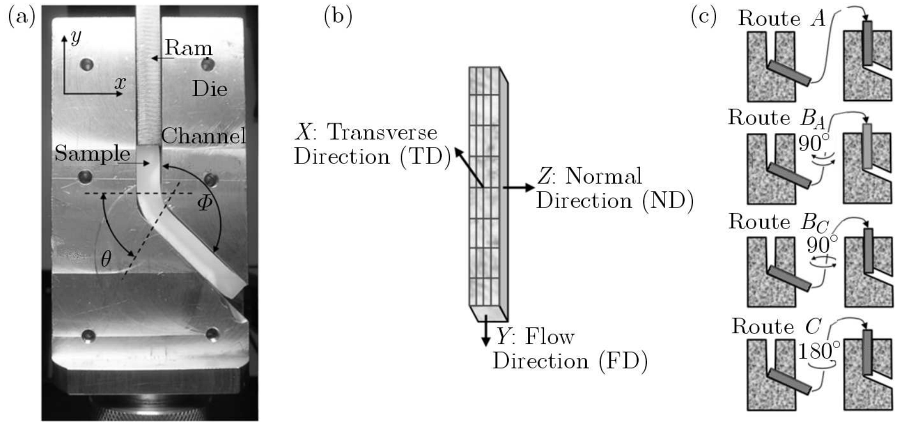

Fig. 1. (a) Photograph of the ECAE device; (b) diagram of the sample showing material axes used to describe different routes; (c) schematic illustration of the processing routes: A, B_A, B_C and C

flow direction (FD) is taken as the Y-direction, and the Z-direction (normal direction: ND) is normal to the plane in which the sample shear occurs. In this study, four different routes are investigated (Fig. 1c):

- Route A: the sample is re-inserted in the same orientation as the previous pass.
- Route B_A: the sample is rotated alternatively by +90° and −90° around the Y-axis between two successive passes.
- Route B_C: the sample is rotated by +90° around the Y-axis after each pass.
- Route C: the sample is rotated around the Y-axis by 180° and then re-extruded.

2.3. Materials and samples preparation

Two semi-crystalline polymers (high density polyethylene HDPE and polypropylene PP) have been selected for this study. These polymers have been supplied by the Goodfellow Company. The crystal content is about 70% for HDPE and 55% for PP. ECAE samples of 10 mm×10 mm cross-section and 70 mm in length have been cut from commercially plates in the same direction, then surfaced simultaneously on the cutting facets and polished. The HDPE and PP samples have been respectively annealed in vacuum at 120°C and 85°C for 2 h.

In this work, four parameters are studied experimentally: the ram speed, number of passes, processing route and temperature effect. The extrusion tests have been performed without lubrication.

3. Experimental results

3.1. Effect of ram speed

Figure 2 illustrates the influence of the ram speed on the evolution of the pressing force using a 135° die in the case of HDPE (Fig. 2a) and PP samples (Fig. 2b). Three different values of ram speeds (0.7, 0.07 and 0.007 mm/s) have been tested without lubrication.

It can be observed that the pressing force required for extrusion increases with an increase in the ram speed for both polymers. Indeed, when the ram speed is increased from 0.7 to 0.007 mm/s, the maximum force required for extrusion of HDPE samples varies from 932 to 1212 N (i.e., a difference of 280 N), however, for PP samples, a difference of 432 N is noticed. Furthermore, at the stage of the steady state of the plastic flow, different trends are revealed for each material. In the case of HDPE, the pressing force remains almost constant, however, in

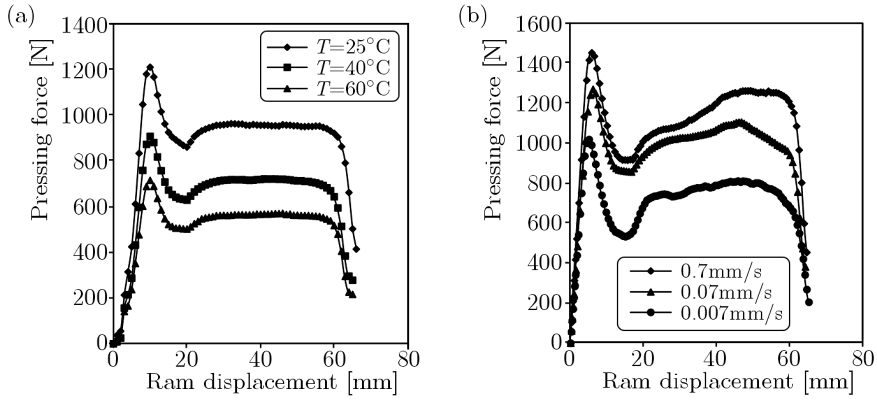

Fig. 2. Variation of the pressing force versus ram displacement in one ECAE pass using 135° die in the case of (a) HDPE and (b) PP samples

the case of PP, a slight increase is observed. This can be attributed to the flexibility of HDPE which is higher than that of PP.

3.2. Effect of the processing route and number of passes

The advantage of the ECAE process, in addition to maintaining constant cross-section of the extruded sample throughout the process, it is possible to generate a number of dissimilar deformation histories and create various forms of molecular orientations if multiple passes with a suitable selection of processing routes are carried out. It was demonstrated by Li *et al.* (2000) that well-controlled morphology can lead to great improvements in physical and mechanical properties of the extruded polymer both along and perpendicular to the extrusion direction. In this subsection, the samples are processed via four ECAE processing routes using a 135° die at room temperature and a ram speed of 0.70 mm/s. In order to make a comparison between the different routes, the evolution of the maximum pressing force versus the number of passes is plotted in Fig. 3. It can be seen that, for routes A and C, the pressing force decreases with an increase in the number of passes, however in the case of routes B_A and B_C, a periodic variation is noticed for HDPE samples, and a random variation is highlighted for PP samples. These variations explain that the materials have different strengths in each direction due to anisotropy and mobility of the crystalline lamellae inside the bulk material with respect to ECAE loading. Moreover, it can be observed that the routes A and C reach their saturation values after almost four passes, while the routes B_A and B_C require a high number of passes to achieve its saturation state.

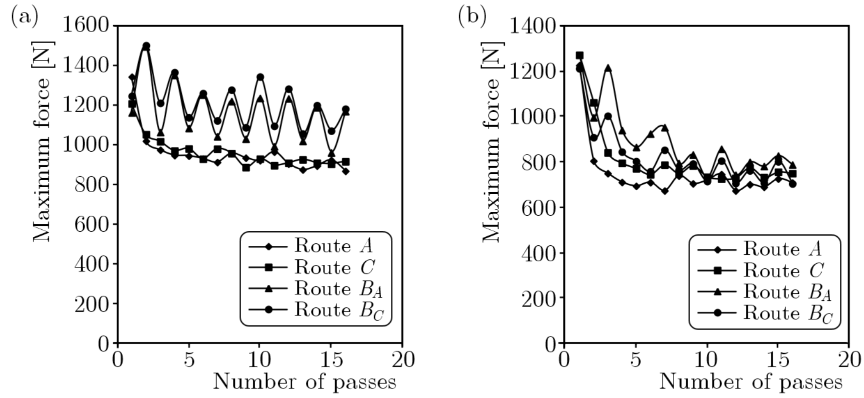

Fig. 3. Variation of the maximum force versus the number of passes during extrusion through a 135° die with different routes for (a) HDPE and (b) PP samples

The warping of the extruded samples due to various processing routes has been also quantified in this experimental part. Figure 4 shows pictures of HDPE samples that have undergone sixteen passes of ECAE by different processing routes. The obtained results for HDPE and PP samples are listed in Table 1. The maximum curvature of the sample (warping) has been quantified by measuring the height of the sample before and after the ECAE process. For both polymers, it has been found that the maximum warping is always obtained by route A, however the minimum warping is obtained by route C. Furthermore, the warping obtained for PP samples is quite high than that of HDPE samples.

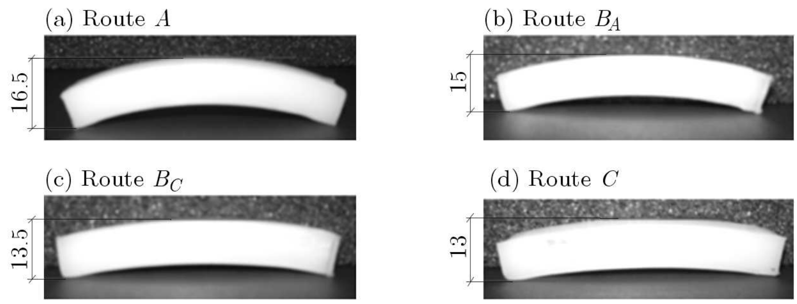

Fig. 4. HDPE samples extruded at room temperature after 16 passes using a 135° die with different processing routes

Table 1. Maximum values of the curvature obtained by different routes using a 135° die and a length of 70 mm after 16 passes on HDPE and PP samples

Route	Extruded material	Height before ECAE H_b [mm]	Height after 16 ECAE passes: H_a [mm]	Curvature $Cu = H_a - H_b$ [mm]
A	HDPE	9.85	16.50	6.65
	PP	9.77	17.20	7.43
B_A	HDPE	10.17	15.00	4.83
	PP	9.29	13.50	4.21
B_C	HDPE	10.13	13.50	3.37
	PP	9.13	13.25	4.12
C	HDPE	9.72	13.00	3.28
	PP	9.65	13.15	3.50

3.3. Effect of temperature

According to Sue *et al.* (1999), the warping is generated due to the existence of residual stress and the concurrent stress relaxation process on the extruded samples. Moreover, it is believed that the stress relaxation process can be greatly accelerated at elevated temperatures. Consequently, in order to highlight the temperature effect on the warping reduction by stress relaxation, the ECAE process has been carried out on HDPE samples at different temperatures $T = \{25°\text{C}, 40°\text{C}, 60°\text{C}\}$ via routes A and C. The obtained results after sixteen passes are illustrated in Table 2.

It can be seen that a slight reduction of warping is obtained even with several passes and at elevated temperatures. Noting that, in the case of PC samples, a significant reduction of warping was found by Sue *et al.* (1999) via elevation of the extrusion temperature. However, in the case of HDPE and PP, it is advised to test other parameters such as the use of back pressure which will be the subject of the last Section.

Table 2. Maximum values of the curvatures of HDPE samples obtained after 16 passes using a 135° die via routes A and C at $T = \{25°\text{C}, 40°\text{C}, 60°\text{C}\}$

Route	Temperature [°C]	Height before ECAE H_b [mm]	Height after 16 ECAE passes: H_a [mm]	Curvature $Cu = H_a - H_b$ [mm]
A	25	9.85	16.50	6.65
	40	9.87	16.50	6.63
	60	9.80	15.00	5.20
C	25	9.72	13.00	3.28
	40	9.72	13.00	3.28
	60	9.75	12.50	2.75

4. Elastic-viscoplastic constitutive model

The constitutive equations governing the behaviour of polymers under the ECAE process loadings must take into account complex phenomena such as viscoplasticity, hardening, relaxation and strain memory effect. These phenomena were studied by many authors basing on physical (Arruda *et al.*, 1995; Ahzi *et al.*, 2003; Bouaksa *et al.*, 2014) or purely phenomenological (Chaboche, 1997; Ho and Krempl, 2002; Colak, 2003) considerations. In this paper, a phenomenological constitutive model based upon Chaboche's model is applied (Lemaitre and Chaboche, 1994; Ambroziak and Klosowski, 2006). This model incorporates the initial linear response, the non-linear behavior and the rate-dependent yield stress.

4.1. Constitutive equations

One of the fundamental principles that all constitutive equations have to satisfy is the principle of objectivity. Tensor rates used in the constitutive equations need to be objective. A corotational objective rate of a tensor $\mathbf{M}$ is denoted by

$$\widehat{\mathbf{M}} = \dot{\mathbf{M}} + \mathbf{M}\boldsymbol{\Omega} - \boldsymbol{\Omega}\mathbf{M} \tag{4.1}$$

where $\dot{\mathbf{M}}$ is the material rate with respect to the basis of $\mathbf{M}$. $\widehat{\mathbf{M}}$ is the objective rate of $\mathbf{M}$, and $\boldsymbol{\Omega}$ is a skew-symmetric spin tensor. A well-known objective rate is the Jaumann rate. It is obtained by setting $\boldsymbol{\Omega} = \mathbf{W}$ in Eq. (4.1)

$$\widehat{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}} + \boldsymbol{\sigma}\mathbf{W} - \mathbf{W}\boldsymbol{\sigma} \tag{4.2}$$

where $\widehat{\boldsymbol{\sigma}}$ is the objective rate of the Cauchy stress tensor $\boldsymbol{\sigma}$ based upon the spin tensor $\mathbf{W}$.

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

$$\mathbf{D} = \mathbf{D}^e + \mathbf{D}^{vp} \tag{4.3}$$

The elastic strain rate tensor $\mathbf{D}^e$ is given by the hypoelastic law

$$\mathbf{D}^e = \mathbf{C}^{-1}\widehat{\boldsymbol{\sigma}} \tag{4.4}$$

where $\mathbf{C}$ is the fourth-order isotropic elastic modulus tensor

$$C_{ijkl} = \frac{E}{2(1+\nu)}\Big[(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) + \frac{2\nu}{1-2\nu}\delta_{ij}\delta_{kl}\Big] \tag{4.5}$$

with E, ν and δ are respectively Young's modulus, Poisson's ratio and the Kronecker-delta symbol.

The viscoplastic strain rate tensor $\mathbf{D}^{vp}$ can be written by

$$\mathbf{D}^{vp} = \frac{3}{2}\dot{p}\frac{\boldsymbol{\sigma}' - \mathbf{X}'}{J(\boldsymbol{\sigma} - \mathbf{X})} \tag{4.6}$$

where $J(\boldsymbol{\sigma} - \mathbf{X})$ is a distance in the stress space. For a material meeting the Von Mises criterion, we use

$$J(\boldsymbol{\sigma} - \mathbf{X}) = \sqrt{\frac{3}{2}(\boldsymbol{\sigma}' - \mathbf{X}') : (\boldsymbol{\sigma}' - \mathbf{X}')} \tag{4.7}$$

where $\boldsymbol{\sigma}$ and $\mathbf{X}$ are the stress and back stress tensors, and $\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \operatorname{tr}(\boldsymbol{\sigma})/3\mathbf{I}$ and $\mathbf{X}'$ are the stress and back stress deviatoric tensors in the stress space, respectively. $\dot{p}$ is the equivalent viscoplastic strain rate written as

$$\dot{p} = \Big\langle \frac{J(\boldsymbol{\sigma} - \mathbf{X}) - R - k}{K} \Big\rangle^n \tag{4.8}$$

The brackets are defined by $\langle w \rangle = wH(w)$, where $H(w)$ is the Heaviside function ($H(w) = 0$ if $w < 0$, $H(w) = 1$ if $w \geqslant 0$). k is the yield stress at zero plastic strain, K is the viscoplastic resistance, n is the rate sensitivity coefficient and R is the isotropic internal stress or the drag stress.

The strain hardening of the material is described by isotropic and kinematic hardening rules which allow both the expansion and translation of the yield.

The isotropic hardening rule is defined by

$$\dot{R} = b(R_1 - R)\dot{p} \qquad \text{with} \qquad R(0) = 0 \tag{4.9}$$

where R_1 is the boundary of isotropic hardening and b defines the rate at which the size of the yield surface changes as the plastic straining develops.

Equation (4.9) may be replaced by its integrated form as (Lemaitre and Chaboche, 1994)

$$R = R_1[1 - \exp(-bp)] \tag{4.10}$$

The nonlinear kinematic hardening is defined from the linear-Ziegler rule by adding the recall term as shown in the evolution of the back stress tensor below (MSC.Marc, 2005)

$$\dot{\mathbf{X}} = \frac{C}{R + k}(\boldsymbol{\sigma} - \mathbf{X})\dot{p} - \gamma\mathbf{X}\dot{p} \qquad \text{with} \qquad \mathbf{X}(0) = 0 \tag{4.11}$$

where C and γ are two material constants. $\gamma = 0$ stands for the linear-kinematic rule.

The evolution law given by (4.11) may be formulated in terms of the objective rate of the back stress $\mathbf{X}$, say $\widehat{\mathbf{X}}$, as follows (Bruhns, 2009)

$$\widehat{\mathbf{X}} = \mathbf{K}(\boldsymbol{\tau}, \mathbf{X}, \kappa) : \mathbf{D}^{vp} \tag{4.12}$$

where $\mathbf{K}(\boldsymbol{\tau}, \mathbf{X}, \kappa)$ is a 4th order tensor-valued constitutive function, $\boldsymbol{\tau}$ is the Kirchhoff stress and κ is a scalar internal variable.

4.2. Identification of the material parameters

The material parameters $(E, k, K, n, b, R_1, C, \gamma)$ of the elastic-viscoplastic constitutive law have been identified from a least-square regression fitting using the experimental data of compression tests on HDPE and PP specimens at room temperature and under different strain rates (Aour, 2007). The values of the identified parameters for the studied polymers are listed in Table 3. Figure 5 shows a fairly good agreement between the identified constitutive model and experimental stress-strain curves of HDPE and PP. Indeed, the constitutive law is able to reproduce three main features of the behaviour: the linear elastic response, the rollover to yield and the post-yield response.

Table 3. Values of material parameters for HDPE and PP

Parameter	Unit	Values for HDPE	Values for PP
E	MPa	500	1100
ν	–	0.38	0.4
k	MPa	10	10
K	MPa	15.6	30.2
n	–	5.2	6.9
b	–	40	65
R_1	MPa	10	18
C	MPa	50	15
γ	–	−1.1	−3.2

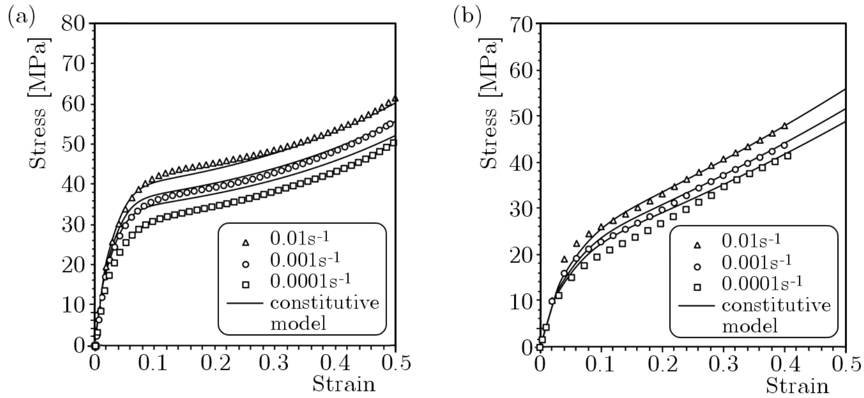

Fig. 5. Stress-strain curves obtained by compression tests and the constitutive model for (a) HDPE and (b) PP at room temperature and different strain rates

5. Finite element results

In order to predict the plastic deformation behaviour of HDPE and PP samples during the ECAE process, finite element simulations have been carried out using the software MSC.Marc© under plane-strain conditions. The die geometry, sample dimensions and processing conditions have been taken similar to those used in the experimental study. The sample has been meshed with 2800 four-node isoparametric elements. The die and the ram have been assumed to be rigid.

5.1. Estimation of the pressing force during ECAE

Figure 6 shows a comparison between the experimental pressing force-ram displacement curves and the finite element results using different friction coefficients for the extrusion of HDPE and PP samples through a 135° die at a ram speed of 0.70 mm/s. The friction conditions between the tooling and the samples are modelled using Coulomb's friction law. As shown in Fig. 6, the FEM results are closer to the experimental data when the friction coefficient is equal to 0.075 for HDPE and 0.025 for PP. It is worth noting that the damage mechanisms, which occur at the elbow of the die (plastic deformation zone), have not been modelled in the present constitutive model. Thus, the comparison is only made for the stage of steady state of the material flow during the ECAE process.

5.2. Estimation of the equivalent plastic strain

Figure 7 shows the equivalent plastic strain contour plots of HDPE and PP samples during the ECAE process with a ram speed of 0.70 mm/s considering the friction coefficients which

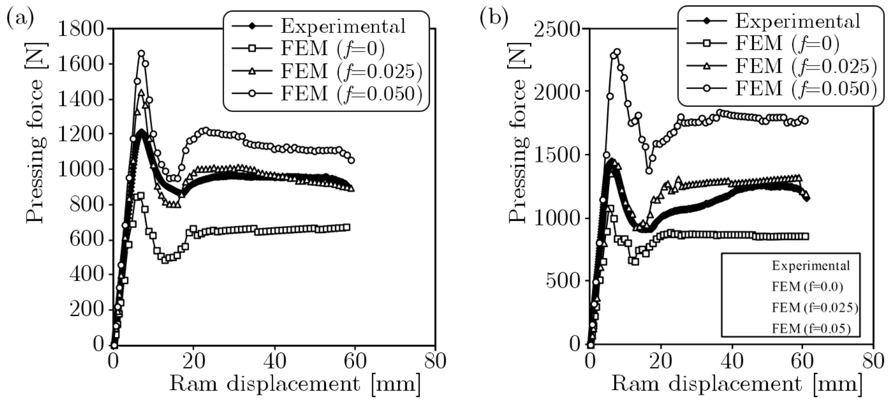

Fig. 6. Comparison between the experimental curve and FEM results using different friction coefficients in the case of (a) HDPE and (b) PP

gave the best agreement with the experimental results, i.e., $f = 0.075$ for HDPE and $f = 0.025$ for PP. It can be observed that the plastic strain is not uniform along width of the samples for both polymers. It should be noted that the effective plastic strain generally decreases from the top surface to the bottom surface of the samples. This can be attributed to the presence of the bending mechanisms since the inner part of the sample flows faster than the outer part. In other words, the deformation mechanism in the bottom region is rather bending than shear. Furthermore, it can be seen that the fronts of the extruded samples have not undergone a high level of plastic deformation. This is mainly due to the filling status of the channel when the sample passed through the elbow.

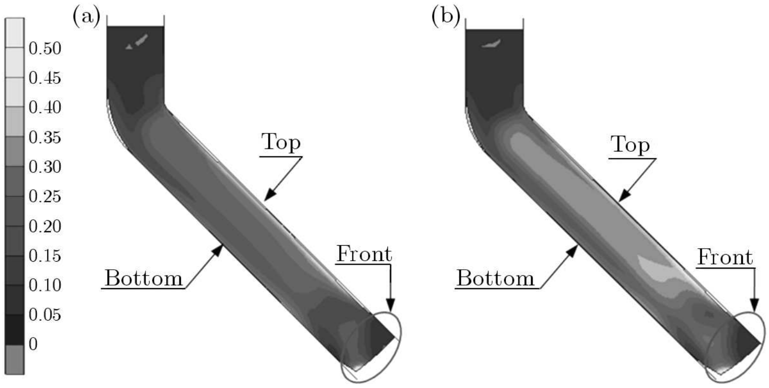

Fig. 7. Equivalent plastic strain contours for ECAE of (a) HDPE and (b) PP samples using a 135° die

In order to quantify the degree of strain homogeneity inside the sample, the distribution of the equivalent plastic strain along the sample width at the steady state region is presented in Fig. 8. It can be seen that the equivalent plastic strain in the PP sample is higher than that of the HDPE sample. However, almost the same degree of strain heterogeneity is obtained for both polymers, since the variation factor is 24% for HDPE and 22% for PP. Noting that the variation factor denoted by V is defined as the ratio of the standard deviation s to the average equivalent plastic strain ε^p_{ave} (Aour *et al.*, 2006)

$$V = \frac{s}{\varepsilon^p_{ave}} = \frac{1}{\varepsilon^p_{ave}} \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\varepsilon^p_i - \varepsilon^p_{ave})^2} \cdot 100\% \tag{5.1}$$

where ε^p_i is the equivalent plastic strain value at a given integration point along the sample width, ε^p_{ave} is the arithmetic average of the equivalent plastic strain values computed on N integration points.

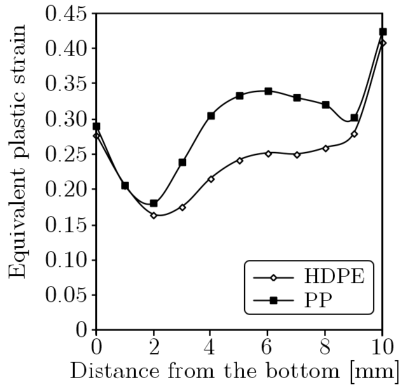

Fig. 8. Distribution of the equivalent plastic strain in HDPE and PP samples extruded by a 135° die

5.3. Equivalent plastic strain rate

It is recognized that the stress-strain behaviour of polymers is strongly dependent on the strain rate due to the viscoplastic nature of polymers (Ward and Hadley, 1995). In order to highlight the spatial variation of the plastic strain and the trends in the degree of homogeneity, the strain rate distribution within the plastic deformation zone (PDZ) is addressed here. Indeed, the more the plastic deformation rate is uniform along the shear plane, the greater is the degree of homogeneity of the plastic deformation into the sample. Figure 9 shows the distribution of the equivalent plastic strain rate $\dot{\varepsilon}^p$ at an intermediate stage of the ECAE process using a 135° die for HDPE and PP samples. It can be seen that the distribution of $\dot{\varepsilon}^p$ inside the PDZ is neither uniform nor symmetrical with respect to the shear plane, which justifies the heterogeneity of the plastic strain distribution. Furthermore, it can be observed that this later decreases significantly from the inner corner to the outer corner. This aspect can be allotted to the coupled effect of the viscoplastic behaviour and geometrical features of the die.

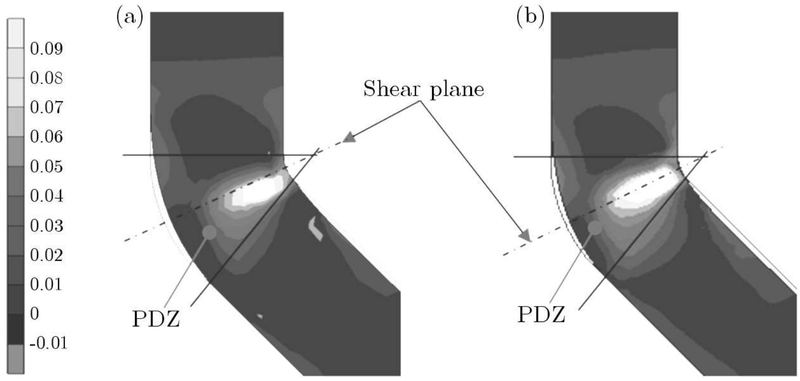

Fig. 9. Distribution of the equivalent plastic strain rate inside (a) HDPE and (b) PP samples during the ECAE process using a 135° die

5.4. Effect of the back-pressure

In order to improve the degree of the plastic strain homogeneity and reduce the warping of the samples, the application of back-pressure seems to be a suitable solution. It consists in applying a constant load to the sample front at the exit channel using a second ram. The obtained results for the equivalent plastic strain distribution along width of the HDPE sample by applying different values of back-pressure are shown in Fig. 10. It can be seen that a significant improvement in plastic strain homogeneity is obtained when the corner angle $\theta = 5°$ and the back-pressure $P = -500\,\mathrm{N}$ (Fig. 10a), however, when $\theta = 34°$, a slight effect is highlighted (Fig. 10b). Indeed, when $\theta = 5°$, the variation factor is reduced by 11% (from $V_{(P=0\,\mathrm{N})} = 28\%$ to $V_{(P=-500\,\mathrm{N})} = 17\%$), however, when $\theta = 34°$, the variation factor is reduced by 4% (from $V_{(P=0\,\mathrm{N})} = 24\%$ to $V_{(P=-500\,\mathrm{N})} = 20\%$). Consequently, in order to improve the plastic strain homogeneity, it is advised to use a low outer corner angle with an adequate back-pressure. This allows one to promote shearing deformations and reduction of the bending mechanisms.

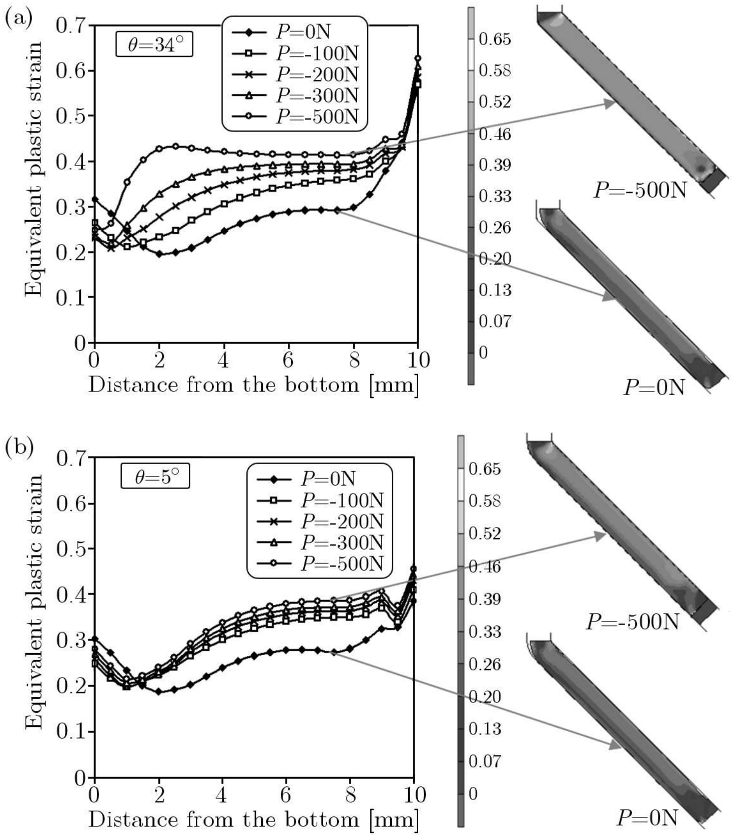

Fig. 10. Effect of back-pressure on the evolution of equivalent plastic strain in the case of a 135° die

6. Conclusion

In this study, the effects of ram speed, processing route, number of passes, temperature and back-pressure on HDPE and PP behaviour during the ECAE process using a 135° die are investigated by experimental testing and finite element modeling. The following conclusions can be drawn:

- It is found that the pressing force required for extrusion increases with an increase in the ram speed, and the pressing force of PP samples is about 200 N higher than that of HDPE.
- For both polymers, the significant reduction of warping is obtained by route C, whereas, the maximum warping is obtained by route A.
- It is found that the pressing force decreases significantly with an increase in temperature, while a slight reduction of warping is observed as the extrusion temperature is increased.
- A good agreement is noticed between the experimental curves and the FEM results when the friction coefficients are equal to 0.075 for HDPE and 0.025 for PP. This allows one to carry out the ECAE process without a lubricant.

- It is found that PP samples display a higher level of plastic strain than HDPE samples. However, almost the same degree of strain heterogeneity is obtained for both polymers.
- The distribution of the equivalent plastic strain rate inside PDZ is found to be neither uniform nor symmetrical about the shear plane.
- It is expected that the use of a low corner angle with an adequate back-pressure can effectively reduce the warping and improve the strain homogeneity as well as the level of shear deformation.

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