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Analysis of HDPE behavior during two equal channels angular pressing using 120° DIE

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Abstract

In this work, an analysis of the high density polyethylene behavior during two turn Equal Channel Angular Extrusion (2-ECAE) has been investigated by finite element using 90° and 120° dies. To this end, the material parameters of an elasto-viscoplastic phenomenological model were derived from compressive tests at different temperatures and strain rates. A good agreement was found between the identified model and experimental results. Then, the effects of the channel angles, the length and thickness of the intermediate channel, the fiction and the temperature on the equivalent plastic strain and the pressing force have been analyzed. Recommendations on process conditions were proclaimed at the end of this work.

Keywords: ECAE, HDPE, Finite element, Temperature, Friction.

1. Introduction

Equal channel angular Extrusion (ECAE) has attracted a great deal of interest primarily due to the substantial microstructural changes it imparts on the extruded samples. It is a method through which large plastic strain can be introduced in a work piece by simple shear without changing it cross-sectional dimensions. First developed by Segal [1], this method has been proved to be very effective in producing ultrafine grain size in polycrystalline materials [2, 3]. Recently, it was applied for polymeric materials by several authors in order to improve the material properties by super plastic deformation of shear. It has been experimentally studied for some amorphous glassy polymers, such as polycarbonate [4,5] and polymethyl-methacrylate[6] or semi-crystalline polymers, such as polyethylene [7, 8], poloypropylene [9], polyethylene terephthalate [5,10] and a reinforced semi-crystalline polymer [11]. However, up to now, the majority of investigations have been conducted on one ECAE die. There are very few numerical investigations of ECAE process and there is not yet a tool design guidelines for 2-ECAE, especially when dealing with polymer materials. Therefore, an analysis of the strain homogeneity in deformed polymers during 2-ECAE process is addressed in this work.

In order to improve the plastic strain homogeneity and circumvent the drawbacks of the traditional ECAE process (the appearance of the cracking phenomenon in certain metallic alloys [12] and obtaining a curvature relatively significant for polymeric materials [4,13], an optimisation of a die geometry composed of two elbows has been investigated in this paper. The general principle of 2-ECAE process is shown in Fig. 1. The tool is a block containing three intersecting equal cross-section channels. A sample which is placed into the entrance channel is extruded through the exit channel by a punch. Under these conditions, the sample passes by two elbows in one pass. The respective influence of the processing variables, such as die geometry and processing conditions, which control the distribution of plastic strain, have been highlighted on 90° and 120° dies.

The present paper is organized as follows. In the second and the third sections, we have presented respectively the constitutive law and the identification of the material parameters, which must be used in the simulation of ECAE process. For this purpose, compressive tests at different strain rates and temperatures on a typical semi-crystalline polymer (high-density polyethylene HDPE) were used. Section 4 introduces details on the finite element modelling. Then, the effects of the potential processing variables, such as the die geometry (channel angle, length and thickeness of the second channel) and processing conditions friction and temperature) have undergoes a detailed analysis in sections 5. Finally, section 6 gives the main remarks.

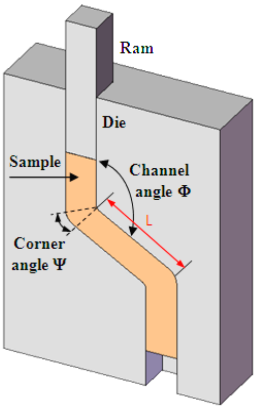


Fig. 1: Schematic illustrations of two turn equal channel angular extrusion process.

2. Constitutive model

The large plastic deformation of the polymer under study (HDPE) is characterized by a strain rate dependent yield followed by a strain hardening. Various constitutive laws, basing on micromechanical or phenomenological considerations [14, 15], were developed to describe the specific behavior of polymers. In this paper, a phenomenological constitutive model was used to describe the behavior of the studied material [16]. It is based on the additive decomposition of the strain rate tensor d into an elastic part d^e and a viscoplastic part d^{vp} as:

$$d=d^e+d^{vp} \tag{1}$$

The elastic strain rate tensor d^e is given by:

$$\mathbf{d}^e=\mathbf{C}^{-1}\tilde{\boldsymbol{\sigma}} \tag{2}$$

$$\tilde{\boldsymbol{\sigma}}=\dot{\boldsymbol{\sigma}}-\mathbf{W}\boldsymbol{\sigma}+\boldsymbol{\sigma}\mathbf{W} \tag{3}$$

Where $\tilde{\boldsymbol{\sigma}}$, the Jaumann derivative of the Cauchy stress tensor, is $\boldsymbol{\sigma}$ based upon the spin tensor $\mathbf{W}$; and $\mathbf{C}$ is the fourth-order isotropic elastic modulus tensor:

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

E, ν and δ are respectively Young's modulus, Poisson's ratio and Kronecker-delta symbol. The viscoplastic strain rate tensor d^{vp} can be expressed by the following relationships:

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

$$\boldsymbol{\sigma}'=\boldsymbol{\sigma}-tr(\boldsymbol{\sigma})/3\mathbf{I} \tag{6}$$

$$\sigma_e=\sqrt{3/2\sigma'\sigma'} \tag{7}$$

where K and n are the viscosity parameters, $\boldsymbol{\sigma}'$ is the deviator stress tensor, σ_e the equivalent stress, and R the isotropic hardening defined by a simple phenomenological evolution law as follows:

$$R=h\left(1+\frac{\varepsilon^p}{\varepsilon_0}\right)^m \tag{8}$$

$$\varepsilon^p=\int_0^t\dot{\varepsilon}^p d\tau=\int_0^t\sqrt{2/3\mathbf{d}^{vp}\mathbf{d}^{vp}}\,d\tau \tag{9}$$

with ε^p the equivalent viscoplastic strain, ε_0 the initial yield strain, m and h the hardening parameters.

3. Fitting experimental date

Fitting experimental date in order to simulate the elasto-viscoplastic behavior of HDPE during 2-ECAE process, a series of compressive tests at different temperatures (T=25, 40, 60 and 80°C) and strain rates (10^{-2}, 10^{-3} and 10^{-4} s^{-1}) were carried out to determine the parameters of the constitutive model presented in the previous section. Indeed, In addition to the Young's modulus and Poisson's ratio, the constitutive equations contain four parameters to be determined:

- K and n : The viscosity parameters;
- m and h : The hardening parameters.

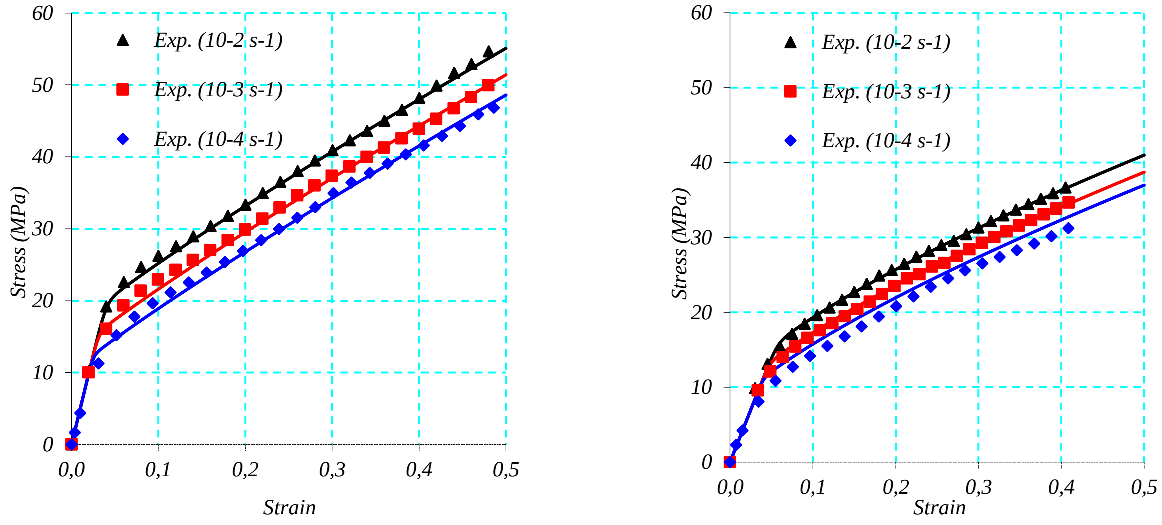
The experimental tests have been performed on an electromechanical Instron testing machine using cylindrical samples of 10mm (diameter)*20*mm* (length). During the tests, the values of displacement, loads and time were recorded by the computer using Bluehill software. It is worth noting that Young's modulus E was obtained at low stresses and strains and Poisson's ratio ν was fixed to 0.38. The parameters *K*, *n*, *m* and *h*were determined using a least squares regression fitting and their values are presented in table1.

Tableau 1
The material parameters for HDPE at different temperatures

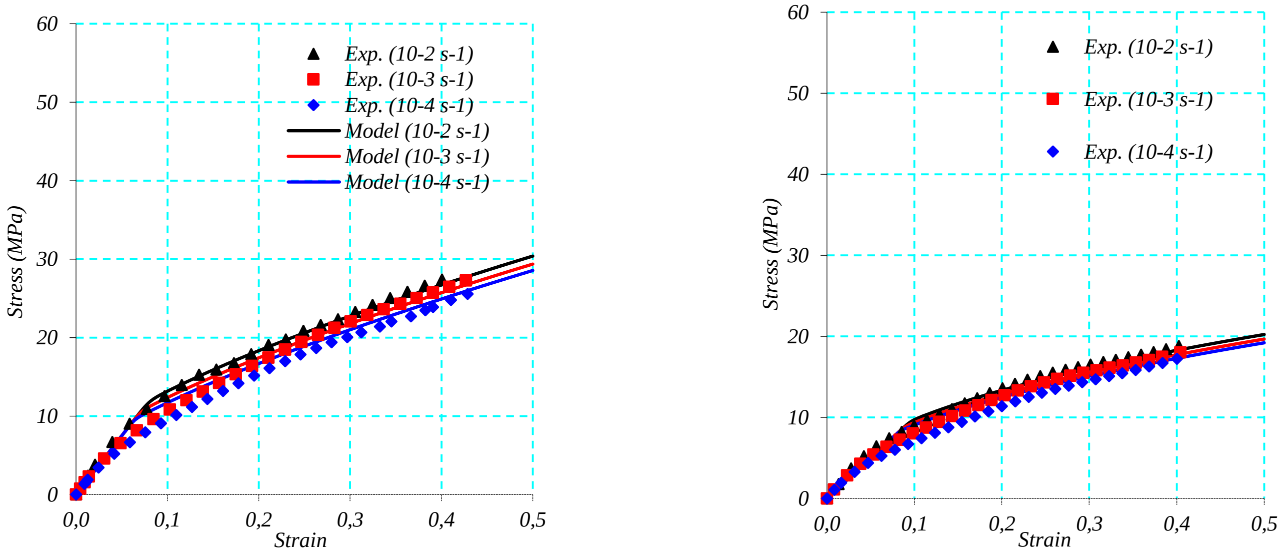
T (°C)	**E (MPa)**	**K (MPa)**	**n (-)**	**h (MPa)**	**m (-)**
25	500	31.2	7.80	3.15	0.88
40	280	20.0	8.30	5.00	0.70
60	150	10.7	10.20	5.50	0.65
80	130	5.7	11.17	6.00	0.45

Figure 2 gives the comparison between theexperimental data (in symbols) and theelasto-viscoplasticconstitutive model (in solid lines) for HDPE at for various temperatures.

It is also noteworthy that, since the model does not include the viscosity effect, an average value of E was adopted for each temperature in the numerical computations.



a: Room temperature (25°C)b: 40 °C



c: 60°Cd: 80°C

Fig.2: Stress-strain curves of HDPE for various temperatures:

4. Finite element modeling

The simulations were carried out using the finite element software MSC.Marc under plane-strain conditions. The sample dimensions were 10mm (width)×10mm(thickness) ×110mm (length). Initially, the die geometry was taken with channel angle $\Phi_1 = \Phi_2 = \Phi = 120°$Cand the two outer corners angles have been fixed to 10°. A radii r = 2*mm* has been taken at the inner corners. Noting that, these values, have been selected according to the previous study undertaken by Aour et al. [17]. Initially, the friction coefficient between the sample and the die channels was assumed to be zero, implying frictionless condition (for the first tests).

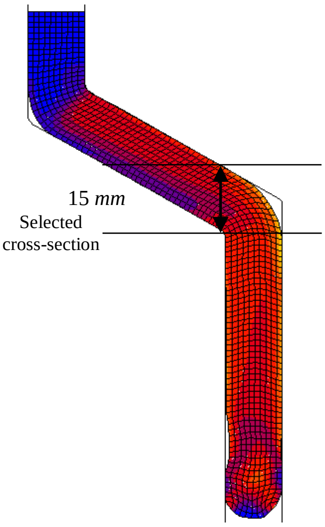


Fig. 3: Illustrations of the finite element mesh of the sample and the selected cross-section for the measurement (120° die).

The die and the ram were considered as rigid bodies in the modeling. A displacement of 110mm was assigned to the ram in the extrusion direction. According to the theoretical and experimental analyses, the isothermal condition can be fulfilled at low pressing speeds. So, all simulations were performed with a ram speed of 0.1mm/s, which generates negligible heat due to the plastic deformation [17]. The sample behaviour was considered as being elastic-viscoplastic. In order to control the plastic strain distribution, the selected cross-section was taken at 15*mm* below the second inner corner (see Fig. 3).

5. Results and discussion

5.1. Equivalent plastic strain distribution

In ECAE process the homogeneity of the plastic strain distribution in the bulk material during successive passes is very important. The aim of this section is to determine the optimal conditions which allow us to improve the homogeneity of the plastic strain distribution in terms of the thickness (t) and the length (L) of the second channel for the two-elbow tool.

Figure 4 shows the evolution of the equivalent plastic strain in terms of the distance from the bottom along the selected cross-section of the sample for each thickness with different lengths of the second channel. It can be seen that the low equivalent plastic strain is obtained with a length of 50*mm* for all four cases. However, the greatest plastic deformation is obtained with a length of 20 *mm* for t = 10 or 12 *mm* while for t=6 and 8 *mm* the greatest deformation is obtained for a length of 30 *mm*.

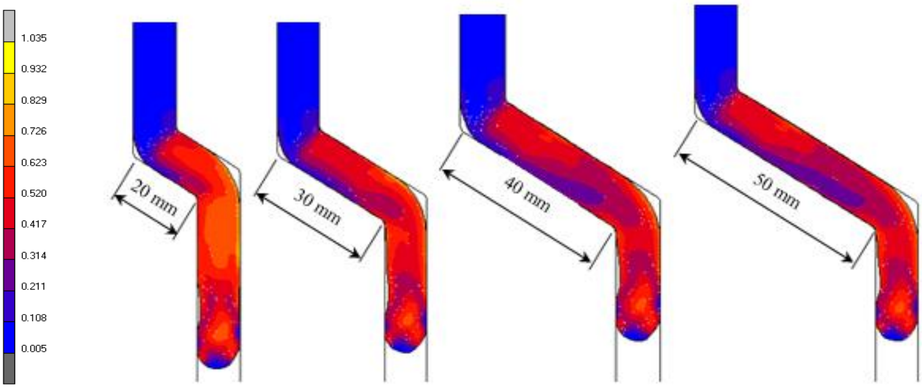
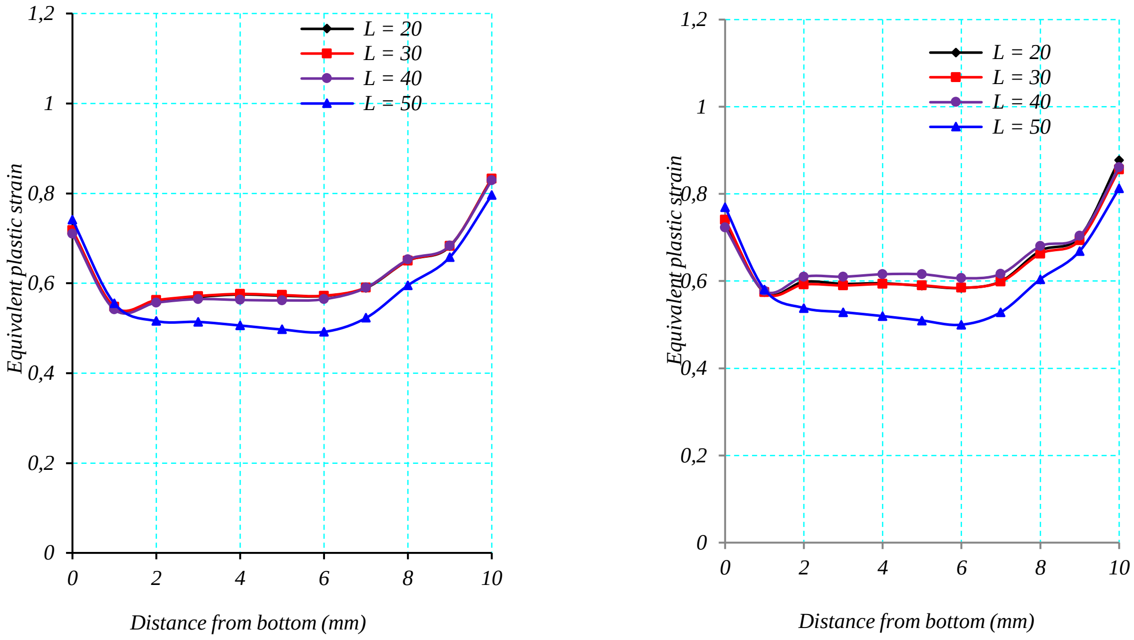


Fig. 4: Equivalent plastic strain contours for HDPE samples during 2-ECAE process using 120° die for different lengths of the second channel

In order to quantify the degree of the plastic strain homogeneity, a statistical analysis has been carried out on the average value of the equivalent plastic strain. The statistical analysis is made by introducing the standard deviation and the variation factor *V*, defined as the ratio of the standard deviation to the average strain,

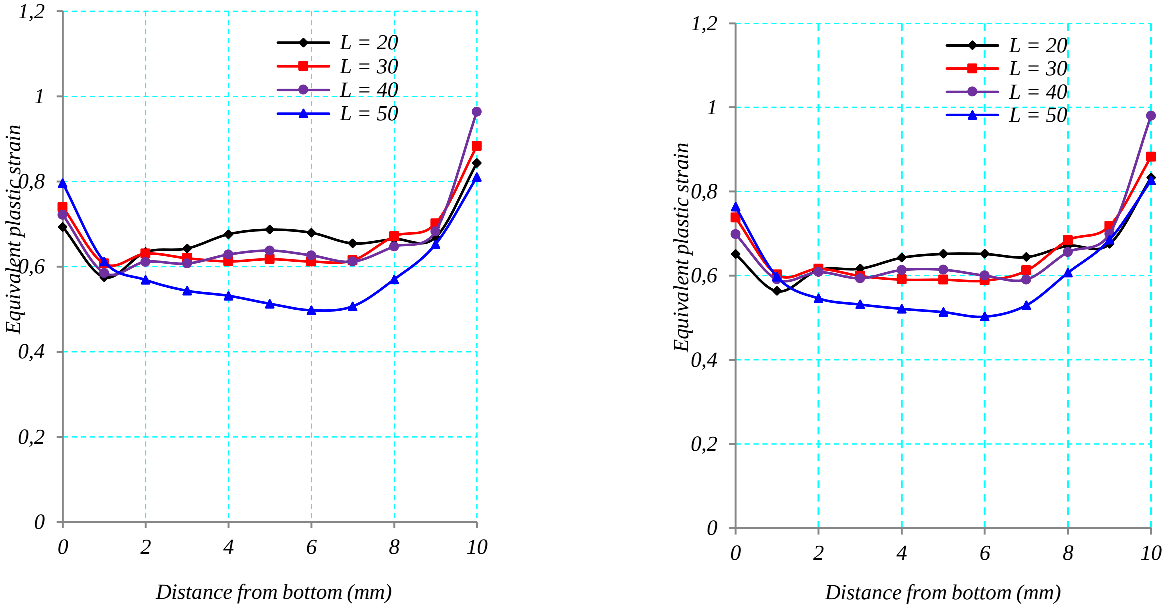
$$V = \frac{1}{\varepsilon_{ave}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_i - \varepsilon_{ave}\right)} \times 100(\%) \quad (10)$$

where ε_i is the equivalent plastic strain value of a given integration point along the sample width, ε_{ave} is the arithmetic average of the equivalent plastic strain values computed on N integration points. It is worth nothing that the variation factor is an important parameter, which can be connected to the strain homogeneity (i.e. the higher is its value, the more important is the heterogeneity of the deformation) [18].



(a) t = 6mm

(b) t = 8mm



(a) t = 10mm

(b) t = 12mm

Fig. 5: Influence of the length of the second channel on the distribution of the plastic strain for different values of thickness in the case of 120° die.

Table 2 shows the values of the maximum punch force required, the maximum and the average values of the equivalent plastic stain given by the numerical solution as well as the variation factor and the standard deviation according to the different geometries. It can be observed that the maximum punch force decreases with the decrease of the sample thickness. Nonetheless, the average plastic strain varies from 0.58 (at t = 6 *mm* and L = 50 *mm*) to 0.67 (at t = 10 *mm* and L = 20 *mm*) for the four cases. By considering the variation factor criterion, it can be seen the best homogeneity of the plastic strain distribution was obtained with a thickness of 10 *mm* and a length of 20 *mm*.

Table 2
Effect of t and L on the punch force and the equivalent plastic strain

Thickness t (*mm*)	**L (*mm*)**	**Maximum punch force required (*kN*)**	**Maximum strain**	**Average strain**	**Standard deviation**	**Variation factor (%)**
6	**20**	2.575	**0.833**	0.624	0.084	13.502
	30	2.618	0.832	**0.625**	0.084	**13.421**
	40	**2.683**	0.829	0.620	0.086	13.824
	50	2.624	**0.796**	**0.581**	0.100	**17.280**
8	20	**3.651**	**0.877**	0.647	0.089	13.763
	30	3.590	0.856	0.643	0.084	13.126
	40	3.612	0.861	**0.656**	0.078	**11.899**
	50	3.622	0.813	**0.596**	0.103	**17.354**
10	**20**	**4.518**	0.844	**0.675**	0.062	**9.176**
	30	4.429	0.883	0.665	0.081	12.137
	40	4.405	**0.964**	0.666	0.101	15.160
	50	4.396	**0.810**	**0.600**	0.105	**17.546**
12	20	5.556	0.833	0.656	0.063	**9.654**
	30	**5.571**	0.882	0.657	0.088	13.396
	40	5.503	**0.980**	**0.659**	0.109	16.508
	50	5.495	**0.826**	**0.602**	0.105	**17.417**

5.2. Evolution of the pressing force

The magnitude and distribution of plastic strain in the sample can be seen as key parameters for the ECAP process. While the magnitude of the pressing force required extruding the material defined the practical limit of the extrusion tool. The numerical results of the pressing force required for extrusion was calculated from the nodal forces in the top of the sample. This force is depicted versus time in Figure 6 for different lengths (L) of the second channel and with a thickness of 10 *mm*. In general, at the beginning of the extrusion, the pressing force starts to increase as soon as it contacts the first outer corner of the second channel. At this level, there will be initiation and growth of the shear band until the sample head crosses entirely the first elbow (up to the stability of the material flow). The first plateau of the curve corresponds to the steady state of the plastic flow for the first pass. It can be seen that this plateau increases with the increase of the length of the second channel. The second increase in the pressing force will take place when the sample comes into contact with the second elbow. After it crosses the second plastic deformation zone, a second plateau with a slight undulation was observed. This can be attributed to the interaction between the plastic deformations induced by the both elbows of the tool. Furthermore, it can be observed that the extrusion force increases quickly when the length is small and the force required for the second pass is slightly higher than three times the force of the first pass. In general, the maximum required force for different lengths does not exceed 4.5 *kN*.

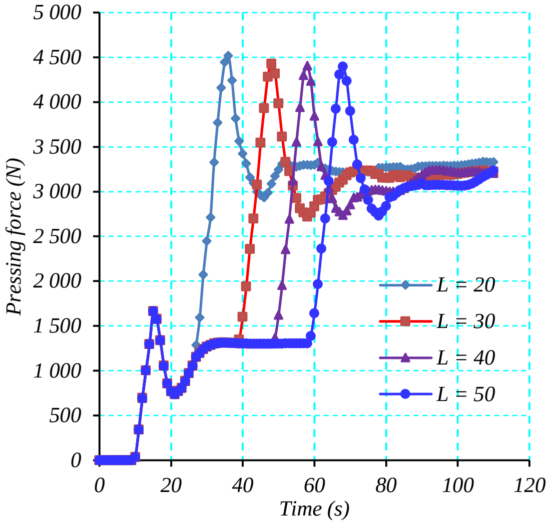


Fig. 6: Variation of pressing force for different lengths with t=10 *mm*

5.3. Effect of friction

In above sections, we have assumed that the friction between the sample and the tool walls is negligible (i.e. frictionless condition). In this section, the friction effects on the equivalent plastic strain distribution and the pressing force are investigated on the optimised geometries of 2-ECAE tools (with t = 10 *mm* and L = 20 *mm*). The friction between the tool and the sample is modelled with Coulomb friction law. The computations have been performed with three friction coefficients f = {0.1, 0.2 and 0.3}. Figures 7a and 7b show respectively the plastic strain distribution across the sample thickness and the evolution of the variation factor for different friction conditions. It can be seen that the friction influences significantly the homogeneity and the magnitude of the equivalent plastic strain in the case of thermoplastic polymers (PEHD). We note that more the friction coefficient increases, more is the increase of the plastic strain and the variation factor (negative influence on the degree of homogeneity).

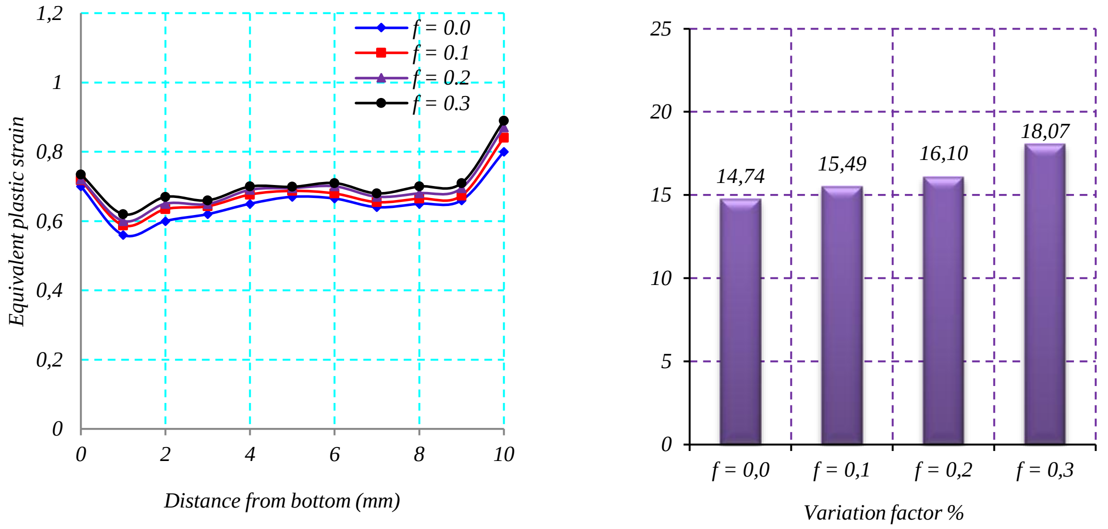


Fig.7. Effect of the friction sample/die channels on the evolution of (a) the equivalent plastic strain and (b) the variation factor.

5.4. Effect of temperature

In order to analyze the sensitivity of the equivalent plastic strain distribution in terms of the temperature, the computations were performed for four values of T = {25, 40, 60 and 80°C} at a constant ram speed of 0.1 mm/s and under frictionless conditions. In the simulations, the die geometrical parameters are t=10 *mm* and L = 20 *mm*

The distributions of equivalent plastic strain along the sample thickness as a function of the temperature and the evolution of the variation factor are shown respectively in Figures 8a and 8b. It can be seen that the temperature strongly influences the magnitude of the equivalent plastic strain (the higher is the temperature, the lower is the plastic strain). It can be also observed that the variation factor increases with the increase of the temperature. Hence, the increase of the temperature has a negative effect on the homogeneity of the plastic strain distribution. Consequently, in order to obtain a high level of plastic strain with a good homogeneity, it is advised to conduct the process as far as possible at room or low temperature according to the processed material.

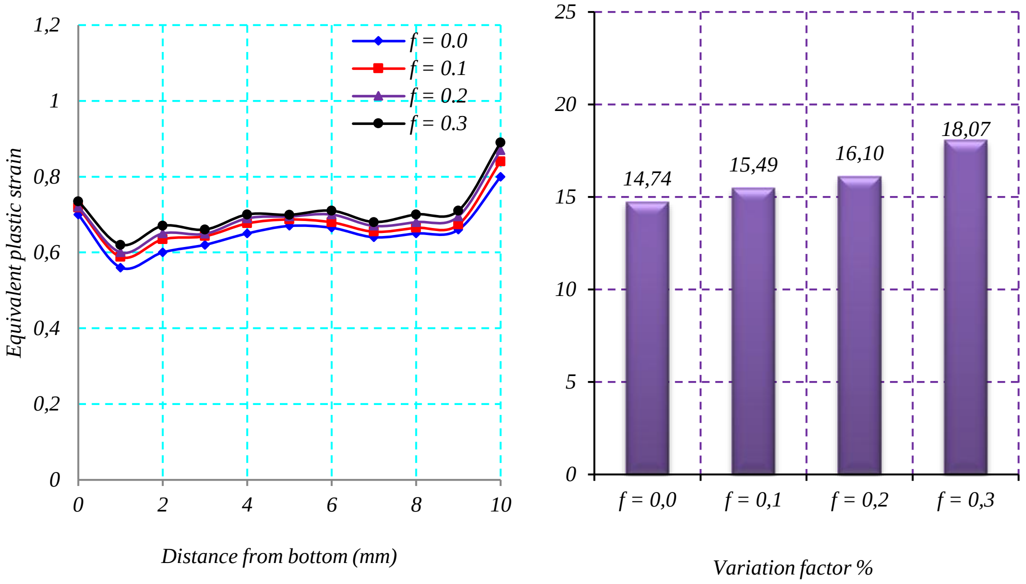


Fig. 08: a: Effect of the temperature on the evolution of the equivalent plastic strain;
b: Effect of the temperature on the evolution of the variation factor

6. Conclusion

In the present work, the finite element method has been used to provide fruitful information on the plastic strain distribution in the thermoplastic polymer (HDPE) during two turn ECAE process using 120° dies. It was found that the length of the second channel, the friction and the temperature play a significant role on the homogeneity of the plastic strain distribution and on the magnitude of the pressing force required for extrusion.

- We noticed that the best homogeneity of the plastic deformation was obtained when the second channel has a thickness of 10mm and a length of 20mm.
- A significant sensitivity offriction conditions on the plastic strain distribution has been found. However, to reduce the friction effect on the magnitude of the pressing force, it is advised to use an appropriate lubricant during the process.
- A temperature increase leads to lower plastic strain in the sample and a higher variation factor during 2-ECAE process. In the particular case of HDPE, room temperature processing is favored, unless force limitations on the equipment require heating. Specific relationship of optimum temperature to intrinsic material behavior has yet to be elucidated.
- Finally, in order to take advantage of this optimised 2-ECAE process, it is essential to combine the modelling analysis of the deformation behaviour of samples with experimental tests and work on this aspect is under development.

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