ON THE AUTOMATIC BALANCING OF PROFILE EXTRUSION DIES

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Abstract

A computer code, previously developed by the authors for the automatic die design, is used to optimise the flow distribution of an extrusion die, whose cross section is composed by walls with several different thicknesses (ranging from 2mm to 4 mm). The optimisations are performed using two alternative strategies: one based on die land length optimisation and the other on thickness optimisation.

For the experimental part of the work one modular profile extrusion die was built. It can adopt three different geometries: one corresponding to the initial trial (non-optimised die) and the other two corresponding to the optimised dies. Extrusion experiments performed with this die evidence the capabilities of the flow balancing code and design strategies implemented to improve the performance of these tools.

The numerical predictions are then compared with experimental data gathered during the extrusion experiments. The results obtained show that the numerical predictions and the experimental results agree within the experimental uncertainty. Generally speaking, measured and predicted values of pressure drop and flow distribution are in good agreement (within 8% and 6%, respectively).

Introduction

The design of profile extrusion dies comprises two main steps: balancing the flow distribution and anticipating the post-extrusion effects. Of these, the former is considered to be the most influential on die performance [1-4]. Due to the large amount of variables involved and to the geometrical complexity of a typical extrusion die, the design of these tools is usually based on trial-and-error procedures, which may be exclusively experimental, or result from a combination of experimental and computational work. Even in the latter case, and in spite of the use of numerical codes, the task is still very time consuming and relies essentially on the designer's experience, since the decisions necessarily involved in this process are always committed to the designer [3] and the employment of numerical tools requires high level skills.

It was the need for a design process less dependent on personal knowledge that motivated the development of the automatic die design concept [3, 5-9]. This is also the main purpose of the die design code currently under development, whose main objective is the automatic search of the optimal flow channel geometry.

Concerning the strategies to optimise the extrusion die flow channel two alternative approaches are usually employed: some authors claim that this should be done through changes in the flow channel parallel zone cross-section [1, 10, 11], or die land, whereas others argue that the parallel zone cross-section should be kept untouched and all modifications of the flow channel should be done in the upstream regions [12-14]. Some works have shown that the optimisation techniques based on adjustments of the parallel zone cross-section generate more robust dies, i. e., leading to flows less sensible to variations in process conditions and/or material rheology [1, 15]. However, if the profile dimensions stability is an issue, this approach increases the propensity of the profile to distortion, since it promotes the occurrence of different draw-down ratios [15].

In this work, for assessment purposes, the die design code is used to optimise the flow channel of a specific profile extrusion die, and the corresponding numerical results are compared with experimental data, gathered during extrusion experiments performed with the same dies.

Die Design Code

The code previously developed [16] designs the flow channel of extrusion dies according to the sequence of operations schematically represented in Figure 1.

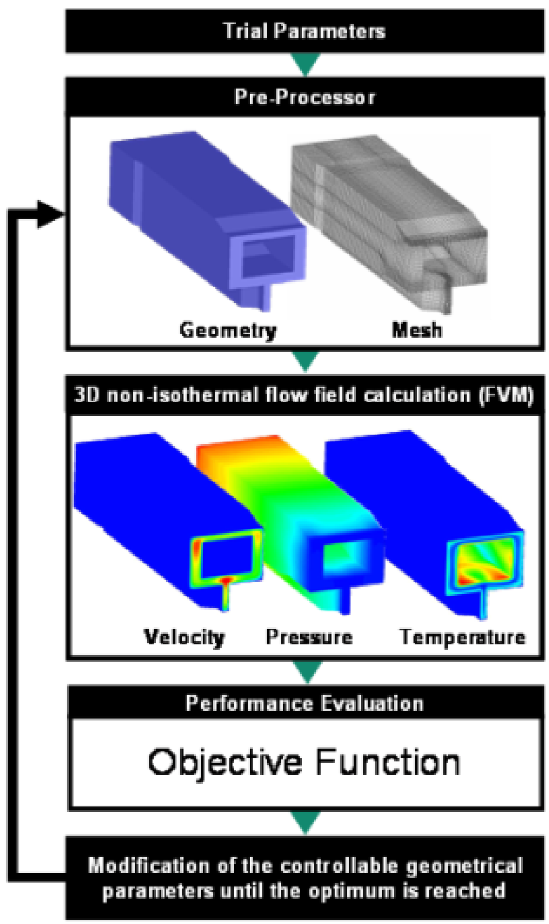


Figure 1 – Optimisation methodology.

The optimisation routines are initialised with the specification of trial values for the geometrical parameters, so that an initial (trial) geometry can be generated. For the flow simulation, a three-dimensional computational mesh needs to be deployed over that geometry. In order to minimise the time spent on the calculations, coarse meshes are employed at the initial iterations of the optimisation code, being progressively refined as the final solution is approached.

The 3D flow and temperature fields are calculated with a computational code based on the finite volume method [17-19], comprising a set of routines to model each relevant physical process. The results of the simulations are used to evaluate the global performance of each trial geometry by resorting to an objective function (F_{obj}), described elsewhere [16], which is always positive and is defined in such a way that its value decreases with increasing performance of the die, being zero for a perfectly balanced condition with all the ES lengths in the advisable range.

The final step of the whole design process consists on the iterative geometry correction. For this purpose, two algorithms were implemented: one is based on the SIMPLEX method and the heuristic of the other mimics the experimental trial-and-error procedure usually employed to manufacture extrusion dies (see [16] for details). The "final" optimised geometry is attained when, at the prescribed highest mesh refinement stage, the algorithm is unable to further improve the geometry performance.

Case Study

The parallel zone cross section of the extrusion die to be optimised is shown in Figure 2. It is composed by several subsections of different thickness, ranging from 2 to 4 mm, as indicated in Table 1. These values were imposed deliberately in order to promote differential local flow restrictions, situation which is intended to represent a typical profile extrusion die.

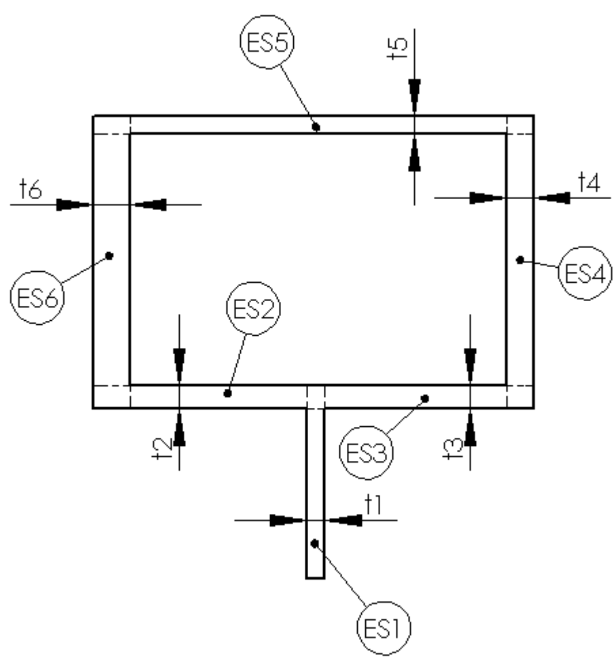


Figure 2 - Cross section of the parallel zone (PZ) of the die used as a case study, subdivision in elemental (ES) sections and identification of the optimisation parameters related to thickness.

Table 1 – Initial flow channel dimensions.

ES	**1**	**2**	**3**	**4**	**5**	**6**
$\mathbf{t_i}$[mm]	2.0	2.5	2.5	3.0	2.0	4.0
$\mathbf{L_i}$ [mm]	30.0	37.5	37.5	45.0	30.0	60.0
$\mathbf{L_i/t_i}$	15.0	15.0	15.0	15.0	15.0	15.0

The layout adopted for the flow channel is illustrated in Figure 3, whose main dimensions are presented in Table 1.

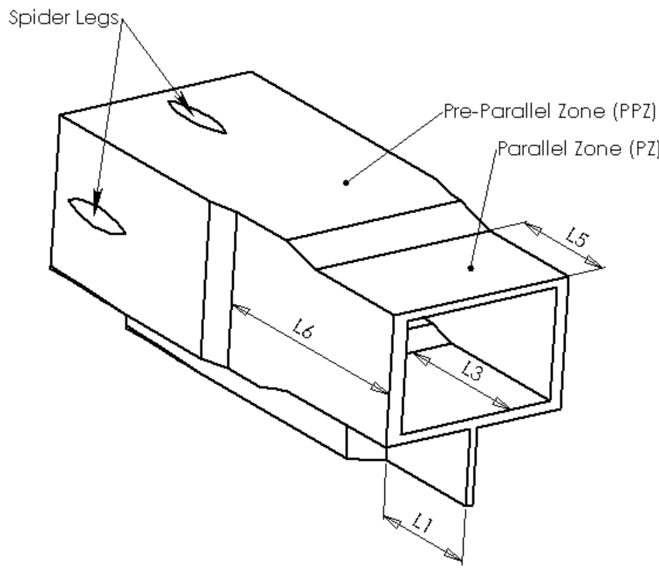


Figure 3 - Die flow channel used as a case study: region corresponding to parallel and pre-parallel zones (PZ+PPZ), identification of some of the optimisation parameters related to length and location of the spider legs.

The polymer used in this work was a polypropylene homopolymer extrusion grade, Novolen PPH 2150, from Targor. Its rheological behaviour was experimentally characterised in capillary and rotational rheometers and the shear viscosity data was fitted with least-squares method by means of the Bird-Carreau constitutive equation combined with the Arrhenius law, as described in [16].

Numerical Optimisation

For the purpose of optimisation, the flow channel cross section was divided into 6 elemental sections (ES), as shown in Figure 1. The flow channel geometry was optimised using the two alternative design strategies. The strategy based on the length optimisation resulted in the geometry denoted by DieL, whereas the strategy based on the thickness optimisation resulted in geometry DieT. In both cases, the "experimental-based" optimisation algorithm [16] was applied using 5 variables denoted as: Opt1 for ES1, Opt2-3 for ES2 and ES3, Opt4 for ES4, Opt5 for ES5 and Opt6 for ES6. These variables assume the value of either the ES length, or the ES thickness, for the optimisation of DieL and DieT, respectively. In order to facilitate the subsequent die

machining, ES2 and ES3 were set equal; consequently, only one variable was used for these two ES.

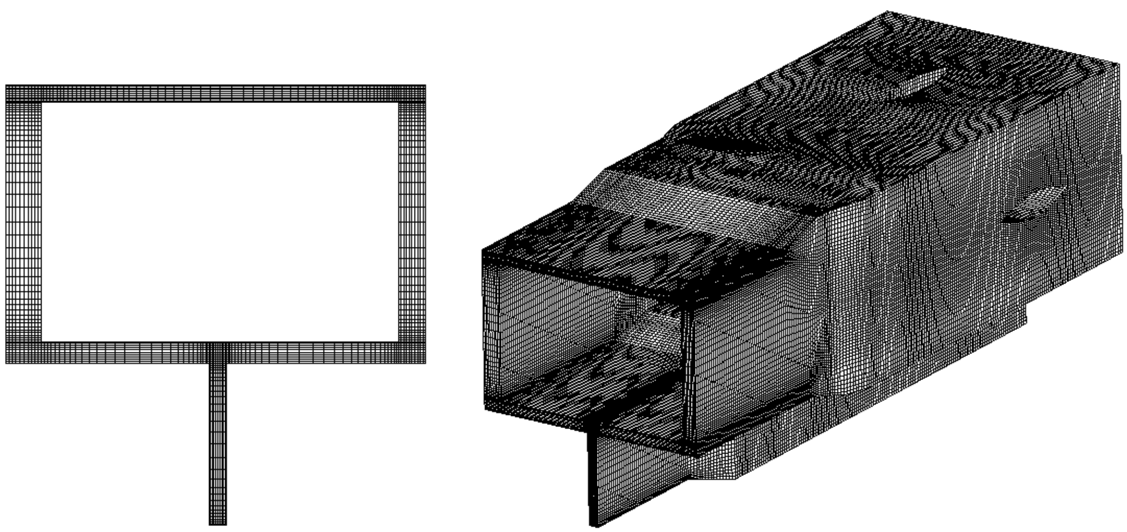
For the first trial of the optimisation algorithm, a constant length/thickness ratio (L/t) equal to 15 was adopted for all ES (see Table 1); the operating and thermal boundary conditions imposed for the flow simulations are listed in Table 2.

Table 2 – Operating and thermal boundary conditions used in the flow simulations.

Flow rate*	20 kg/h
Melt inlet temperature	230 ºC
Outer die walls temperature	230 ºC
Inner (mandrel) die walls	Adiabatic

* Corresponding to an average velocity of 1 m/min at the die exit

As mentioned before, the optimisation algorithm initially calculates the flow of the polymer melt using a coarse mesh which is then progressively refined as the procedure evolves towards a final solution. The initial meshes were rather coarse, with 2 cells along the thickness for each ES mapped; in this case, a typical mesh is composed by 7,500 computational inner cells and the number of degrees of freedom is approximately 37,500. The most refined meshes, used during the final stages of the calculation process, had 10 cells across the thickness for each ES, as shown in Figure 4, which implies 570,000 computational cells and 2,850,000 degrees of freedom. The calculation time required for the grid generation and the flow field computation was approximately 36 seconds and 7 hours for the coarsest and the finest meshes used, respectively, on a Pentium IV computer running at 2.4 GHz.



(a) (b)

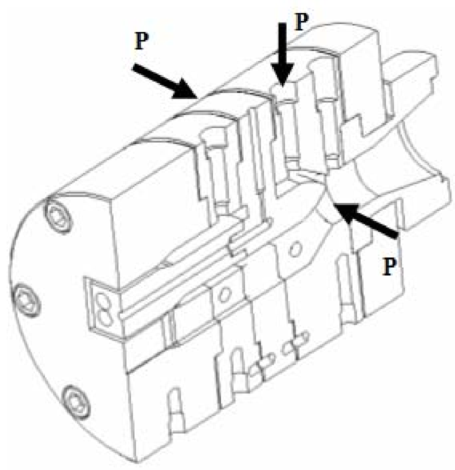
Figure 4 - Typical mesh used in the calculations, at the highest mesh refinement stage: (a) cross section of the parallel zone; (b) global 3D view.

Experimental Facility and Techniques

To assess and validate the results of the simulations several experiments were carried out. Three instrumented extrusion dies were designed and manufactured: one using the same L/t ratio for all elemental sections (DieINI), matching the initial trial of the optimisation algorithm, and

the other two dies (DieL and DieT) corresponding to the optimised geometries proposed by the die design code.

The constructive solution adopted for the dies is shown in Figure 5. Their modular conception enabled to built the die flow channel (corresponding to DieINI, DieL or DieT) changing only the last die region (mandrel and outer part), since the remaining components are common to all geometries. In order to monitor the process, the extrusion dies were instrumented with several pressure transducers (location marked P in Figure 5(a)), from Terwin, model 2000 series, that have an accuracy of 0.5% FSD. Considering the measured pressures and the propagation of uncertainties the total uncertainty was estimated to vary between 8% and 10% for the highest and the lowest pressures, respectively.



(a)

(b)

Figure 5 - Modular extrusion die used in the experimental work: (a) sectioned view of a typical die and location of the pressure transducers (P); (b) set of pieces used to built the three dies used.

Extrusion experiments were carried out in a single-screw extruder (screw diameter of 45 mm and L/D=20) under similar operating conditions to those used during the design stage, described in Table 3. For assessment purposes, all the experimental runs were simulated with the computer code.

Table 3 – Extrusion experiments performed.

Run ID	**Extrusion Die**	**Mass Flow Rate** [kg/h]	**Die Wall Temperature** [º C]	**Average Melt Exit Velocity** [m/min]
INI	**DieINI**	20.4	230	0.99
L	**DieL**	19.8	230	0.96
T	**DieT**	19.3	230	0.90

To assess the flow distribution it is necessary to quantify the flow rate in each ES at the die exit. The direct measurement of local flow rates in polymer extrusion is extremely difficult [3], hence they have to be estimated from the cross section area. Assuming that after leaving the die flow channel the melt does not migrate among ES, neglecting differences in shrinkage

between thicker and thinner sections, and since all sections are pulled simultaneously by the haul-off unit at the same velocity, the relative flow distribution can be evaluated through the measurement of the relative area of each ES, as suggested by Szarvasy *et al.* [3]. The protocol used to measure the profile ES areas was the following:

1) Slices of the profile were cut at different axial locations;
2) Each slice was surrounded by plasticine and photographed with a digital camera using a back illumination setup - Figure 6(a). As the material is translucent, the profile area can be easily identified. The digital photo was sent to a computer and was automatically processed using a commercial image editor. After this step a new image was created (see Figure 6(b));
3) The new image was vectorized and the profile elemental areas (identified in Figure 6(c)) were measured using a commercial CAD software.

There are two main sources of uncertainty in measuring the area of each ES: the inherent variation of cross section dimensions of the ES along the extrudate, which leads to the precision uncertainty, and the ±1 pixel systematic uncertainty in measuring the corresponding ES thickness.

The total relative uncertainty (U_M/M) in the measured relative area M of each ES is given by Eq. 1:

$$\frac{U_M}{M} = \sqrt{\left(\frac{1}{N_P}\right)^2 + \left(\frac{t\sigma}{M\sqrt{N}}\right)^2} \qquad (1)$$

where N_P is the number of pixels across the thickness, M is the average value of the sample measured relative cross section area, σ is the sample standard deviation, N is the sample size and t is the t-distribution parameter at a 95% confidence level.

To evaluate the level of induced internal stresses, a longitudinal sample of each ES was cut and annealed in an oven at 170ºC for 15 minutes. Their lengths were measured, before and after annealing test.

Results and Discussion

The results of the numerical simulations are presented first and are followed by their comparison with the experimental data.

The improvement of the flow distribution promoted by the optimisation process can be confirmed by the decrease of the ratio between the maximum of all bulk ES velocities and each bulk ES velocity, $\overline{V}_{max}/\overline{V}$, between the initial trial (DieINI) and the optimised (DieL and DieT) dies, shown in Table 4. The maximum values of this ratio were reduced from 7.46, at the initial trial geometry, to 1.15 and 1.68 for DieL and DieT, respectively.

Table 4 – Ratio $\overline{V}_{max}/\overline{V}$ obtained numerically for the initial trial and optimised extrusion dies.

Extrusion Die	ES1	ES2	ES3	ES4	ES5	ES6
DieINI	6.20	3.72	3.39	2.18	7.46	1.00
DieL	1.08	1.15	1.03	1.12	1.15	1.00

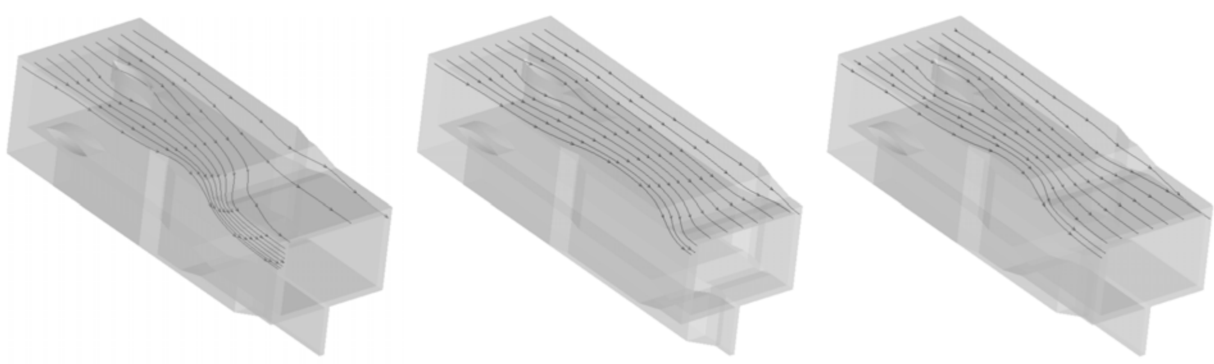
DieT	1.68	1.38	1.33	1.24	1.56	1.00

Table 5, where the final dimensions of the optimised dies are given, shows that the optimisation of DieL does not involve any change in the die land cross-section, which is certainly not the case for DieT. Consequently, in DieL the extrudate leaves the extrusion die at similar velocities, while in DieT the velocities must be different, in order to obtain the required profile dimensions after pulling. This explains the higher values of $\overline{V}_{max} / \overline{V}$ for DieT seen in Table 4.

Table 5 – Optimised flow channel dimensions.

		ES1	**ES2**	**ES3**	**ES4**	**ES5**	**ES6**
DieL	$\mathbf{t_i}$[mm]	2.0	2.5	2.5	3.0	2.0	4.0
	$\mathbf{L_i}$ [mm]	7.50	11.50	11.50	17.50	7.00	60.00
	$\mathbf{L_i/t_i}$	3.75	4.60	4.60	3.83	3.50	15.00
DieT	$\mathbf{t_i}$[mm]	2.42	2.64	2.64	2.89	2.42	3.19
	$\mathbf{L_i}$ [mm]	30.0	37.5	37.5	45.0	30.0	60.0
	$\mathbf{L_i/t_i}$	12.40	14.20	14.20	15.57	12.40	18.81

As expected, the data in Table 5 for DieL show a drastic reduction in the final L/t ratios for all ES except ES6, which have the thickest wall. In contrast, for DieT the values of L/t are larger. As noted in references [1, 3, 15] an extrusion die with low L/t values has a naturally higher sensitivity to processing conditions because the length of its parallel zone is insufficient to filter oscillations coming from upstream regions. The differences between DieL and DieT can be further understood by analysing the flow streamlines. Figure 6 shows calculated streamtraces in the region corresponding to ES5, one of the thinner walls, for all the manufactured dies. In all cases differences in thickness promote lateral flux, from thinner to thicker regions. Therefore, for DieL (having a shorter parallel zone but equal cross section to DieINI) the melt leaves the die channel before a fully developed flow is attained, to avoid loosing the flow balance obtained upstream. On the other hand, for DieT the flow becomes fully developed in the parallel zone and this contributes to its higher stability, typical of the dies optimised through thickness adjustment [1, 3, 15].



(a) **(b)** **(c)**

Figure 6 - Streamlines developed in ES5: (a) DieINI; (b) DieL; (c) DieT.

Figure 7 shows photographs of the polymer melt emerging from the dies, during the experiments, and the corresponding computed velocity fields. For the initial trial die (DieINI), the excessive flow in the thicker ES produces a clearly visible melt rippling, which was eliminated in the optimised dies.

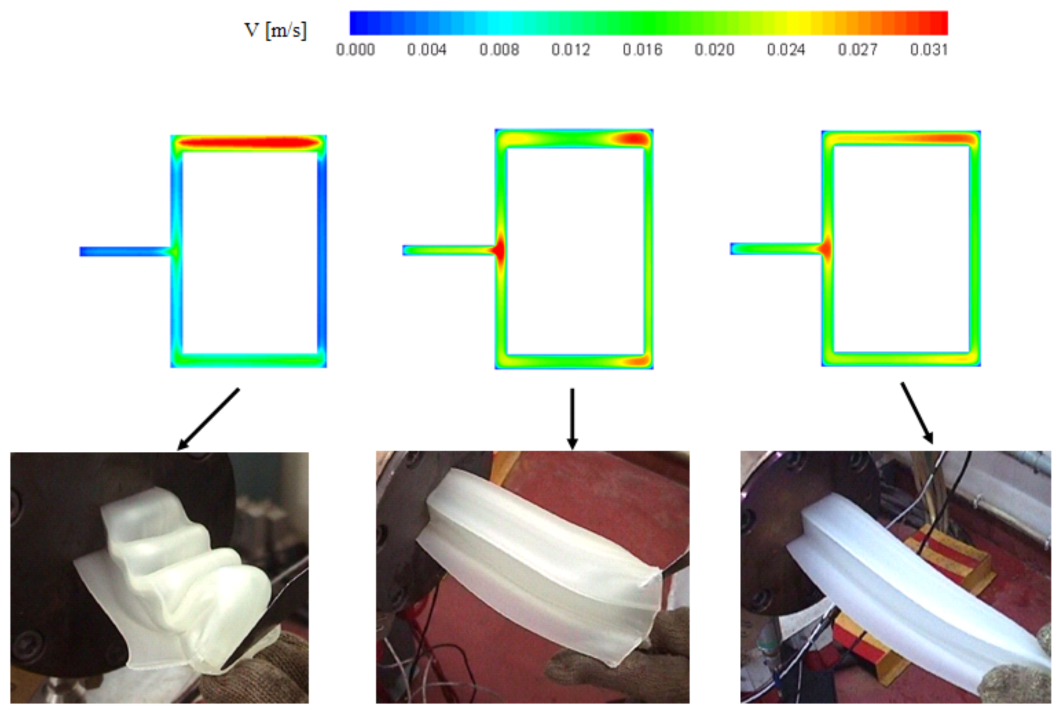


Figure 7 - Velocity contours and polymer melt leaving the die flow channel (photo taken during extrusion): (a) DieINI; (b) DieL; (c) DieT.

Table 6 compares measured and predicted pressure drops for the extrusion runs listed in Table 3. The predicted values are always lower than the measured data, showing a maximum difference not exceeding 8.8%, a value of the same order of magnitude of the experimental uncertainty.

Table 6 – Comparison between predicted and measured pressure drop values.

Run ID	**Pressure Drop**		
	Predicted [MPa]	***Measured Value*** [MPa]	***Difference*** [%]
INI	3.65	4.00	-8.75
L	2.56	2.80	-8.57
T	3.65	3.84	-4.95

Table 7 compares the predicted and the measured flow distributions. Generally speaking, the numerical predictions are in excellent agreement with the experimental measurements considering the corresponding experimental uncertainty of these difficult measurements. The maximum difference is of about 11.5% occurring in ES2+3 of DieINI, but usually the differences are of the order of just a few percent.

Table 7 – Relative elemental cross-section areas: measured areas (M), predicted areas (P), difference between predicted and measured areas (D) and overall uncertainty (U) of measured values.

Run ID		ES1	ES2+3	ES4	ES5	ES6
INI	M	3.2	18.3	19.2	7.1	52.2
	P	2.9	16.2	19.2	6.7	55.0
	D	*-9.4 %*	*-11.5 %*	*0.0 %*	*-5.6 %*	*5.4 %*
	U	*9.0 %*	*9.5 %*	*4.2 %*	*14.2 %*	*3.9 %*
L	M	8.3	26.0	18.7	18.2	28.7
	P	8.2	25.4	19.1	18.9	28.4
	D	*-1.2 %*	*-2.3 %*	*2.1%*	*3.8%*	*-1.0%*
	U	*6.7%*	*4.9%*	*5.6%*	*8.8%*	*3.9%*
T	M	7.4	26.2	20.2	20.2	26.0
	P	7.4	25.8	19.7	20.3	26.8
	D	*0.0 %*	*-1.5 %*	*-2.5 %*	*0.5 %*	*3.1 %*
	U	*6.3 %*	*4.4 %*	*4.9 %*	*8.2 %*	*5.6 %*

The values of $\overline{V}_{max} / \overline{V}$ in Table 4 can be interpreted as the relative draw-down ratios at which the different ES of the profile are subjected to. Different draw-down ratios across the exit section are expected to induce different levels of residual stresses and, as a consequence, the profiles produced with DieT may have a higher tendency to distort. This was confirmed by the results of the annealing tests shown in Figure 8. The retraction of the samples cannot be directly correlated with the stresses induced by pulling, because there are several other phenomena involved. However, the ratio between the longest and the shortest sample after annealing have values of approximately 1.4 for DieL and 2.6 for DieT, an indication that DieT produces profiles with a stronger tendency to distortion.

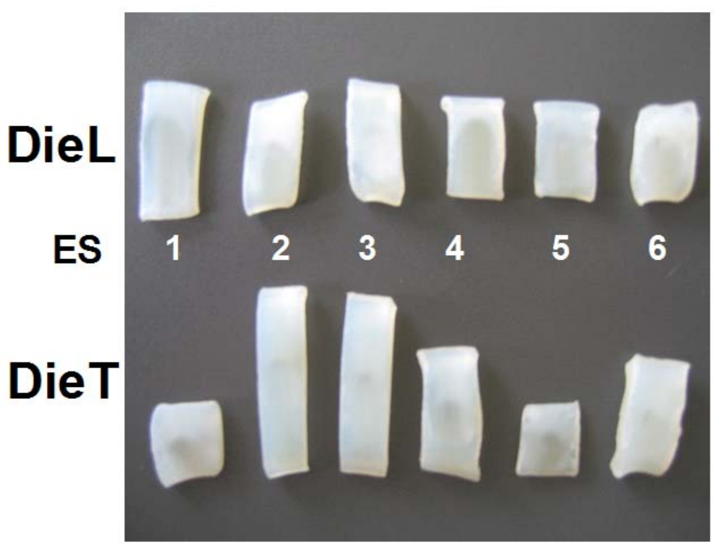


Figure 8 - Profile samples after annealing: (a) DieL; (b) DieT.

Conclusion

In this work a numerical methodology, which has been developed to carry out the automatic optimisation of profile extrusion dies, is further tested and is compared with results from experiments. The design methodology was here used to optimise the flow channel of an extrusion die using two alternative approaches: variation of the length of the die elemental sections or variation of their thicknesses. In the experiments, three extrusion dies were used and their extrudates measured. The first geometry corresponded to the initial trial die submitted to the optimisation algorithm, and the other two dies corresponded to the optimised geometries.

The main conclusions of this work are the following:

i) The optimisation algorithm improved significantly the extrusion die flow distribution thus demonstrating the effectiveness of the numerical methodology and design strategies implemented;

ii) The experimental measurements and the flow dynamic results of the numerical calculations were in excellent agreement, within the experimental uncertainty, thus demonstrating the ability of the code to predict the melt flow distribution and pressure drop for all dies/processing conditions considered. Thus, it may be asserted that the present computer code is a valuable tool to aid the design of extrusion dies;

iii) Extrusion dies optimised on the basis of length control have a higher sensitivity to processing conditions compared to those optimised on the basis of thickness;

iv) Profiles produced with dies optimised with thickness control have more tendency to distort due to the induced internal stresses, promoted by differential pulling.

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