AUTOMATIC BALANCING OF PROFILE EXTRUSION DIES: EXPERIMENTAL ASSESSMENT

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Abstract

In this work a previously developed die design code is used to optimise the flow distribution of a profile extrusion, using two alternative strategies. The numerical predictions are compared with experimental data gathered during extrusion experiments, the results of which are used to assess the rheological code and the effectiveness of the optimisation algorithm and design strategies implemented.

Introduction

There are two main issues to solve when designing a profile extrusion die: to uniform the flow distribution and to anticipate the post-extrusion effects, where the former having the main influence on the die performance [1-4]. Due to the large amount of variables involved and to the geometrical complexity of a typical extrusion die flow channel, especially in the case of complex cross-section geometries having different local flow restrictions, the design of these tools is usually based on trial-and-error procedures, that can be performed either on an exclusively experimental basis or on a combination of experimental and computational work. In any case, even when numerical tools are employed, the process is 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].

In terms of the techniques used to optimise the flow channel of profile extrusion dies there are two main approaches: some authors claim that this should be done through changes performed in the flow channel parallel zone cross section [1,5,6], or die land, and others argue that the parallel zone should be kept constant, being the flow channel optimised through modifications performed in upstream regions [7-9]. Some of the works published showed that the optimisation techniques based on adjustments of the parallel zone cross section generate more robust dies, i.e., dies showing higher stability to variations occurred in process conditions and/or material rheology [1,10]. The design approach involving corrections that do not affect the parallel zone cross-section minimises the differential pulling, though it may be insufficient to entirely balance geometries having several different flow restrictions [10]. The use of flow separators may allow bypassing this problem [9,10], but turns the die more sensitive to process variations [10] and gives rise to the formation of weld lines, which may negatively affect the mechanical performance of the profile.

It was the need to have a design process less dependent on personal knowledge that motivated the development of the automatic die design concept [3,11-15]. This is also the main purpose of a die design code that is currently being developed, which main objective is to carry out the automatic search of the optimal flow channel geometry. The code consists of an optimisation routine coupled with geometry and mesh generators and 3D computational routines based on the finite volume method, able to predict, within acceptable computation times, the complex 3D flow patterns developed and the temperature distribution [11].

In this work, the above-mentioned die design code is used to optimise the flow channel of a specific profile extrusion die. The numerical results obtained are compared with experimental data gathered during extrusion experiments performed with the dies proposed by the numerical routines. This set of experiments enabled to assess the rheological code and the effectiveness of the optimisation algorithm and design strategies implemented.

Die Design Code

The code previously developed to automatically design the flow channel of extrusion dies for profiles [11] involves the steps illustrated in Figure 1.

The optimisation routines, whose purpose is to find the best set of geometry parameters that better approaches the required flow distribution, start with the generation of some trial parameters that allows the creation of an initial trial geometry. In order to minimise the time spent on the calculations, the process starts with coarse meshes that are progressively refined as the final solution is approached.

The 3D flow and temperature fields are calculated using an in-house developed numerical modelling routine based on the finite volume method [16,17] that was recently extended to deal with non-isothermal flows [18]. The results thus obtained are used to evaluate the performance of each trial geometry by resorting to an objective function (F_{obj}), described elsewhere [11]. The final step consists on the geometry correction. For this purpose, two algorithms were implemented: one based on

the SIMPLEX method and other that mimics the experimental trial-and-error procedure usually employed to manufacture these tools (see [11] for details). The final geometry is set when the highest mesh refinement stage is achieved and the algorithm is unable to further improve the geometry performance.

Case Study

The parallel zone cross section of the extrusion die to be optimised, depicted in Figure 2, is composed by several subsections of different thickness, ranging from 2 to 4 mm (see Table 1). Those values were imposed in order to deliberately promote different local flow restrictions, which is intended to be representative of a typical profile extrusion die.

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 [11].

Numerical Optimisation

For optimisation purposes the flow channel cross section was divided into 6 elemental sections (ES), shown in Figure 2.

The flow channel geometry was optimised using the methodology described in *Nóbrega et al*. [11] considering two different approaches: one exclusively based on length optimisation (which will define DieL) and other exclusively based on thickness optimisation (defining DieT). For both cases the experimental based optimisation algorithm [11] was applied, using 5 variables: Opt1 for ES1, Opt23 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 considered to have the same dimensions; consequently, only one variable was used for these two ES.

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

Experimental Work

For assessment purposes, three modular instrumented extrusion dies were designed and manufactured: one using the same ratio length/thickness for all elemental sections (DieINI), matching the initial trial of the optimisation algorithm, and two corresponding to the optimised geometries (DieL and DieT) proposed by the die design routines.

Extrusion experiments were carried out in a single-screw extruder (screw diameter of 45 mm and L/D=20) using the before mentioned polypropylene extrusion grade. The set of runs performed is described in Table 3. The dies were tested under similar conditions to those used during the design stage. For assessment purposes, all the experimental runs were modelled with the numerical routines.

In order to compare the experimental values obtained for the flow distribution with the corresponding numerical predictions it is necessary to quantify the flow rate in each ES at the die exit. However, the direct measurement of local flow rates is very difficult [3]. Assuming that after leaving the die flow channel the melt does not migrate among ES and knowing that all the sections are pulled at the same velocity by the haul-off unit, the relative flow distribution can be evaluated through the measurement of the relative area of each ES, as suggested by *Szarvasy et al.* [3]. Adopting this methodology, the flow distribution predicted by the software was assessed comparing the predicted relative flow rates with the relative areas of the different ES measured in the extruded profiles. In order to surpass difficulties in identifying the ES limits, the corner zones were included in the measurements, divided by the two adjacent ES, and the areas corresponding to ES2 and ES3 were merged.

Having the objective of evaluating the level of induced differential internal stresses, a longitudinal sample of each ES, cut as described in Figure 3, was annealed in an oven, at 170ºC, during 15 minutes. The length of these samples was measured before and after annealing.

Results and Discussion

The improvements obtained by the optimisation routines are illustrated in Figure 4 that shows pictures of the polymer melt emerging from the dies and the corresponding computed velocity fields. For the initial trial die (DieINI), the excessive flow verified in the thicker ES produces a clearly visible melt rippling. This effect vanished in the optimised dies. This improvement is also patent in the final values of $\overline{V}_{max} / \overline{V}$ (ratio between the maximum average velocity value of all ES and the average velocity obtained for each ES) presented 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 5 summarizes the values of pressure drop (measured and predicted) for all the extrusion runs listed in Table 3, which show the same trend. However, the predicted values are always lower than those measured, showing a maximum error that rounds 8.8%. Despite the good matching between the measured and predicted pressure drop values, some of them are not intuitive. These are mainly due to differences in viscous dissipation (and, thus, temperature), which is dependent on both shear rate

(related to channel thicknesses) and residence time (related to channel lengths). The remaining results shown in Table 6 facilitate this interpretation.

The flow distribution predicted by the software was assessed through comparison of the predicted and measured relative areas of the different ES considered for optimisation purposes, shown in Table 7. Generally, the numerical predictions are close to the experimental measurements. The maximum error (11.5%) occurs in ES(2+3) of DieINI.

The values depicted 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 are expected to induce different levels of residual stresses. As a consequence, profiles produced with DieT (thickness strategy) may have a higher propensity to distort. This was confirmed by the annealing tests performed. The retraction of the samples, shown in Figure 5, cannot be directly correlated with the stresses induced by pulling, because there are several other phenomena involved (for example, thicker sections have a higher cooling time and, consequently, have more time to relax these stresses). However, the ratio between the longer and the shorter sample after annealing have values of approximately 1.4 for DieL and 2.6 for DieT, an indication that DieT produces profiles with stronger tendency to distortion.

Conclusions

In this work a methodology previously developed to carry out the automatic optimisation of profile extrusion dies was used to optimise the flow channel of an extrusion die using two alternative strategies. Three extrusion dies, one corresponding to the initial trial of the optimisation algorithm and two corresponding to optimised geometries were manufactured and tested.

The results obtained allowed to conclude the following:

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

ii) The numerical modelling routines were able to predict accurately the melt flow distribution and the pressure drop for all the dies/processing conditions, thus being a valuable tool to aid the design of extrusion dies;

iii) Profiles produced with extrusion dies whose optimisation process is based on thickness control present a higher propensity to distort.

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Table 1 – Initial flow channel dimensions.

ES	1	2	3	4	5	6
t_i[mm]	2.0	2.5	2.5	3.0	2.0	4.0
L_i [mm]	30.0	37.5	37.5	45.0	30.0	60.0
L_i/t_i	15.0	15.0	15.0	15.0	15.0	15.0

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

Table 3 – Extrusion experiments performed.

Run ID	Extrusion Die	Mass Flow Rate [kg/h]	Melt Exit Vel. [m/min]
INI	DieINI	20.4	0.99
L	DieL	19.8	0.96
T	DieT	19.3	0.90

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 – Numerical and experimentally measured pressure drop for all the extrusion runs.

Run ID	Pressure Drop			
	Predicted [MPa]	*Measured* *Value* [MPa]	*Measured* *Accuracy* [%]	Difference [%]
INI	3.65	4.00	± 4.3	-8.75
L	2.56	2.80	± 6.1	-8.57
T	3.65	3.84	± 4.5	-4.95

Table 6 – Numerical predictions corresponding to all the extrusion runs.

Run ID	Maximum Shear Rate [1/s]	Melt Temperature at the Die Exit [ºC]	
		Average	*Maximum*
INI	135.81	231.40	236.97
L	135.00	230.96	233.93
T	109.65	231.32	234.75

Table 7 – Relative elemental cross-section areas: measured average (M), predicted (P), difference between predicted and measured (D).

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 %*
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%*
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 %*

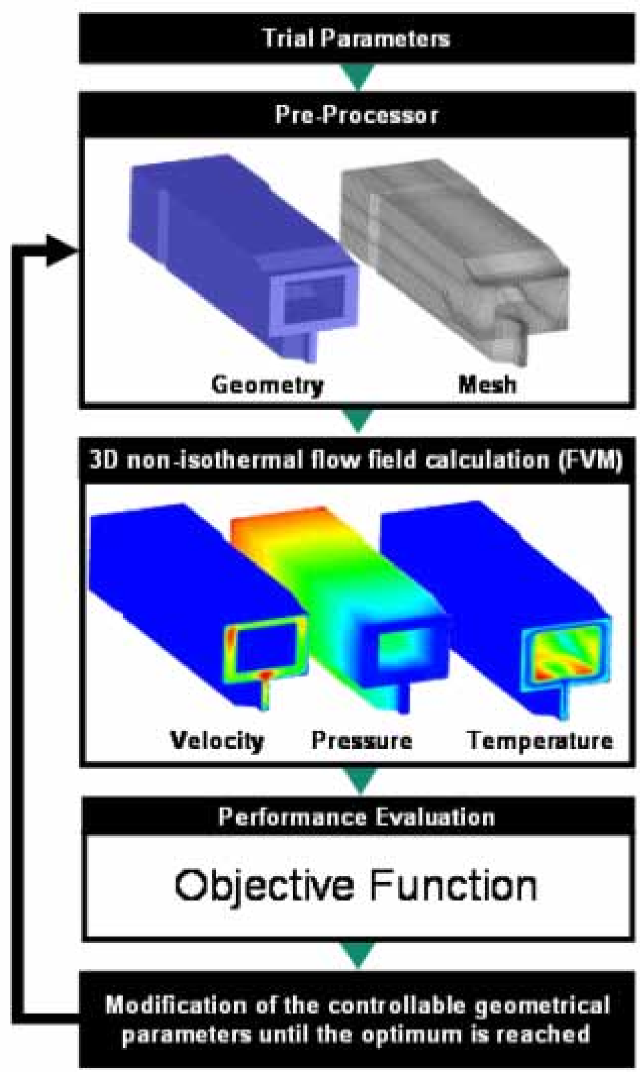


Figure 1 – Optimisation methodology.

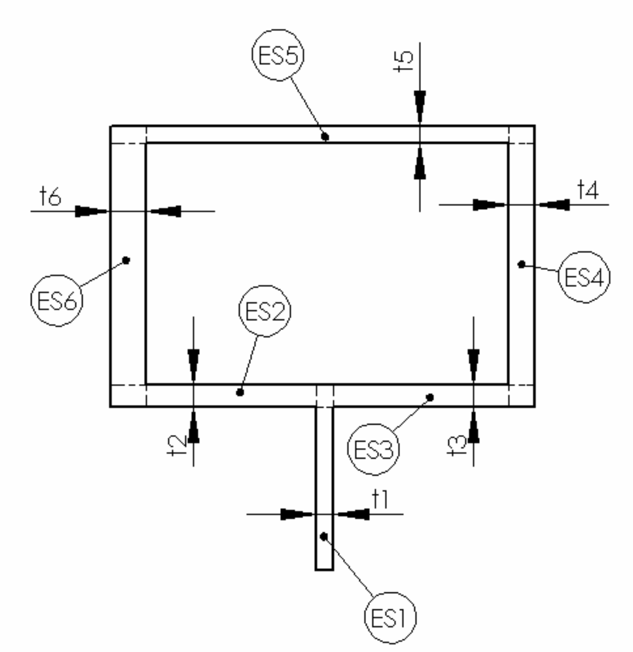


Figure 2 – Cross section of the parallel zone of the die used as a case study and subdivision in elemental sections (ES)

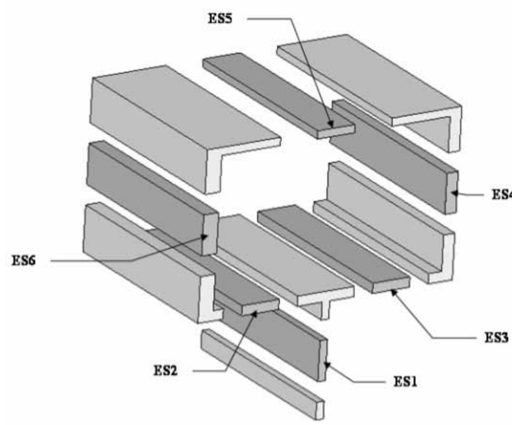


Figure 3 – Location of the samples used in the annealing tests.

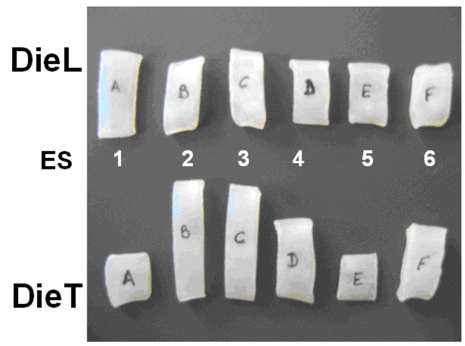
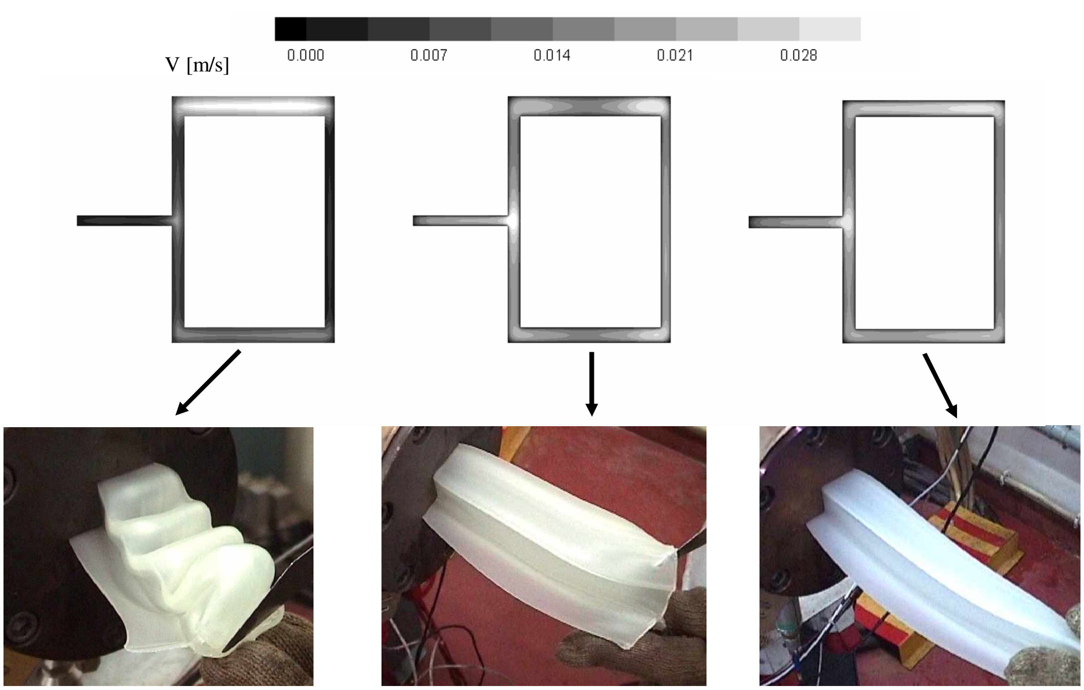


Figure 5 – Profile samples after annealing.



(a) **DieINI** (b) **DieL** (c) **DieT**

Figure 4 – Velocity contours and polymer melt leaving the die flow channel (photo taken during extrusion): (a) DieINI; (b) DieL; (c) DieT.