NUMERICAL BALANCING OF EXTRUSION DIES : A VALIDATION STUDY WITH A TPV AUTOMOTIVE WEATHERSEAL PROFILE

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Abstract

Extrusion is a continuous processing method used to manufacture products with a uniform cross section. It is the role of the die to convert the cylindrical flow from the extruder barrel into the required, sometimes quite complex, cross section. When a molten material is pushed into the die, it tends to flow where the pressure is the lowest, with the result that thick sections are favored over thin sections and deformations result, therefore the extrudate geometry can never be at drawing size. This is why the flow has to be balanced in the die to minimize those deformations.

The die balance is traditionally worked out via a trial-and-error process whose length is dependent upon the ratio between the flow path thicknesses. The larger the difference in the thickness, the longer the process. This process typically requires multiple stages of die trial and balancing modification. The main reason for this lengthy design process is that the flow patterns inside the dies are not known and the balancing cannot be assessed *a priori*.

Through 3D numerical analysis of the polymer flow in the die based on suitable material properties, it is now possible to predict and simulate the die balance and to cut the die from the electronic file containing the data from the analysis. A validation of the methodology has been performed to illustrate the applicability of the tool to real life extrusion situations. The example described here is related to the extrusion of an automotive glass run channel extruded with Santoprene® TPV, grade 121-58W175.

The finite element code POLYFLOW® has been used to evaluate the flow in the die and to modify its geometry to test different configurations. The calculation of the velocity distribution balancing at the die outlet is gradually improved on the computer model before any single die is manufactured. Once a satisfactory balance is obtained numerically, the resulting die is tested on the extrusion line and shown to provide very stable extrusion conditions and a close respect of the geometric requirements *at the first trial*. This technology can be further extended to more complex geometries and/or coextrusion situations to reduce the die design and cutting time, reduce set-up times, losses of productivity and waste.

Introduction

Shaping of plastics and rubber compounds by extrusion is a widely used process to produce semi-finished products such as tread bands in the tire industry and finished products such as profiles for automotive applications, construction, appliances, etc. The complex transition from the unbalanced flow in the die to the freely streaming polymer results in a rearrangement of the velocity which induces deformations in the extruded profile, requiring die corrections to obtain the target product. Elastic effects and slipping at the walls can, when significant, further contribute to this effect.

Until recently, extrusion die design has been more an art than a science; a costly and time-consuming process largely dominated by empirical know-how based on the experience of expert tool manufacturers and repeated trials to improve the initial design. This situation often leads to non-repetitive results and the set-up and optimization of extrusion dies often remains a slow, empirical process.

Modern computational tools exist today [1, 2] that provide additional information and practical and cost-effective ways to improve the die design process. Finite element techniques are coupled with advanced free

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surface calculations and advanced rheological models [3, 4] to allow the simulation of the three dimensional flow of plastics or rubber through a die. The combination of the designers' knowledge of the extrusion process with the insight provided by numerical simulation permits the evaluation of several possible designs to yield the required product. The use of those advanced techniques results in savings in the number of trial dies, therefore reducing cost, time-to-market, and scrap material [3, 4]. In addition, this technique provides a means to introduce a more formal, reproducible engineering practice in the improved design of extrusion dies in a cost-effective and more easily transmissible manner.

There exists a significant body of applications of extrusion modeling including the stream of deforming polymer coming out of the die, and therefore making use of free surface and die lip design calculations [3, 4, 5, 6, 7]. However, the objective of the current work is to illustrate and validate the methodology suggested to use this tool to provide assistance to die designers in concrete, practical and effective ways, in realistic extrusion situations. Therefore we will use the tool to perform work as required by the practice of die designers and assess its usability by those designers as enhancement to their current methodology.

Die balancing application

We consider the flow of a TPV material which is being used for a growing number of applications. The specific grade is Santoprene® 121-58W175, particularly suitable for the extrusion of automotive weatherseal profiles, as illustrated in fig 2. The material is extruded on an extrusion line at 10 m/min under isothermal conditions.

The requirements are (i) to numerically balance the die sufficiently so that it is possible to cut a die to the dimensions of the required profile (with only minor deformations that can be corrected by a slight increase in drawing velocity), (ii) to export the modified die format successfully into the manufacturing process to demonstrate a tight integration when cutting the die and (iii) to jointly assess the accuracy of the design in extrusion tests.

Numerical method

We use advanced 3-D Finite Element (FE) techniques, to solve the momentum, incompressibility (and possibly energy for non-isothermal situations) equations [8]. Furthermore, to accurately model the viscous or viscoelastic behavior of the material, the Navier-Stokes equations are coupled with an appropriate constitutive equation. This results in a description of the flow patterns for the fluid enclosed in the die cavity, including the pressure gradients, the velocity and shear-rate distribution, the trajectories of particles, etc.

The shear-thinning behavior of the material is modeled by a Bird-Carreau law

$$F(\dot{\gamma}) = \eta_0 \left(1 + (\lambda\dot{\gamma})^2\right)^{(n-1)/2} \quad (1)$$

where η_0 = 567,000 Pa.s, λ =66.24 s and n = 0.217

Based on comparison of the modeling with available pressure drop measurements [9], the slip behavior of our Santoprene® has also been evaluated and found to be negligible. Adhesion boundary condition is thus used along the die walls and a stress free condition is applied at the die exit.

Numerical results

We thus begin with the numerical die design process. As a reference case, we are considering a straight 15 mm constant section die land without any converging feeding section (fig. 2). The die is symmetrical. This first calculation, which is performed as baseline to obtain an evaluation of the measure of 'unbalance' of the profile, indeed reveals a strongly non-homogeneous velocity profile, with high velocities for thick flow sections and low speed across the narrow flow sections. The average velocity is 166.7 mm/sec or 10 m/min. To obtain a more useful evaluation of the velocity unbalance for the purpose of further modifications, we define the parameter R as the following ratio:

$$R = \frac{Local\ velocity}{Average\ velocity} \quad (2)$$

Zone 1 (fig. 2) is indeed a high speed fluid region, 500 mm/sec, where R is around 3. Zone 5 (fig. 2) is a low speed region, 25 mm/sec, with R equals to 0.15. The ideal balancing will give a ratio of 1 for the whole die outlet. This can strictly only be reached in an idealized full slip condition case, but it serves as an ideal target to our balancing efforts and we performed several geometry modifications in order to have a ratio close to unity.

From the second calculation, the geometry has been split in two parts. The 15 mm thick die consists first of a 12 mm converging section part at the entrance to direct more flow to the thin extremities of our profile. A second part is a 3 mm constant section at the exit. In zone 1, the ratio is around 1.6, but in spite of the large opening and converging sections, this ratio is still approximately 0.15 and 2 in zones 2 and 3, respectively (fig. 3).

In the third calculation, we removed the constant section in zone 5, so the convergent goes throughout the whole die in that region. The peak in this calculation is due to the constant section modification. The converging section produced a very high speed region in zone 5 (fig.4).

For the fourth calculation, a compromise has been found and a constant section of 1.5 mm has been set up for the zone 5. On the other hand a 3 mm constant section has been kept for the other zones. This also demonstrates the importance of the differential constant section length in the die balancing process, alongside the convergent openings.

Figure 5 shows more homogeneous velocity contours after four calculations, or four geometry modifications and overall a ratio closer to unity, with a maximum value lower than 1.5 and a minimum value larger than 0.75. At this stage, the balancing was considered as acceptable for a first industrial test.

Experimental validation

Electronic files of the modified die have been transferred to the die machining shop in an IGES format and used to manufacture the required die using electro-erosion techniques. The die has then been placed on the extrusion line and tests have been performed at the appropriate speed.

The first observation has been that a very stable profile has been extruded from the beginning, thus qualitatively validating the overall numerical balancing approach. A closer look at the resulting profile allowed for the quantitative verification of the design at several important control points.

The extrudated profile has been compared with the desired shape along two sections A and B described in fig. 1. An excellent agreement between the design and the actual values has been obtained. Along section AA, a discrepancy of 2.2 % between the extrudated material and the expected profile is measured while a difference of less than 1.3 % has been measured along the line BB.

Conclusions

The use of numerical simulation enables the efficient design of dies for rubber and plastic extrusion by allowing to sort out rapidly and at a lower cost potential designs, therefore reducing the set-up time and avoiding waste of efforts, material and lost production in dead ends. Numerical simulation provides a wealth of information without inducing any disturbing effect to the flow to offer the designers more insight to improve their die designs. Complex effects can be analyzed separately in their relative importance to the final product shape.

The validity of the numerical simulation profile extrusion has been demonstrated for a relatively complex automotive profile and numerical results have been validated against experimental data with excellent accuracy.

The main objective of the industrial user is to reduce the number of unsuccessful trials in the extrusion die design process. The first benefit is that substantial direct money saving will be made because of reduced re-design and manufacturing of dies, and waste of rubber during the trials. Indirectly, money will be saved by reducing the set-up time and the immobilization time of production extrusion lines, therefore allowing more profile types to be manufactured.

The second, not less important, industrial objective is innovation and increase in the product quality. Using simulation, better insight into flow behavior can be achieved. Experience will be accumulated in a more formal way, and new approaches can be tried more easily.

A consistent improvement of the product quality through numerical simulation and extrusion know-how has been reported [3], as well as dramatic reductions in set-up time and increase of production rates [4], as the major gains of the application of the technique by experienced designers. In addition, this technique provides a means to introduce a more formal, reproducible engineering practice in the improved design of dies for rubber extrusion in a cost-effective and more easily transmissible manner.

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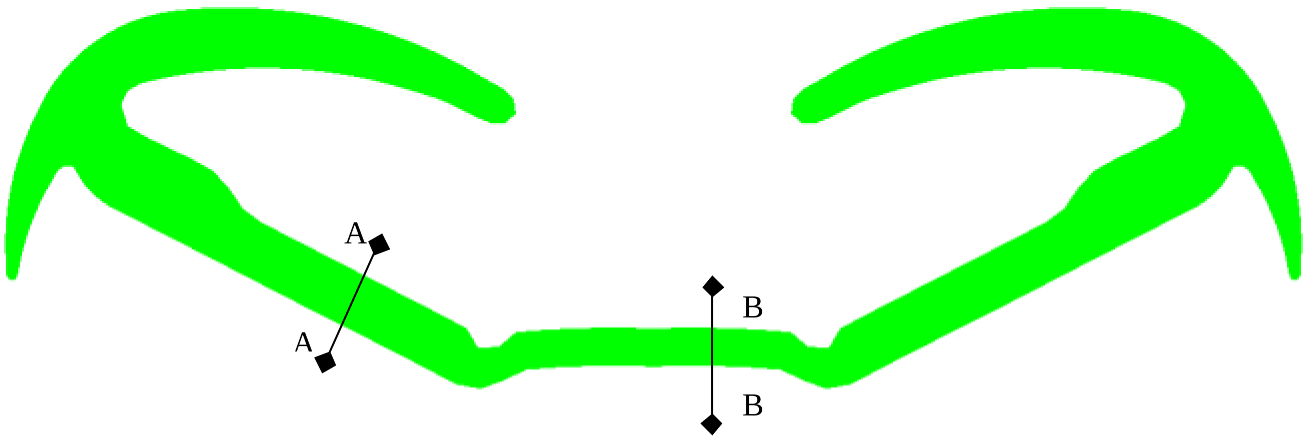

Figure 1 Targetted automotive profile. Comparison betweeen the desired profile and the actual one is done along the section AA and BB

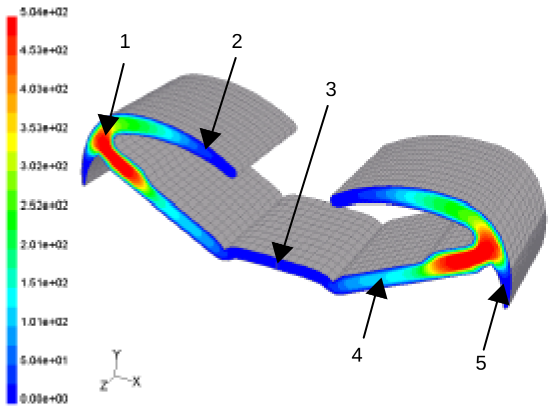

Figure 2.- Typical automotive profile.

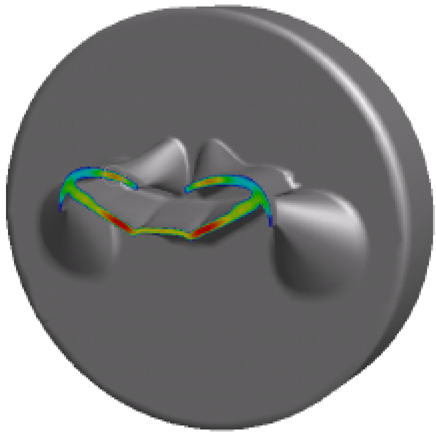

Figure 3.- Contour lines of the velocity magnitude across the die lip. A die land of 3 mm together with converging sections modify the velocity profile

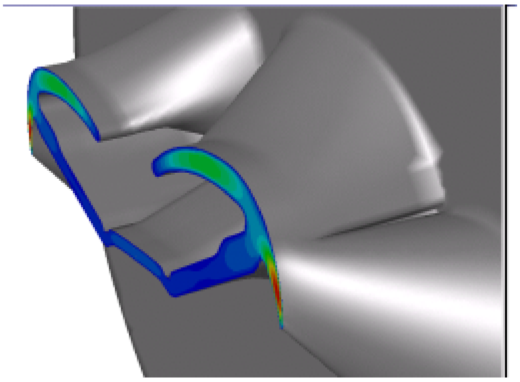

Figure 4.-Contour lines of the velocity magnitude. The die land has been removed close to section 5 inducing a too large local velocity.

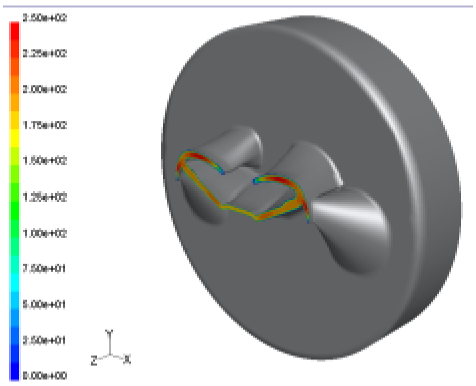

Figure 5 – Contour lines of the velocity magnitude across the die lip for the fully balanced die. The variation of the maximum velocity (in red) is much smaller than in Figure 2

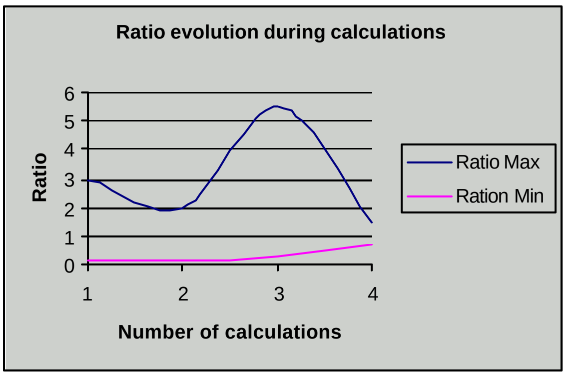

Figure 6.- Evolution of the maximum and Minimum R ratio converging to wards the ideal value (1)

Keywords: Extrusion, Die balancing, Die Design, Numerical Simulation, Automotive weatherseal profile