AUTOMATIC OPTIMISATION OF EXTRUSION DIES

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In order to produce an extrusion profile, the polymer melt has to be shaped from a cylindrical into a near-product form within the extrusion die. Because of the complex melt behaviour the rheological design of the flow channel is done by changing the geometry iteratively until the design goals are achieved. The primary objective of a rheological design of a flow channel for complex profile geometries is an even velocity distribution at the outlet. However, during the rheological design of an extrusion die not only the flow conditions inside the die have to be considered but also the die swell after leaving the die has to be accounted for. In recent years progress has been made to realise an automatic optimisation of flow channels and to predict the die swell behind extrusion dies.

Introduction

During the profile extrusion process the extruder has the purpose of melting the polymer and of building up enough pressure for the polymer melt to flow through the die at the desired throughput. The intention of the following profile extrusion die is to shape the polymer melt from a cylindrical into a near-product form. Usually the polymer melt has a non-Newtonian behaviour. Thus, up to now there is no method available to predict the flow channel geometry required to gain an even velocity profile at the outlet. In practice the die design and optimisation, respectively, is performed by means of an iterative process. Therefore, a tentative draft e.g. a starting geometry is generated and this geometry is optimised with respect to a homogeneous velocity distribution at the outlet. The variations are usually performed by an experienced die designer. Today, by means of flow simulation programmes, it is possible to compute the pressure and velocity fields inside the die. This enables the designer to look inside the die and hence perform a more directed optimisation than only by considering the velocity distribution at the outlet. At the Institute of Plastics Processing (IKV) a new optimisation method has been developed which combines a calculation method and an optimisation strategy. The result is a method which is able to optimise a flow channel geometry automatically.

Nevertheless, during the rheological design of an extrusion die not only the flow conditions inside the die have to be considered but also the die swell after leaving the die has to be accounted for. Due to the viscoelastic behaviour the melt stores portions of introduced shear and elongational deformations as stresses. At the die exit the stresses lead to die swell. The prediction of die swell is still a big challenge in plastics processing today. In an L-shaped die, the flow conditions, stresses and die swell behind the outlet are calculated using the finite-element-analysis (FEA). A material is modelled using different viscoelastic models, e.g. the Giesekus- and the Phan-Thien-Tanner-model. The calculated die swell is compared to experimentally measured die swell.

The primary research objective is to reduce the development time of extrusion dies. In the future the IKV is aiming at developing a strategy which will be able to optimise flow channel geometries while automatically taking into account the die swell.

Automatic optimisation method

In [1] Michaeli and Kaul present a new calculation method which combines the FEA and a flow analysis network (FAN). By means of this method it is possible to accelerate the iterative optimisation process. In a further development this new calculation method is combined with an optimisation scheme based on the evolution strategy [2, 3]. The result is an algorithm to optimise the flow channels in extrusion dies automatically.

As a demonstration scenario a die for producing a roller-blind profile is chosen (Fig. 1). The optimisation allows for the cross-section highlighted in Figure 1 to be changed by the optimisation algorithm. This cross-section is chosen because in this way the die land, which is essential to soothe the flow, is not affected by the geometrical changes. During the calculations of the velocity field and the pressure inside the flow channel the material is modelled with the Carreau-model, which describes the shear-thinning behaviour of the polymer melt.
Fig. 1: Flow channel of a roller-blind die

Fig. 2 shows the velocity distribution at the outlet of the starting geometry (not optimised) and of the optimised flow channel. It can be clearly seen that in the area of the hooks the melt is leaving the optimised die with a much higher velocity in contrary to the not optimised die. On the other hand the velocity maximum at the cross-over points is lowered due to the optimisation.

Study on die swell

After leaving the die the dimensions of the extrudate are likely to change because of the viscoelastic behaviour of the melt. Thus, to produce a product of good quality not only an even velocity distribution has to be accomplished but also the deformation of a melt particle has to be taken into account. The polymer melt has to be modelled with the help of viscoelastic models. Today in the field of rheology many viscoelastic material models are known. In this study the Giesekus and the Phan-Thien-Tanner model are chosen. These material models are numerically more simple models and are able to describe the material behaviour as the shear-thinning behaviour of polymer melts. This way convergence of the simulation including viscoelastic models and the computation of the free surface can be achieved more easily compared to other material models as the integral K-BKZ-model.

The state of stress for an incompressible fluid is formulated as follows:

\[
\sigma = -pI + T_{ve} + T_v
\]

\[
\sigma : \text{state of stress}
\]

\[
p : \text{hydrostatic stress}
\]

\[
I : \text{unit tensor}
\]

\[
T_{ve} : \text{viscoelastic component of the extra stress tensor}
\]

\[
T_v : \text{viscous component of the extra stress tensor}
\]

As mentioned before the viscoelastic component of the extra-stress can be computed in different ways. The Giesekus-model computes the viscoelastic component (Equation 2) [4, 5]:

\[
\left( I + \frac{\alpha \lambda}{\eta_{ve}} T_{ve} \right) \cdot T_{ve} + \alpha T_{ve} = 2\eta_{ve} D
\]

\[
\alpha : \text{coefficient of anisotropy}
\]

\[
\eta_{ve} : \text{viscoelastic viscosity}
\]

\[
\lambda : \text{relaxation time}
\]
\[ D : \text{rate of deformation-tensor} \]

\[ T_{ve}: \text{upper convected time derivative of } T_{ve}, \text{ which follows the mathematical equation:} \]

\[ \nabla \cdot \frac{DT_{ve}}{Dt} = T_{ve} - \nabla \cdot \nabla \cdot \nabla T_{ve} \]

\[ \text{Eq. 3} \]

The viscous component is defined as follows:

\[ T_{v} = \frac{2}{\eta} D \]

\[ \text{Eq. 4} \]

\[ \eta : \text{viscosity of the viscous component} \]

The Phan-Thien-Tanner model (PTT-model) is based on the network theory of polymer melts \[6, 7\]. Following Equation 5 the Phan-Thien-Tanner model is formulated.

\[ \exp \left( \frac{\xi}{\eta} \right) \left[ \left( 1 - \frac{\xi}{2} \right) T_{ve} + \frac{\xi}{2} T_{ve} \right] = 2\eta D \]

\[ \text{Eq. 5} \]

\[ \xi, \varepsilon : \text{material properties} \]

\[ T_{ve}: \text{lower convected time derivative of } T_{ve}, \text{ which follows the mathematical equation:} \]

\[ \nabla \cdot \frac{DT_{ve}}{Dt} = T_{ve} - \nabla \cdot \nabla T_{ve} \]

The material parameters were determined by measuring the linear viscoelastic properties and the shear viscosity of a high-density polyethylene using a cone-plate rheometer. Using the Software Polymat which is part of the commercial Polyflow software package, Fluent, Lebanon, USA, the parameters are fitted on basis of the measured curves.

The flow simulation inside and outside an extrusion die which forms the melt into an L-shaped profile are performed using the commercial Software Polyflow.

Figure 3 shows the flow channel geometry. At the inlet the flow is fully developed. This boundary condition causes not only a velocity profile but also a stress profile across the inlet. The velocity is set to zero at the wall (no-slip condition). Behind the die exit the nodes are able to move. Thus, the shape of the extrudate is computed as a part of the solution. There are no forces on the extrudate and the surface tensions are neglected. Because a nonlinear equation system has to be solved and the free surface has to be computed, an evolution procedure is used which is available in the Polyflow package \[8\].

To evaluate the calculated die swell, of the die swell was measured experimentally. Figure 4 and 5 show the measured as well as calculated area swell ratios at different throughputs. The area swell ratio is defined as the ratio of the calculated area of the cross-section at a certain distance behind the die and the area of the cross-section at the outlet. Right behind the die the area swell is predicted too high and hardly changes until the end of the measuring range. Using the Phan-Thien-Tanner model the area swell is computed lower than the measured one at the end of the measuring range. On the other hand using the Giesekus-model higher area swell is predicted compared to the measured area swell. Although the course of the swell is not calculated correctly the final area swell is computed in a close range to the measurements depending on the model. Using the Phan-Thien Tanner model the calculated area swell is in close range to the measured one at a low throughput. The Giesekus-model however shows better results at higher throughputs. In all simulation and experimental results it can be observed that a higher throughput causes a higher die swell. Because with a higher output the residence time decreases and the melt has less time to reduce the introduced stresses and a higher die swell is computed.
Fig. 4: Die swell measured and calculated at a throughput of 0.48 kg/h

Fig. 5: Die swell measured and calculated at a throughput of 0.88 kg/h

Conclusion

Combining a method which computes the flow conditions inside a flow channel with an optimisation strategy, complex flow channel geometries can be optimised. An even velocity distribution at the outlet is achieved. However, using the current calculation method only the shear-thinning behaviour of the polymer melt can be considered. Because of the elasticity of polymer melts, the shape of the extrudate changes after leaving the die. If the die swell is taken into consideration, the behaviour of the melt has to be modelled using viscoelastic material models. Modelling the material with the Giesekus and PTT-model the shape of the extrudate behind the die is calculated in fairly good agreement to the experimentally measured shape.

In the future to reach the aim of optimising flow channels considering the die swell, the calculation method has to be expanded to viscoelastic material models and to calculate the free surface.

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