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Effect of die's annual width on the extrudate swell of plastic tube

Zhong Ren[1, 2*] and Xingyuan Huang[2]

[1]Key Laboratory of Optic-Electronic and Communication, Jiangxi Science and Technology Normal University, Nanchang, 330038, China
[2]School of Mechanical and Electrical Engineering, Nanchang University, Nanchang, 330031, China

*Corresponding author e-mail: renzhong0921@163.com

Abstract. To ascertain the effect of annual width on the extradite swell of plastic tube, the 3D extrusion forming of plastic tube was numerically studied. The geometric models and finite element meshes with different annual widths were established. Under the same material properties, boundary conditions, and numerical methods, the extradite swell situations of plastic tube (i.e., inner radius, outer radius, and wall thickness) were obtained. Numerical results show that the extradite swell ratio of plastic tube decreases with the increasing of the annual width.

1. Introduction

Extrusion forming is one of most important methods of manufacturing the plastic tube. The plastic tube can be widely used in some fields, such as, architecture engineering, medical diagnosis, optical communication, etc. The extrusion forming of plastic tube is achieved by using the extruder, cooling device, and traction device. Moreover, the extrusion die of plastic tube is also an important component. The structure of the extrusion die directly impacts the quality of the extruded plastic tube. As we know, the polymer melt has the strong viscoelastic characteristics, which will generate the serious extrusion swell problem of the extruded plastic tube [1, 2], especially for the higher flow velocity. The extradite swell of plastic tube will bring the more difficulty to the adjusting of the extrusion process. The extradite swell of plastic tube is dependent to many factors, such as, the physical properties of polymer melt, screw speed of extruder, temperature, structure of the extrusion die, etc. [3]. In this paper, the effect of the structure of extrusion die on the extradite swell of plastic tube was studied. For the extrusion die of plastic tube, there is the mandrel in the channel of die, which lead to form the annual channel. To ascertain the effect of die's annual width on the extrusion swell of plastic tube, the numerical simulation of polymer melt flow in the annual channel of die was investigated. The velocity distributions, pressure distribution, and stress distribution were obtained. The mechanism of extradite swell of polymer melt induced by the annual width was analyzed.

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2. Numerical simulation

2.1. Geometric model.
The geometric model of plastic tube is shown in Figure 1.

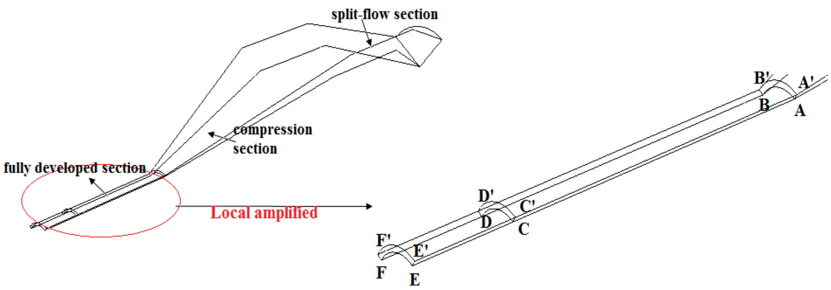

Figure 1. Geometric model of plastic tube extrusion forming

From Figure 1, it can be know that the structure of plastic tube consists of the split flow section, compression section, and fully developed section. The local amplified figure of the fully developed section is shown in the right side of the Figure 1. That is, AA'BB'CC'DD' is the fully developed section of plastic tube. The length of fully developed section is about 30mm. The split-flow angle is about 51°, the length of compression section is about 58mm. The diameter of the mandrel is 5mm.

2.2. Governing equations
The governing equations are given as follows:

$$\textit{Continuity equation:}\ \nabla \cdot v = 0 \tag{1}$$

$$\textit{Momentum equation:}\ \nabla p - \nabla \cdot \tau = 0 \tag{2}$$

Where ∇ is Hamilton operator, v is the velocity of melt, p is the pressure, τ is the extra stress tension.

In this paper, PTT model [4] was used as the constitutive equation, which is given as follows:

$$\exp\left[\frac{\varepsilon\lambda}{(1-\eta_r)\eta} tr(\tau_1)\right]\tau_1 + \lambda\left[\left(1-\frac{\xi}{2}\right)\overset{\nabla}{\tau_1} + \frac{\xi}{2}\overset{\Delta}{\tau_1}\right] = 2(1-\eta_r)\eta D \tag{3}$$

where $\eta_r = \eta_2 / \eta$ is the viscosity ratio, η is the total viscosity of the melt, η_2 is the Newtonian viscosity component of the melt, λ is the relaxation time, ε and ξ are the parameters of the melt correlated with the material tensile and the shear characteristics, respectively. $\overset{\nabla}{\tau_1}$ Is the upper convicted derivative of the extra stress tensor τ_1, η_1 is the Non-Newtonian component viscosity of the melt, D and is the strain-rate of the tensor.

In this paper, the viscosity (η) of PTT construction model is 6000 Pa.s, relaxation time (λ) is 0.2 s, the parameter of ε and ξ are 0.18, and 0.23, respectively. The viscosity ratio is 0.12.

2.3. Boundary conditions
(1) Inlet: Supposed that the flow of melt is looked as the full-developed, steady and laminar flow:

$$\partial v_z / \partial z = 0, v_x = v_y = 0 \tag{4}$$

Where v_x, v_y, and v_z are the flow velocities of melt at the direction of x, y, and z , respectively.

(2) Wall: The no-slip boundary condition is imposed on the wall of die's channel:

$$v_n = v_s = 0 \tag{5}$$

Where n, and s are the normal and tangential direction, respectively.

(3) Free boundary: the zero normal stress and entangle velocity are imposed, i.e.

$$f_n = 0\,,\ f_s = 0 \text{ and } v_n = 0 \tag{6}$$

At the same time, the surface tension was ignored. There is no any pressure in the lumen of plastic tube.

(4) Symmetric boundary: The following conditions should be satisfied,

$$v_n = 0,\ f_n = 0,\ f_s = 0 \tag{7}$$

(5) Outlet: The zero trance force and entangle velocity are imposed, i.e.

$$f_n = 0\,,\ v_s = 0 \tag{8}$$

3. Numerical results and analysis

3.1. Extradite swell ratio

In this paper, three extradite swell ratios, i.e., inner radius, outer radius, and wall thickness were computed. The extradite swell ratios of plastic tube with different annual widths are obtained, which are shown in Figure 2.

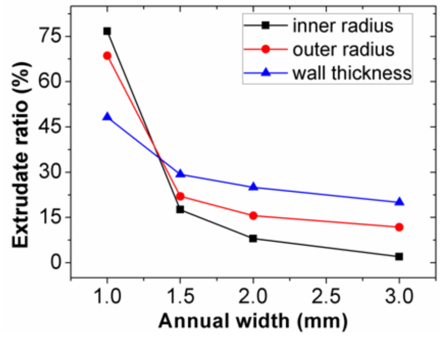

Figure 2. Extradite swell ratio of plastic tube with different annual widths

From Figure 2, it can be seen that, when the annual width is equal to 1mm, the extradite swell ratio of inner radius is larger than others, the extradite swell ratio of wall thickness is smallest. However, when the annual width is larger than 1.5mm, the extradite swell ratio of inner radius is smallest, but the extradite swell of wall thickness is largest. Moreover, from Figure 2, it can be seen that with the increase of the annual width, the extradite swell ratio of plastic tube decreases. In order to ascertain the mechanism of the effect of annual width on the extradite swell of plastic tube, the physical field distributions should be analyzed.

3.2. X velocity distribution

In this paper, four different annual widths of plastic tube were used, i.e., 1mm, 1.5mm, 2mm, and 3mm. On the inlet face, the same inlet volume flow rate of melt was imposed, i.e., Q=25mm^3/s. The X velocity distributions of plastic tube at the outlet of the die are shown in Figure 3.

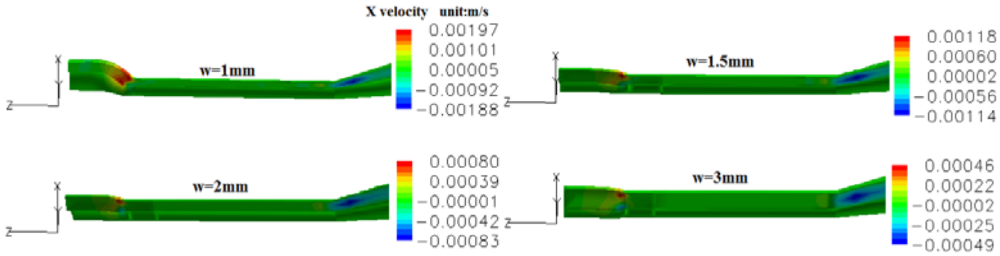

Figure 3. X velocity distributions of plastic tube with different annual widths

From Figure 3, it can be seen that with the increase of the annual width (i.e., w), the X velocity of polymer melt at the outlet of the die decreases.

3.3. Pressure distribution

The pressure distributions of plastic tube with different annual widths are shown in Figure 4.

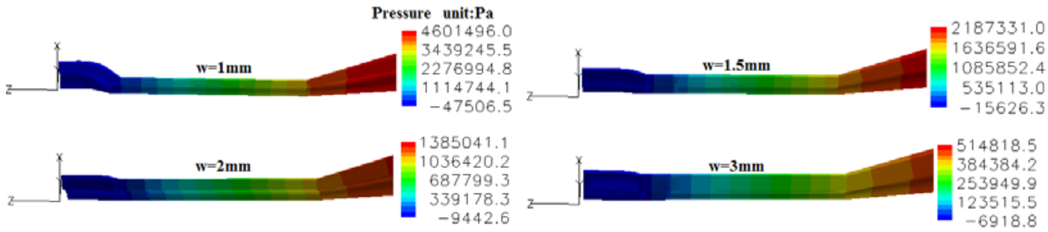

Figure 4. Pressure distributions of plastic tube with different annual widths

From Figure 4, it can be seen that, when the melt with same volume flow volume was imposed on the inlet surface of the die, with the increasing of the annual width of die, the pressure of the plastic tube’s melt decreased.

3.4. First normal stress difference distribution

The first normal stress difference (i.e., N1) distributions of plastic tube with different annual widths are shown in Figure 5.

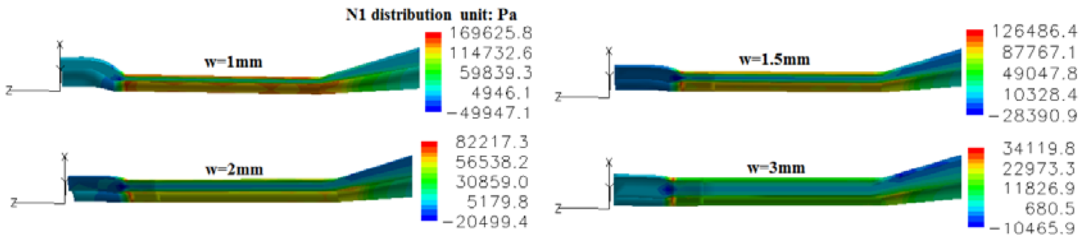

Figure 5. N1 distributions of plastic tube with different annual widths

From Figure 5, it can be seen that, when the melt with same volume flow volume was imposed on the inlet surface of the die, with the increasing of the annual width of die, the first normal stress difference of the plastic tube’s melt decreased.

According to Figure 3, 4, and 5, the reason of decreasing the extradite swell for the plastic tube can be expressed as follows: under the same inlet volume flow rate, with the increasing of the annual width, the X velocity at the outlet of die, pressure, and first normal stress difference of plastic tube all decrease. Therefore, the extradite swell effect should be fully considered when the plastic tubes with thin wall thickness are extruded.

4. Conclusion

In this paper, the effect of annual width on the extradite swell of plastic tube was numerically studied by using the computed fluid dynamics software POLYFLOW. The geometric model and finite element meshes of plastic tube with different annual widths are established. The same material properties, boundary conditions, and numerical methods are imposed. Numerical results show that with the increase of the annual width, the extradite swell of plastic tube decrease.

Acknowledgments

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