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Numerical Study on Effect of the Slippage on the Cross-Section Size and Profile for Inverse Extrusion Forming of Plastic Micro-Tubes

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Abstract. We studied the effect of slippage on the size and profile of outlet cross-section for the extrusion forming of plastic micro-tubes by means of finite element software Polyflow. The same material and process parameters were imposed on the established geometric model and mesh. The inverse extrusion forming method was used in the numerical simulation. The different slip coefficients were imposed on the surface of the inner and outer wall of plastic micro-tube. Numerical results show that with the increasing of the slip coefficient, the size of inner and outer diameter for the outlet cross-section is smaller and the profile is gradually distorted, which will increase the difficulty of the design and manufacture for the outlet cross-section of extrusion die. The filed distributions of melt with different slip coefficients were also obtained. The results show that the increasing of X flow velocity, nonuniform Z velocity and the increasing of the shear rate at the outlet face induced by the increasing of the slip coefficient are the main factors of changing the size and profile for the outlet cross-section of plastic micro-tube extrusion forming.

1. Introduction

Plastic micro-tubes have a great deal of economic and application values because it can be used in many fields including the medical diagnosis [1], optical communication, automobile oil or gas tube, precision instruments etc. The main manufacture way of the plastic micro-tubes is the extrusion forming [2, 3] of molten melt by means of the extruder, die, cooling device, tractor, etc. In the process of the extrusion forming of the plastic micro-tubes, the design and manufacture of the extrusion die [4] is one of most important work. At the same time, the size and profile of the cross-section for the outlet of the die can directly impact the extrudate quality of the plastic micro-tubes. Except for the material properties, structure of die, process parameters, the interface situations between the melt and the surface of die's channel can also impact the extrusion quality of plastic micro-tubes. As we know, the interface between the melt and the surface of die's channel can be different when the shear stress of melt is changed at the interfaces, which will impact the flow behaviors of melt and extrudate qualities. Therefore, during the design of the outlet cross-section of the die, the slippage between the melt and the surface of the die's channel should be considered. In this paper, the effect of the slippage on the cross-section profile of die for extrusion forming of plastic micro-tubes was numerically studied by using the finite element software Polyflow [5]. The change laws of slippage on the size and profile of outlet cross-section for the plastic micro-tubes were obtained under the fixed process and material parameters.

2. Numerical Simulations

2.1. Geometric Models

The geometric model of plastic micro-tube was established, which is shown in Figure 1(a). The cross section is shown in Figure 1(b). The outer diameter and the wall thickness of plastic micro-tube are 3mm and 0.5mm, respectively. The lengths of plastic micro-tube's melt inside and outside die are all 10mm.

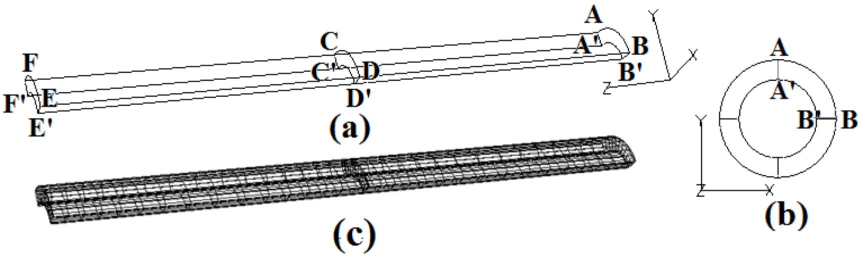

Figure 1. The geometric model of plastic micro-tubes (a), the cross section (b), and the finite element mesh (c).

The finite element mesh is shown in Figure 1(c). To improve the numerical precision, the mesh was refined near the surface and interface of the boundaries. The finite element mesh number is 1920.

2.2. Governing Equations

The melt of plastic micro-tubes is regarded as the iso-thermal, steady, non-Newtonian, and laminar fluid. At the same time, the gravity and inertia force were neglected due to the properties of high viscosity and low flow velocity. Based on these above reasonable hypotheses, the governing equations are given as follows,

$$\nabla \cdot v = 0 \tag{1}$$

$$\nabla p - \nabla \cdot \tau = 0 \tag{2}$$

where, ∇ is Hamilton operator, which is equal to $\nabla = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$. v is the flow velocity, p is pressure drop, τ is the extra stress.

In the numerical simulation, the constitutive model should be used to describe the rheological properties of plastic micro-tube's melt. In this paper, Phan-Thien–Tanner (PTT) constitutive model [6] was used, which is shown as follows,

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

where, ε and ξ are the parameters correlated with the characteristics of tensile and the shear, respectively. λ is the relaxation time of melt, $\overset{\nabla}{\tau}$ and $\overset{\Delta}{\tau}$ are the upper and lower convected derivative of the extra stress tensor τ, respectively. η is the total viscosity of melt, $\eta_r=\eta_2/\eta_1$ is the viscosity ratio, η_1 is the Non-Newtonian component viscosity of the melt, η_2 is the Newtonian viscosity component of the melt. D is the strain-rate of the tensor.

2.3. Boundary Conditions

(1) inlet face: In Figure 1(a), ABA'B' is the inlet face. Supposed that the melt flow has already full-developed, the following relationship should satisfy, i.e., $\partial v_z/z=0$, $v_x=v_y=0$, where, v_x, v_y, and v_z are the flow velocities of melt at x, y, and z direction.

(2) wall face: ABCD and A'B'C'D' are the outer wall and inner wall of plastic micro-tube,

respectively. In this paper, the different slip conditions are considered, the slip equation is given as follows, i.e., f_s=-$F_{\text{slip}}\times(v\text{-}v_{\text{wall}})^{eslip}$, where, F_{slip} is the slip coefficient, for the no slip flow, $F_{\text{slip}}=10^9$. For the full slip flow, $F_{\text{slip}}=0$. e_{slip} is equal to 1.

(3) free face: CDEF and C'D'E'F' are the free faces. The following relationships are satisfied, i.e., $f_n=f_s=0$.

(4) exit face: EFE'F' is the exit face. Supposed that the traction velocity of 0.04m/s was imposed on the exit face, the following relationship should be satisfied, i.e., v_n=-0.04m/s, v_s=0.

2.4. Rheological Parameters

In the simulations, the rheological parameters of PTT constitutive model is given in Table 1.

Table 1. The rheological parameters of PTT constructive model

Parameters	η(Pa.s)	λ(s)	ε	ξ	η_r
Values	2700	0.2	0.23	0.18	0.12

3. Numerical Results and Analysis

3.1. Effect of Slippage on the Size and Profile of Outlet Cross-Section

The volume rate of 40mm^3/s was imposed on the inlet face, the traction velocity of 0.04m/s was imposed on the exit face. By means of the finite element computing for inverse extrusion of plastic micro-tube, the outlet cross-section profiles and sizes of the plastic micro-tubes with different slip coefficients of die's channels were obtained, which are shown in Figure 2(a), and (b).

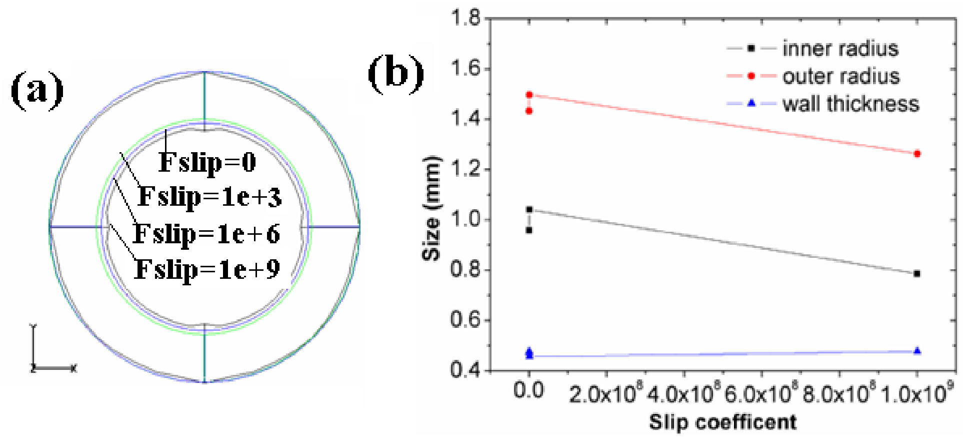

Figure 2. Effect of slippage on the size and profile of outlet cross-section. (a) outlet cross-section profiles, (b) sizes of the plastic micro-tubes with different slip coefficients of die's channels

From Figure 2, it can be seen that the sizes and profiles of plastic micro-tube are nearly same when the slip coefficient is less than $1\times10^{+3}$. However, when the slip coefficient is larger than $1\times10^{+3}$, it can be seen that the inner radius of cross-section at the outlet of die decreases, and the outer radius of cross-section at the outlet increases, which result in the increasing of the wall thickness, i.e., the annular width of die's channel was increased with the increasing of the slip coefficient when the process and material parameters are same. At the same time, from Figure 2(a), it can be found that the profile of outlet cross-section is distorted when the slip coefficient is equal to $1\times10^{+9}$, i.e., the extrusion forming of plastic micro-tube with no slippage, which will increase the difficulty of die designing and process stability controlling.

3.2. Distribution of Flow Velocity

To ascertain the effect of slippage on the size and profile of plastic micro-tube, the field distributions of X and Z flow velocity are obtained, which are shown in Figure 3(a), and (b).

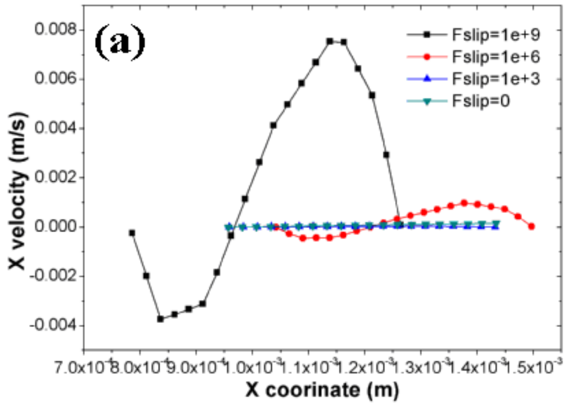

Figure 3. Effect of slippage on the flow velocity. (a) X velocity; (b)Z velocity.

From Figure 3(a), it can be seen that when the slip coefficient is less than $1\times10^{+3}$, the field distributions of X and Z flow velocities are same. Moreover, for the slip coefficient is less than $1\times10^{+3}$, the X flow velocity is equal to 0. However, with the increasing of the slip coefficient, the amplitudes of X flow velocity increase. When the slip coefficient reach the maximum value, i.e., the extrusion forming of no slip, it can be seen that the X flow velocity obviously occurs at the outlet cross-section of die, which show that the extrudate swell phenomenon is generated at the time of traditional extrusion forming with no slip, and the extrusion forming with full slip can greatly eliminate the extrudate swell of plastic micro-tube. From Figure 3(b), it can be seen that when slip coefficient is less than $1\times10^{+3}$, the field distribution of Z velocity is uniform. However, with the increasing of the slip coefficient, the Z velocity near wall will be decreased, but the Z velocity in the middle of the channel is increased, which illustrates that with the increasing of slip coefficient, non-uniformity of the Z flow velocity will result in the extrusion distortion (See Figure 2(a)). At the same time, from Figure 2, it can be seen that the position at X coordinate and size of outlet cross-section is different for the different slippages.

3.3. Distribution of the Shear Stress

Then, the field distributions of shear stress at the outlet cross-section of die with different slip coefficients were obtained, which are shown in Figure 4.

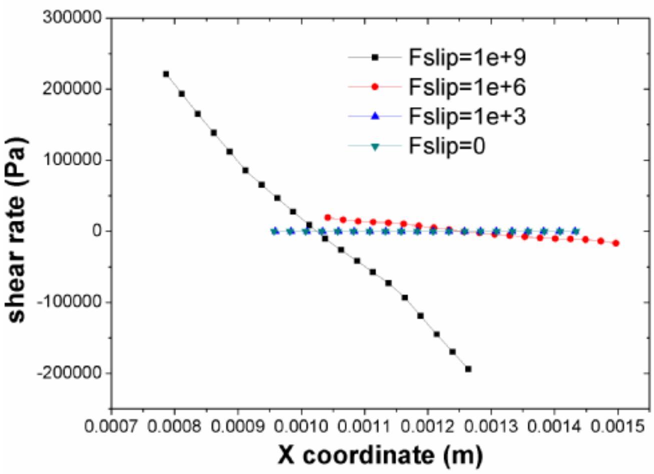

Figure 4. Distributions of shear stress with different slip coefficients

From Figure 4, it can be seen that the shear stress is very large especially near the surface of wall for the slip coefficient is equal to $1\times10^{+9}$, i.e., the traditional extrusion forming with no slip. With the decreasing of the slip coefficient, the shear stress of melt decreases, the shear stress of melt is equal to 0 when the slip coefficient decrease to 0, i.e., extrusion forming with full slip. As we know, the shear stress is one of most important factors of not only storing the elastic energy of melt molecular to generate the extrudate swell phenomenon, but also generating the extrudate fracture when the shear stress reaches the inherent tensile resistance. Therefore, the effect of slippage on the size and profile of outlet cross-section is also induced by the melt suffered from different shear stress effects in the channel of die.

4. Conclusion

In this paper, the effect of slippage on the size and profile of outlet cross-section of die for extrusion forming of plastic micro-tube were numerically studied by using the finite element method. Based on the same geometric model, material parameters and process parameters, the inverse extrusion forming method was used. The different slip coefficients were imposed on the boundary of the die's channel, i.e., the inner and outer wall of melt. Numerical results show that the inner and outer radius of outlet cross-section decrease but the annular width increases with increasing of the slip coefficient. Moreover, the profile of outlet cross-section is distorted when the no slip effect occurs on the surface of channel wall. The field distributions results illustrate that the slippage effect results in the different distributions of flow velocities and shear stress.

Acknowledgments

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