Numerical Simulation of Gas-Assisted Extrusion of Four-Lumen Micro-Catheter based on FEM Method

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Abstract. In this work, the gas-assisted extrusion of four-lumen micro-catheter (FLMC) was numerically studied by computed fluid dynamics (CFD) software software Polyflow. The extrudate profiles and die swell ratios of FLMC for the gas-assisted extrusion are gotten, and compared with those of the traditional extrusion. Results show that the die swell of FLMC is eliminated by the gas-assisted extrusion. To analyze the effects of gas-assisted on the elimination of die swell, the flow velocities, pressure, shear stress, and the first normal stress difference distributions of melt were obtained for both extrusions. Results show that compared with the results of traditional extrusion, the radial velocities, pressure, shear stress and the first normal stress difference of FLMC for the gas-assisted extrusion are very little, and the axial flow velocity of melt is uniform, which can reduce the elastic energy storage and finally eliminate the die swell problem.

1. Introduction

In the medical interventional micro-catheters, the four-lumen micro-catheter (FLMC) can be used in some catheters, such as central vena cava catheter, urinary catheter, balloon catheter. In general, the FLMC is manufactured by the continuous extrusion forming of polymers. In practice of production, the manufacture of FLMC should mainly rely on the special design of extrusion die. Since the molten melt has the high properties of viscosity and elasticity, and suffers from the large shear and tensile stresses in the channel of die, the die swell [1, 2], and extrusion deformation [3, 4] problems will be easily produced. To overcome these problems, the cross-section profile of die outlet is usually designed to different from the cross-section profile of FLMC [5]. And lots of times of die trail and repair should be performed to get a specified die [6]. However, when some processes of extrusion, e.g., screw speed, temperature, traction speed, the unsatisfactory products will easily be produced. Therefore, for a kind of FLMC with a fixed profile and size, a set of process parameters are usually fixed. To improve the quality and efficiency of the products, as well as to solve the extrusion problems, the gas-assisted extrusion technique [7-10] was used in this study. To analyze the effect of gas-assisted on the elimination of the extrusion problems, the numerical simulations of gas-assisted extrusion of FLMC were performed by using finite element method (FEM). At the same time, the numerical results of gas-assisted extrusion of FLMC were compared with those of traditional extrusion.

2. Model

Figure 1 is the geometric model of FLMC. The cross-section and size are given in Figure 1(a), the
outer radius of FLMC and inner radius of inner cavity are 1.5mm, and 1.1mm. The thicknesses of outer wall and the inner ribs are 0.3mm, and 0.2mm. The axial section of FLMC is shown in Figure 1(b), the lengths of inside and outside die are all 10mm. The finite element mesh of Figure 1(b) is also given. Hexahedral mesh structure was used, and the meshes are refined near the boundaries to improve the numerical precision. The mesh number is 2000.

![Figure 1. Geometric model. (a) cross-section and size; (b) 1/4 part of axial section and finite element mesh](image)

3. Numerical Simulations

3.1. Governing Equations

The visco-elastic, non-Newtonian, steady, iso-thermal, and laminar fluid was used for melt during the extrusion process. Additionally, the gravity force and inertia force were all neglected. The continuity and momentum equations are given,

$$\nabla \cdot \mathbf{v} = 0$$

$$-\nabla p + \mathbf{\tau} = 0$$

where $\nabla$ is the Hamilton operator. $\mathbf{v} = \left( v_x, v_y, v_z \right)$ is the flow velocities of melt at $x$, $y$, and $z$ coordinates, respectively. $p$ is the pressure. $\mathbf{\tau}$ is the extra stress tensor.

In this work, the constitutive model was Phan-Thien-Tanner model [11], i.e.,

$$\mathbf{\tau} = \tau_1 + \tau_2$$

$$\exp\left[ -\frac{\varepsilon}{\left(1 - \eta_2/\eta_1\right)\eta} \right] \tau_1 + \lambda \left[ \left(1 - \frac{\xi}{2}\right)\tau_1 + \frac{\xi}{2}\tau_1 \right]$$

$$= 2(1 - \eta_2/\eta_1)\eta D$$

$$\tau_2 = 2\eta D$$

where $\tau_1$ and $\tau_2$ are respectively the elastic component and viscous component of $\tau$. $\varepsilon$ and $\xi$ are respectively the parameters about shear viscosity and elongational behavior. $\lambda$ is the relaxation time. $\eta$ is the total viscosity of melt. $\eta_i = \eta_2/\eta$ is the viscosity ratio. $D$ is the melt rate-of-deformation tensor. $\nabla$ and $\Delta$ are respectively the upper convected derivative and below convected derivative of $\tau_1$.

3.2. Boundaries

In Figure 1(b), the boundaries were set as follows,

ABCDOE: the inlet face. The volume flow rate of 0.1mm$^3$/s was imposed on ABCDOE.
LMNPRQ: the exit face. Without any normal force and tangential velocity imposed on exit face.

ABGF, CDGH, CEJH, DEJI: the walls. For the traditional extrusion, the fixed wall condition was used. But for the gas-assisted extrusion, the full-slip condition was simply used to represent the gas-assisted role.

FLMG, HGPN, HJQR, IJQP: the free faces. These faces can be free when they are extruded from die.

ALRO, OBMR: symmetric faces. Without the normal force and tangential velocity on the symmetric face.

3.3. Parameters of Constitutive Model

The parameters of PTT model in the simulation are given in Table 1.

| Parameter | Value |
|-----------|-------|
| $\eta$ (Pa·s) | 2700 |
| $\lambda$ (s) | 0.2 |
| $\epsilon$ | 0.23 |
| $\xi$ | 0.18 |
| $\mu$ | 0.12 |

4. Results and Discussions

4.1. Profiles

The extrudate profiles of FLMC based on traditional and gas-assisted extrusions are obtained by the FEM, which are shown in Figure 2(a), and (b). Figure 2(a) gives the cross-section of inlet and exit faces, and the integrated profiles for the traditional extrusion of FLMC. From figure, we can find that the profile and size of cross-section are very different between the inlet face and exit face. The cross-section of FLMC becomes more and more quadrate, and the fan-shaped inner cavities become rounder and rounder. The outer diameter, radius of inner cavities, wall thickness are all larger. From the axial profile, we can see that the swell problem is generated when the melt was extruded from the die outlet. However, for the gas-assisted extrusion, from Figure 2(b), the profile and size are nearly not changed. And the swell phenomenon at the die outlet doesn’t appear.

To further compare the profile and size changes of FLMC between the gas-assisted extrusion and the traditional extrusion, the swell ratios of diameters and thicknesses were computed, which are shown in Figure 3(a), and(b), respectively.
Figure 3. Swell ratios of FLMC. (a) swell ratios of diameter; (b) swell ratios of thickness.

From Figure 3, we can know that the swell ratios of diameter are about 50% for the traditional extrusion, and the swell ratios of wall thickness are about 90%, although the few shrink appears at the inner ribs for FLMC. However, for the gas-assisted extrusion of FLMC, the swell ratios of diameters and thicknesses are nearly equal to 0. Therefore, the swell phenomenon of FLMC is eliminated by the gas-assisted extrusion.

4.2. Physical Fields Distributions

(1) Flow velocities distributions

To analyze the effect of gas-assisted role on the elimination of die swell for FLMC, some physical field distributions of melt for both extrusions were obtained by FEM. The flow velocities, radial velocities and axial velocity of melt are shown in Figure 4(a)-(f).

Figure 4. Flow velocities distributions of melt. (a) X velocity of traditional; (b) X velocity of gas-assisted; (c) Y velocity of traditional; (d) Y velocity of gas-assisted; (e) Z velocity of traditional; (f) Z velocity of gas-assisted.

From Figure 4(a)-(d), it can be found that the radial velocities of melt for traditional extrusion is about 4 orders of magnitudes more than those of the gas-assisted extrusion. Those large radial flow velocities just are the direct reflection of radial swell for FLMC. For the Z velocity, the Z velocity distribution of melt for traditional extrusion is non-uniform, the Z velocity of melt is zero on the walls and the Z velocity gradually increases towards the middle of die channel. However, for the gas-assisted extrusion, the radial velocities of melt outside die are very little, and the Z velocity distribution inside die is uniform. These little radial velocities and uniform axial velocity illustrate that the die swell of FLMC is eliminated.
(2) Pressure and stresses distributions
To find the reason that the die swell can be eliminated by the gas-assisted method, the pressure, shear stress, and the first normal stress difference distributions of melt for both extrusions were all obtained, which are shown in Figure 5(a)-(f).

Figure 5. Pressure and stresses distributions. (a) pressure distributions of traditional; (b) pressure distributions of gas-assisted; (c) shear stress distributions of traditional; (d) shear stress distributions of gas-assisted; (e) first normal stress difference distributions of traditional; (f) first normal stress difference distributions of gas-assisted

From Figure 5, we can find that the pressure, shear stress and the first normal stress difference distributions of melt for traditional extrusion is about 4-6 orders of magnitude to those of the gas-assisted extrusion. Since the larger pressure, shear stress and first normal stress difference of melt, the larger elastic energy storage and orientation effect of molecular chains, which will produce the larger die swell at the time of extruding from the die outlet. However, for the gas-assisted extrusion, the pressure, shear stress, first normal stress difference of melt are too much small, the elastic energy storage and orientation effect of molecular chains are also few, which eliminates the die swell of FLMC.

5. Conclusion
FLMC is usually used in the fields of medical interventional diagnosis and treatment. But in the manufacture of FLMC, the die swell and deformation can be generated. In this paper, the gas-assisted extrusion technique was used to eliminate the die swell problem of FLMC. The numerical simulations of gas-assisted extrusion of FLMC were performed by using the CFD software Polyflow. The extrudate profile and die swell ratio of FLMC based on the gas-assisted extrusion were obtained and compared with those of the traditional extrusion. Then, the flow velocities, pressure, stresses distributions of melt for both extrusions were all obtained and compared. Results show the gas-assisted extrusion can reduce the pressure, stresses distributions in the die channel. In addition, the radial velocities of melt near the die outlet can be decreased, and the axial velocity of melt is uniform. These reasons eliminate the die swell phenomenon of FLMC under the gas-assisted extrusion.

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7. References
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