Influence of gas layers length on the gas-assisted extrusion molding of plastic microtubule

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Abstract: The influence of gas layers length (GLL) on gas-layers assisted extrusion molding (GAEM) for plastic microtubule (PMT) was investigated by the numerical method in this paper. Meanwhile, 3D models with different GLLs of die’s channel were established. Based on the same flow rate imposed on inlet and other boundaries, the influences of the GLL on the extrusion swell of PMT were studied. The extrusion swell ratios of the different GLLs were obtained. Results show that with the increasing of the GLL, the extrusion swell phenomenon of PMT is reduced. To clear the mechanism for the influence of GLL on the GAEM of PMT, the pressure, stresses distributions were also obtained. Numerical results show that with the increasing of GLL, the decreased pressure, stresses of melt are the main reason of eliminating the extrusion swell of GAEM for PMT.

1. Introduction

PMT has popularly applied in varies of fields, for example, interventional medical treatment, optical fiber sleeve, and precision instrument. Among them, the application in the medical field for PMT is especially very important, and its demands become more and more significant. There are many kinds of PMTs applied in the medical field. For example, central venous catheter, arteriography tube, balloon catheter, arteriovenous pressure catheter, medical trachea, drug administration catheter, etc. In general, the high quality and size precision is very important factors of influencing the quality of the PMT. The manufacture of the PMT is achieved by using the extrusion molding of the plastic melt [1, 2]. For the melt with inherent high viscoelastic properties, extrusion swell [3], surface rupture [4], and extrusion deformation [5] problems are easily generated during the extrusion molding of the PMT. Moreover, melt suffers from strong shear stresses and tensile stresses in the barrel and channel of die, which will result in the storage of elastic energy of melt and the orientation effect of melt molecular. At the time
of the melt is extruded from the die’s outlet, the extrusion swell of PMT occurs because the constraint of die’s channel is cancelled. Moreover, the melt fracture or surface shark-skin phenomenon will also occur due to the flow velocity rearrangement and rapid radial or axial swell effect of PMT. These problems are more serious with the increasing of the extrusion speed of PMT. In order to overcome these drawbacks of the extrusion molding for the PMT, the GAE molding method [6-8] was used in this study. However, the length of GL will influence the quality of the GAEM of PMT. If the length of GL is short, the extrusion swell phenomenon will still exist in the extruded plastic products. Although the extrusion swell can be eliminated by the longer length of GL, the unsteady situation, e.g., surface waveform, will be occurred on the surface of the PMT. However, in order to obtain the optimum length of GL, the influence of GLL on the GAEM of PMT was numerically studied.

2. Numerical simulations

2.1 Models

Geometric model of PMT is shown in Fig.1, where Figure 1(a) is the cross sectional sizes of PMT. The internal radius is set to 2mm, and external radius is set to 3mm. Since geometric structure of PMT is axis-symmetric, 1/4 part of geometric model was used in this study, which is presented in Figure 1(b). The model consists of three sections, i.e., without GL, GL, and the free section. The length of without GL and free section are set to 5mm and 10mm, respectively. To study the influence of GLL on the GAEM of PMT, the GLL can be adjusted, which is respectively set to 1mm, 2mm, 5mm, 10mm, and 15mm.

Figure 1. Numerical models of PMT. (a) cross sectional sizes; (b) 1/4 part geometric model

2.2 Governing equations

Governing equations of numerical computing are as follows,

$$\nabla \cdot \vec{u} = 0$$  \hspace{1cm} (1)

$$\nabla \vec{P} - \nabla \cdot \vec{\tau} = 0$$ \hspace{1cm} (2)

In Eq.(1) and (2), $\vec{P}$ is melt’s pressure vector, $\vec{u}$ is melt’s velocity vector, $\nabla$ is Hamilton operator, $\vec{\tau}$ is the partial stress tensor.

Material properties of melt described by using phan thien tanner constitution model was chosen in simulations, i.e.,

$$\exp\left[\frac{\varepsilon \lambda}{(1 - \eta_s)}tr(\vec{\tau})\right] \vec{\tau} + \Lambda \left[1 - \frac{\zeta}{2} \frac{\varepsilon}{\tau} \frac{\zeta}{\tau} \right] = 2(1 - \eta_s)\eta D$$ \hspace{1cm} (3)

In Eq.(3), $\varepsilon$, $\zeta$ are the melt’s material parameters with tensile and shear, respectively. $\Lambda$ is relaxation time, $\frac{\zeta}{\tau}$ and $\frac{\varepsilon}{\tau}$ are lower and the upper adjoint derivatives of partial stress tensor $\vec{\tau}$. $D$ is the
deformation stress tensor. $\eta$ is total viscosity, $\eta_1$ and $\eta_2$ are melt’s Non-Newtonian component viscosity and Newtonian viscosity component, respectively. $\eta_r=\eta_2/\eta_1$ is viscosity ratio.

2.3 Configuring of boundary conditions

1) walls: IJLK and I’J’K’ are respectively internal and external walls at without GL of die. For these two walls, no slip boundary was set, i.e., $v_s=v_n=0$. In addition, KLAB and K’L’A’B’ are the internal and external walls at the GL section, the full slip boundary was set, i.e., $v_n=f_s=0$. $v_n$ and $v_s$ are melt’s velocities at normal direction and tangential direction, respectively. $f_s$ is the tangential force of melt.

2) inlet: in Fig.1, IJJ’I’ is the boundary of melt’s inlet. Supposed that the melt has been already full-developed when it flows to the forming section of die’s channel, the kinetic equations can be abided, i.e., $\partial v_z/\partial z=0$, $v_z=v_y=0$, where, $v_x$, $v_y$, and $v_z$ are the melt’s velocities at direction of $x$, $y$, and $z$ coordination.

3) free faces: ABEH and A’B’E’H’ are the two free faces. Since no any forces at normal direction and tangential direction were exerted on the free faces, the kinetic relationships should be abided, i.e., $f_n=f_s=0$. where, $f_n$ is the normal stress of melt.

4) symmetric faces: II’E’E and JJ’H’H are the symmetric faces. The symmetric faces should satisfy the following relationships, i.e., $v_n=f_s=0$.

5) exit: EHH’E’ is the boundary of melt’s exit. Since there are no dragging forces were exerted on the exit, the following equations should be obeyed, i.e., $v_s=f_n=0$.

2.4 Parameters of constitutive model

The constitutive parameters of melt are offered in Table 1.

| Parameter | $\eta$ | $\dot{\lambda}$ | $\varepsilon$ | $\xi$ | $\eta_r$ |
|-----------|--------|-----------------|---------------|-------|---------|
| Value (Unit) | 2700(Pa.s) | 0.2(s) | 0.23 | 0.18 | 0.12 |

3. Simulation results

3.1 Influence of GLL on extrusion swell

In numerical simulation, at the inlet of melt, the flow rate was set to $1.5\times10^{-8}$. Under different GLLs, different extrusion swells of PMT were obtained and given in Figure 2.

![Figure 2. extrusion swell for different GLLs. (a) 1mm; (b) 2mm; (c) 5mm; (d) 10mm; (e) 15 mm](image)

From Figure 2, we can see that extrusion swell of PMT is very evident when the GLL is very short,
e.g., from 1mm to 5mm. When the length of GLL is larger than 10mm, extrusion swell of PMT can be eliminated.

To better reflect the impact of GLL on extrusion swell of PMT, extrusion swell ratios under the different GLLs are given in Figure 3.

![Figure 3. PMT’s extrusion swell ratios](image)

In Figure 3, swell ratios of PMT’s internal radius, external radius and wall thickness for plastic micro-tube exponentially all decrease with the increasing of the GLL. When the GLL reaches 15mm, the swell ratios of plastic micro-tube are equal to 0.

3.2 Influence of GLL on the pressure

To further clear the mechanism of GLL on GAEM of PMT, the influence of GLL on the pressure of PMT was researched, the pressures of PMT’s melt under the different GLLs were obtained, which are shown in Figure 4.

![Figure 4. Pressures of PMT’s melt under different GLLs](image)

In Figure 4, when GLL increases, the pressure of PMT’s melt exponentially decreases. The pressure value of PMT’s melt is nearly equal to 0 when the GLL reaches about 15mm.

3.3 Influence of GLL on the shear stress

The influence of GLL on the shear stress of PMT’s melt was also numerically researched, melt’s shear stress radial distributions at die outlet for different GLLs were gotten and shown in Figure 5.
In Figure 5, shear stresses of melt near the internal and external walls are largest for each length of GL. Moreover, with the increasing of the GLL, the melt’s shear stress gradually decreases. Shear stress of melt is nearly 0 when GLL is 15mm, that is, the melt’s elastic storage energy can be well eliminated when the length of the GL is set to about 15mm, which lead to eliminate the extrusion swell problem.

### 3.4 Influence of GLL on the first normal stress difference (FNSD)

Then, the research about the influence of GLL on the FNSD of PMT’s melt was performed, the FNSD distributions are shown in Figure 6.

Since extrusion swell of melt is also corrected with the FNSD of melt in the die’s channel, that is, the more FNSD, the more serious extrusion swell. From Figure 6, the FNSD radial distributions of melt decreases when the GLL increases. Moreover, when the GLL reaches about 15mm, the melt’s FNSD is nearly 0, which shows that the extrusion swell is eliminated.

### 4. Conclusion

In this study, the GAEM method was used to overcome the extrusion swell problems of PMT. To ascertain the influence of GLL on GAEM of PMT, the numerical simulations were numerically carried out. In the simulations, different GLLs of PMT were used. With the same flow rate was imposed on melt[s inlet, the swell ratio, pressure value, stresses of melt were obtained. Numerical results show that swell ratio, pressure value, stresses are all decrease when the GLL increases. Moreover, when the GLL reaches about 15mm, the extrusion swell problem can be well eliminated.
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