The Effects of Traction Velocity on the Gas-assisted Extrusion Forming and Traditional Extrusion Forming of Plastic Micro-tubes

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Abstract. The effects of traction velocity on gas-assisted extrusion (GAE) and traditional extrusion (TE) of plastic micro-tubes (PMTs) were numerically studied in this paper. Under same 3D geometric model, boundary conditions setting and constitutive parameters, the extrudate profile change and swell ratios of GAE and TE were all obtained. The radial and axial flow velocities, shear stress and first normal stress difference distributions of melt under different traction velocities were also gotten and compared. Results show that with the increase of traction velocity, the swell ratio increases first and then decreases. When the traction velocity is less than the axial velocity of melt, the radial velocity of melt outside of die increases, which demonstrates the generation of radial swell. When traction velocity is larger than that of the melt, the negative radial velocity of melt generates, which demonstrates the generation of shrinkage phenomenon. In addition, the changes of shear stress values and first normal stress difference values are not large, and the sudden increase of stresses always generates at the outlet die for the TE. However, the stresses of melt are well removed at the outlet of die, which demonstrates that extrudate swell and melt fracture problems are well eliminated by the GAE during the extruded PMTs dragged by traction velocity.

1. Introduction

Plastic micro-tubes (PMTs) have been used into many fields, such as optical communication, interventional medical treatment, and precision instrument system. In generally, the PMTs are produced by using the extrusion method of polymer melts, e.g., polypropylene, polyethylene, polyurethane, etc. In the process of extrusion forming, there are some extrusion problems, such as extrudate swell [1, 2], melt fracture [3] easily generated because the melt has the high viscoelasticity and suffers from the large stresses in the metal die channel. In this work, to overcome the extrusion problems of PMTs, the GAE method [4, 5] was used. At the same time, to obtain the PMTs with a certain size of cross section, the PMT should be dragged by a tractor in practice. Moreover, the traction velocity can be adjusted according to the practical needs. To study the effects of traction velocity on the GAE and TE forming of PMTs, the numerical simulations were performed by using the finite element computing software Polyflow in this paper. Under the same traction velocity and other parameters, the extrusion swell of PMTs for both extrusions was obtained. At the same time, to
compare the difference for the traction velocity effect on the both extrusion formings of PMTs, the flow velocities, pressures, stresses distributions of melt were obtained and compared.

2. Simulations

2.1 Model
The 3D geometric model of plastic micro-tube is shown in Figure 1(a). The inner radius and outer radius of PMTs are 1.0 and 1.5mm, respectively. The length of PMTs inside and outside die are all 5mm. In Figure 1(a), IJJ’I-KLL’K is the melt zone inside die, KLL’K-MNN’M is the zone outside die. The finite element mesh of Figure 1(a) is shown in Figure 1(b).

![Figure 1. Geometric model of PMTs(a), and finite element mesh (b)](image)

2.2 Equations
The numerical equations in the simulations are shown as follows,

\[
\nabla \cdot \mathbf{v} = 0
\]

\[
\nabla p - \nabla \cdot \tau = 0
\]

where, \( \mathbf{v} \) is the velocity vector of melt, \( p \) is the pressure vector of melt, \( \tau \) is the extra stress tension of melt, \( \nabla \) is Hamilton operator.

To describe the viscous-elastic properties of plastic pipe’s melt, in the simulations, Phan-Thien–Tanner (PTT) constitutive model [6] was used,

\[
\tau = \tau_1 + \tau_2
\]

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

\[
\tau_2 = 2(1-\eta_2)\eta_1 D
\]

where, \( \varepsilon \) and \( \xi \) are the parameters correlated with the material tensile and the shear characteristics, respectively. \( \tau_1 \) and \( \tau_1 \) are the upper and lower convected derivative of the extra stress tensor \( \tau_1 \). \( \eta_2/\eta_1 \) is the viscosity ratio, \( \eta_1 \) is the total viscosity, \( \eta_1 \) is the Non-Newtonian component viscosity, \( \eta_2 \) is the Newtonian viscosity component. \( \lambda \) is the relaxation time. \( D \) is the strain-rate of the tensor.

2.3 Setting boundary
Based on Figure 1(a), the boundary settings are given as follows,

1) The Inlet face: IJJ’I’ is the inlet face of plastic micro-tube. In the simulations, the melt is looked as the full-developed fluid in the forming section of die channel, the dynamic conditions are satisfied as follows, \( v_x=0, \ v_y=0 \). where \( v_x \) and \( v_y \) are the flow velocities of melt at the direction of \( x \) and \( y \) coordination, respectively.

2) The Walls: IJKL and I’J’K’L’ are the outer and inner walls. For the TE, the no slip condition was used, i.e., \( v_n=v_t=0 \); However, for the GAE, the full slip condition was used, i.e., \( v_n=v_t=0 \). where \( v_n \) and \( v_t \) are the normal and tangential flow velocities, \( f_n \) and \( f_t \) are the normal and tangential stresses.
3) The free faces: KLMN and K'L'M’N’ are the free faces. \( f_i = f_s = 0 \), and \( v_n = 0 \).

4) End face: MNN'M is the end face of plastic micro-tube. Since the effect of traction velocity on the TE and GAE formings will be studied, a certain normal traction velocity was imposed on the end face. Therefore, the following condition should be satisfied, i.e., \( v_n \neq 0, v_s = 0 \).

2.4 Constitutive parameters

In the simulations, constitutive parameters of melt are given in Table 1.

| Parameters | \( \eta \) (Pa.s) | \( \lambda \) (s) | \( \varepsilon \) | \( \xi \) | \( \eta_r \) | \( \rho \) (kg/m\(^3\)) |
|------------|-----------------|----------------|-------|------|-------|-----------------|
| melt       | 2700            | 0.2            | 0.23  | 0.18 | 0.12  | 920             |

3 Numerical results and analyses

3.1 Effect of traction velocity on the extrudate swell of PMTs

In simulations, the volume flow rate of 1.0mm\(^3\)/s was imposed on inlet face of PMTs. Six different traction velocities were respectively imposed on the end face of PMTs. The extruded profiles of PMTs for different traction velocities for both extrusions are shown in Figure 2(a), and (b), respectively.

![Figure 2. Extruded profiles of PMTs for different traction velocities for both extrusions. (a) TE; (b) GAE](attachment:image)

The extrudate swell ratios (swell ratio of inner radius \( S_i \), swell ratio of outer radius \( S_o \), swell ratio of wall thickness \( S_w \)) of PMTs under the different traction velocities are shown in Figure 3.

![Figure 3. Effect of traction velocity on the extrudate swell of PMTs](attachment:image)

In Figure 3, when no traction velocity imposed on the end face of plastic micro-tube, the extrusion swell phenomenon is generated for the TE (\( S_i = 37.7\% \), \( S_o = 36\% \), and \( S_w = 32.6\% \)), but there is no any extrudate swell for the GAE (\( S_i = S_o = S_w = 0 \)). With the increase of the traction velocity, e.g., 0.4mm/s, the swell ratios all increase for both extrusions, i.e., for the TE, \( S_i = 61.547\% \), \( S_o = 58.267\% \), and \( S_w = 51.706\% \). For the GAE, \( S_i = 51\% \), \( S_o = 55.941\% \), and \( S_w = 65.822\% \). It can be found that although the
swell ratios of inner radius and outer radius for the TE are larger than that of GAE, the swell ratio of wall thickness is less than that of GAE. The reason is that for the TE, the swell ratio of inner radius is larger than that of the outer radius, but for the GAE, the swell ratio of outer radius is larger than that of the inner radius. Then, with the increase of traction velocity, e.g., 0.8mm/s, the swell ratios of PMTs for both extrusions all decrease. At the same time, the swell ratios for the GAE are slightly larger than that of the TE. When the traction velocity was continuously increased, the shrinkage phenomenon of PMTs was generated for both extrusions because the swell ratios of PMTs are negative. Moreover, with the continuous increase of traction velocity, the shrinkage phenomenon is more and more obvious because the negative swell ratios are increased.

3.2 Flow velocities distributions of melt
The radial velocity distributions of melt for TE and GAE of PMTs are shown in Figure 4(a), and (b), respectively. The axial velocity distributions of melt for TE and GAE of PMTs are shown in Figure 4(c), and (d), respectively.
Figure 4. Flow velocities distributions of melt for both extrusions under different traction velocities. (a) radial flow velocities distributions of melt for TE; (b) radial flow velocities distributions of melt for GAE; (c) axial flow velocities distributions of melt for TE; (d) axial flow velocities distributions of melt for GAE

In Figure 4(a) and (b), the radial flow velocity of melt is always generated at the outlet of die for all traction velocity for the TE. However, for the GAE, only when the traction velocity is less than the axial velocity of melt, the radial velocity of melt is generated at the outlet of die. Then, when the traction velocity of melt is larger than the axial velocity, the radial flow velocity of melt is negative, which demonstrates that the shrinkage phenomenon is generated. In Figure 4(c) and (d), the axial flow velocity outside of die increases with the traction velocity. Moreover, when the imposed traction velocity is less than the axial flow velocity of melt inside of die, the axial velocities of melt all decrease for both extrusions. When the imposed traction velocity is larger than the axial flow velocity of melt inside of die, the axial flow velocity of melt outside of die increase with the traction velocity. At the same time, there is a obvious difference can be found between the axial flow velocities of melt for both extrusions, i.e., at the outlet of die, the sudden increase of axial flow velocity is generated for the traditional extrusion rather than the gas-assisted extrusion, which demonstrates that the extrudate swell and melt fracture still be occurred at the outlet of die for TE. However, the extrusion problems can be eliminated by the GAE.
3.3 Stress distributions of melt

The effect of traction velocity on the shear stresses and the first normal stress differences of melt for TE and the GAE of PMTs are shown in Figure 5(a), and (b), respectively.

![Figure 5](image)

In Figure 5(a) and (b), although the shear stress change and the first normal stress difference change of melt are not large with the increase of the traction velocity, the shear stresses and first normal stress differences of melt inside of die for the TE are larger than that of the GAE. Moreover, at the outlet of die, the sudden increase of the shear stresses and the first normal stress differences of melt for the TE are always generated under all traction velocities. However, for the GAE, the stresses of melt at the outlet of die were greatly removed, which demonstrates that the extrudate swell and the melt fracture problems can be well eliminated by the GAE although the traction velocity is imposed on the end face of PMTs.

4. Conclusion

In this work, the effects of traction velocity on the TE and GAE of PMTs were numerically studied and compared. Numerical results show that with the increase of traction velocity, the swell ratio all increases first and then decreases for both extrusions. At the same time, the extrudate swell problems
are always generated at the outlet of die for the TE rather than the GAE. When traction velocity is less than axial velocity of melt, the radial flow velocity of melt outside of die all increases for both extrusions. Conversely, the negative radial velocity of melt outside of die is generated, which shows that the generation of shrinkage phenomenon. The shear stress and the first normal stress difference of melt at the outlet of die always exist in TE, which show that the extrudate swell and melt fracture problems always exist in the TE, but some extrusion problems are well overcomed by the GAE.

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