Numerical simulation on the influence of geometric size on the swell for traditional and gas-assisted extrusion of plastic micro-pipe

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Abstract. In this paper, to study the influence of geometric size on the swell of extrusion forming of plastic micro-pipe, we performed the numerical simulation based on the finite element software Polyflow. The geometric models of plastic micro-pipes with different inner diameters but same wall thickness were established. Under the same boundary conditions and material parameters, the extrusion forming and swell ratios of plastic micro-pipes with different sizes were obtained. At the same time, the numerical results of traditional extrusion forming were compared with that of the gas-assisted extrusion forming. Numerical results show that the swell ratio of outer diameter and wall thickness increase with the decreasing of the geometric size for the traditional extrusion, but the extrudate swell of plastic micro-pipe is well eliminated by using the gas-assisted method.

1. Introduction
Up to now, the plastic micro-pipe has lots of useful values in many fields, such as bio-medical diagnosis [1], optical communication [2], automobile gas/oil way, etc. Extrusion forming technique is the mainly traditional method of manufacturing the plastic micro-pipes [3, 4]. However, the extrudate swell [5], extrusion fracture [6] and extrusion distortion phenomenon will occur due to the pressure oscillation, uniform temperature distribution, residual elastic energy of melt, and rearrangement velocities etc. These above-mentioned problems are taken place for the macro size of plastic pipe. However, for the extrusion problems of the micro-pipe, there are few studies reported in the past time due to the micro-size effect should be considered. In this paper, the influence of geometric size on the traditional extrusion forming of the plastic micro-pipe was numerically studied by using the finite element software package Polyflow [7]. The extrudate swell ratios of plastic micro-pipe with the different inner diameters and same wall thickness were obtained. In order to ascertain the mechanisms of geometric size on the extrusion forming of plastic micro-pipe, the physical field distributions were also presented. In order to eliminate the extrusion problems of plastic micro-pipe, the gas-assisted extrusion method was used. At the same time, the influence of geometric size on the gas-assisted extrusion forming of plastic micro-pipe was also numerically investigated and compared with that of the traditional extrusion forming.
2. Numerical Simulation

2.1. Geometric Models
Figure 1(a) is the geometric model of plastic micro-pipe. A quarter section of plastic micro-pipe was used in the paper due to the axial symmetric structure. The cross section of the plastic micro-pipe was given in the right of Figure 1(a). In the figure 1(a), AA’ is the wall thickness of plastic micro-pipe, which is equal to 0.5mm. Six different inner diameters of plastic micro-pipes were used in this numerical simulation, which are 5mm, 4mm, 2mm, 1.5mm, 1mm, and 0.5mm, respectively. ABCD-A’B’C’D’ and CDEF-C’D’E’F’ are the section of plastic micro-pipe inside and outside the metal die, the length are all 10mm. The finite element meshes of the plastic micro-pipes with different inner diameters and same wall thickness are shown in Figure 1(b). In the finite element meshes, the meshes were refined near the boundaries and interfaces to improve the computing precision. The meshes numbers are all 1920.

![Figure 1. Geometric models. (a) unified geometric model (left), and cross section (right); (b) geometric models with different inner diameters and same wall thickness.](image)

2.2. Governing Equations
The molten melt of plastic micro-pipe is regarded as the iso-thermal, steady, Non-Newtonian, and laminar flow. The gravity and inertia forces of molten melt were neglected due to the high viscosity and low flow velocity. Based on these above hypothesis, the mass conservation and momentum conservation equations are shown as follows,

\[ \nabla \cdot \mathbf{v} = 0 \] (1)

\[ \nabla p - \nabla \cdot \mathbf{\tau} = 0 \] (2)

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

Phan-Thien–Tanner (PTT) constitutive model [8] was used to describe the viscous-elastic properties of plastic pipe’s melt, i.e.,

\[ \exp \left[ \frac{\varepsilon \lambda}{(1-\eta_1)} tr(\mathbf{\tau}) \right] \tau + \lambda \left[ 1 - \frac{\varepsilon}{2} \right] \nabla \mathbf{\tau} + \frac{\varepsilon \Delta \mathbf{\tau}}{2} = 2(1-\eta_1)\eta D \] (3)

where, \( \lambda \) is the relaxation time, \( \varepsilon \) and \( \varepsilon \) are the parameters of the melt correlated with the material tensile and the shear characteristics, respectively. \( \mathbf{\tau} \) is the upper convected derivative of the extra stress tensor. \( D \) is the strain-rate of the tensor. \( \eta = \eta_2/\eta_1 \) is the viscosity ratio, \( \eta \) is the total viscosity of the melt, \( \eta_1 \) is the Non-Newtonian component viscosity of the melt, \( \eta_2 \) is the Newtonian viscosity component of the melt.
2.3. Boundary Conditions

(1) inlet: In the Figure 1(a), AA’BB’ is the inlet face of plastic micro-pipe. Supposed that the flow of melt has fully developed before it flow into the stereotype section of die, the following dynamic conditions should be satisfied, i.e., \( v_x = v_y = v_z = 0 \). Where \( v_x, v_y \) and \( v_z \) are the flow velocities of melt at the direction of \( x, y \) and \( z \) coordination, respectively.

(2) wall: ABCD and A’B’C’D’ is the inner and outer wall. For the traditional extrusion of plastic micro-pipe, the no-slip condition was used, i.e., \( v_n = v_s = 0 \). For the gas-assisted extrusion, the full-slip condition was used, i.e., \( f_t = f_n = 0 \), where, \( v_n, v_s \) are the flow velocities of melt at the normal and tangential direction, \( f_t \) is the shear stress at the tangential direction.

(3) free face: CDEF and C’D’E’F’ are the free faces outside the die. The following relationship should be satisfied, i.e., \( f_n = f_s = 0 \), and \( v_n = 0 \). where, \( f_n \) is the shear stress at the normal direction.

(4) exit: EFE’F’ is the exit face. No any traction force is imposed on the exit of melt, the following condition is satisfied, i.e., \( f_n = v_y = 0 \).

2.4. Material Parameters

The material parameters of PTT constitutive model are shown in Table 1.

| Parameters | \( \eta \) (Pa.s) | \( \lambda \) (s) | \( \varepsilon \) | \( \xi \) | \( \eta_r \) |
|---|---|---|---|---|---|
| Values | 2700 | 0.2 | 0.23 | 0.18 | 0.12 |

3. Numerical Results and Analysis

3.1. Extrudate Shape of Plastic Micro-Pipes

For the geometric models with different inner diameters but same wall thickness, the volume flow rate of 0.05mm³/s for melt was imposed on the inlet face of plastic micro-pipe. Under the same boundary conditions, the swell effects of the traditional extrusion were obtained, which are shown in Figure 2(a-f).

Figure 2. Extrusion swell effects of traditional extrusion forming of the plastic micro-pipes. (a) inner diameter=5mm; (b) inner diameter=4mm; (c) inner diameter=2mm; (d) inner diameter=1.5mm; (e) inner diameter=1mm; (f) inner diameter=0.5mm.

The extrusion forming of the plastic micro-pipes by using the gas-assisted method are shown in Figure 3.

Figure 3. The extrusion shape of plastic micro-pipes by means of gas-assisted method. (a) inner diameter=5mm; (b) inner diameter=4mm; (c) inner diameter=2mm; (d) inner diameter=1.5mm; (e) inner diameter=1mm; (f) inner diameter=0.5mm.
From Figure 2, and Figure 3, it can be obviously seen that the extrudate swell phenomenon of plastic micro-pipes are occurred for the traditional extrusion forming. However, for the gas-assisted extrusion forming, the sizes of plastic micro-pipes are not changed at the inner face, exit face, and wall thickness, which demonstrate that the extrudate swell effect of melt can be eliminated by using the gas-assisted extrusion forming method.

3.2. Swell Ratios of Plastic Micro-Pipes

In order to quantitatively analyze the swell effects of plastic micro-pipes with different inner diameters under the traditional and gas-assisted extrusion forming, three swell ratios were used to describe the swell degrees of plastic micro-pipes with different inner diameters and same wall thickness, i.e., swell ratio of outer diameter \( B_o = (r_0' - r_0) / r_0 \), swell ratio of inner diameter \( B_i = (r_i' - r_i) / r_i \), and swell ratio of wall thickness \( B_w = (w' - w) / w \), where, \( r_i \), \( r_i' \) are the inner diameters of plastic micro-pipe at the inlet and exit faces, respectively. \( r_o \), \( r_o' \) are the outer diameters of plastic micro-pipe at the inlet and exit faces, respectively. \( w \) and \( w' \) are the wall thicknesses at the inlet and exit faces, respectively.

The extrudate swell ratios of plastic micro-pipes with different inner diameters for traditional and gas-assisted extrusion forming are shown in Figure 4.

![Figure 4. Swell ratios of plastic micro-pipes under the traditional and gas-assisted extrusion forming](image)

From Figure 4, it can be seen that for the traditional extrusion forming of the plastic micro-pipe, when the inner diameter is less than 4mm, the swell ratios of outer diameter for plastic micro-pipe increase but the swell ratio of the inner diameter decreases with the decreasing of the inner diameter, which results in the swell ratio of wall thickness increases with the decreasing of the inner diameter. However, for the gas-assisted extrusion forming, from Figure 4, it can be seen that the swell ratios of the inner diameter, outer diameter, and the wall thickness are all equal to 0, which demonstrates that the extrudate swell phenomenon is well eliminated by using the gas-assisted method.

4. Conclusion

The influence of geometric size on the extrudate swell of plastic micro-pipe was numerically studied in this paper. Additionally, the numerical results of traditional extrusion forming for plastic micro-pipe were compared with that of the gas-assisted extrusion forming. Numerical results show that the swell degree was increased with the decreasing of geometric size for the traditional extrusion forming of plastic micro-pipe. However, the swell phenomenon can be eliminated by using the gas-assisted extrusion method.

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