Numerical study on the influence of gas flow rates on the gas-assisted extrusion deformation of plastic micro-tubes

Zhong Ren* and Xingyuan Huang

1Key Laboratory of Optic-Electronic and Communication, Jiangxi Science and Technology Normal University, Nanchang, 330038, China
2School of Mechanical and Electrical Engineering, Nanchang University, Nanchang, 330031, China

*Corresponding author: renzhong0921@163.com

Abstract. In this paper, the effects of flow rate of assisted gases on the gas-assisted extrusion forming of plastic micro-tube were numerically investigated by using the finite element software Polyflow. Three phases fluid model was established and same volume flow rate was imposed on the inlet face of melt, different flow rate of inner and outer assisted gases were imposed on the inlet faces of two layers of assisted gases. Giesekus constitutive model was used to describe the rheological properties of melt. Numerical results show that with the increase of inner assisted gas’s flow rate, the inner and outer diameter will exponentially increase, that is, the inner cavity becomes bigger and bigger. When excessive flow rate of inner assisted gases is imposed, the inner cavity will be blown and broken. On the other hand, with the increase of the flow rate of outer assisted gas, the inner cavity shrinkage becomes more and more serious. The inner gas-assisted extrusion will be failed at the time of excessive flow rate of outer assisted gas imposed on the inlet face of outer assisted gas layer. Therefore, the reasonable controlling flow rates of inner and outer assisted gases are very important in the practice.

1. Introduction
Gas-assisted extrusion technique [1-3] is a kind of well-promising processing method of plastic products. It can eliminate the extrusion problems including extrudate swell [4, 5], melt fracture [6, 7] and extrusion deformation [8] by means of assisted gas layer. The plastic micro-tubes is a kind of plastic products widely used in lots of fields, such as medical interventional diagnosis and treatment, optical communication, and precision instruments. Likes other polymer products, the extrusion problems will be generated during the processing of plastic micro-tubes. In this paper, the gas-assisted extrusion technique was used to overcome the extrusion problems of plastic micro-tube. In the gas-assisted extrusion of plastic micro-tubes, two layers of assisted gas layers should be formed between the annual melt and the walls of die channel. However, the reasonable controlling of process parameters for the gas layers is very important [9]. In this work, the effect of gas flow rate on the gas-assisted extrusion forming and deformation of plastic micro-tubes was numerically studied by using the finite element method. Moreover, in this simulations, the role of inner gas layer on the profile changes of internal cavity for plastic micro-tubes were also considered. Under a certain boundary conditions imposed on the established geometric model, the numerical results about the effect of different gas flow rates of inner assisted gas layer and outer assisted gas layer on the extrusion forming and deformation of plastic micro-tubes were obtained. At the same time, the
physical field distributions of melt impacted by the inner or outer assisted gas layer were also gotten to analyze the influence mechanisms of gas flow rate on the extrusion deformation of plastic micro-tubes.

2. Numerical simulation

2.1. Three phases flow model

In the numerical simulations, three phases flow model was used to establish the geometric model of gas-assisted extrusion of plastic micro-tubes because there are two walls (inner wall and outer wall) in the plastic micro-tubes. Therefore, two layers of assisted gases should be formed between the outer wall of plastic micro-tube and the inner wall of die channel, as well as between the inner wall of plastic micro-tube and the outer wall of mandrel. The geometric model of gas-assisted extrusion of plastic micro-tube is shown in Figure 1(a).

![Figure 1](image)

Figure 1. Gas-assisted extrusion geometric model of plastic micro-tubes

In Figure 1(a), the wall thickness of plastic micro-tube is 0.5mm. The width of gas layers are all 0.2mm. The length of melt inside and outside die are all equal to 6mm. In Figure 1(a), JOPK is the area of melt inside die, OFHP is the area of melt outside die. KPQL is the area of outer assisted gas layer. IEFJ is the area of inner assisted gas layer. Figure 1(b) is the finite element mesh of Figure 1(a). The meshes were refined near the boundaries and interfaces between the melt and two layers of assisted gases. The meshes number is about 1360.

2.2. Numerical equations

The continue equation and momentum equation are given as follows,

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

$$\nabla p_k - \nabla \cdot \tau_k = 0$$  \hspace{1cm} (2)

where, $\nabla$ is Hamilton operator, $v_k$ is the velocity vector, $p_k$ is the pressure vector, $\tau_k$ is the extra stress tension. $k = I, II$ are the melt and gases, respectively.

In the simulations, Giesekus constitutive model [10] was used to describe the rheological properties of melt, which is given as follows,

$$\tau_I = \tau_{Iv} + \tau_{Ie}$$  \hspace{1cm} (3)

$$\tau_{Iv} = 2\eta_{Iv}D_I$$  \hspace{1cm} (4)

$$\tau_{Ie} + \frac{\lambda}{\eta_{Ie}} \{\tau_{Ie} \cdot \tau_{Ie}\} = 2\eta_{Ie}D_I$$  \hspace{1cm} (5)

In Eq.(3)-Eq.(5), $\tau_I$ is the extra stress tension, which consists of extra stress tensions of viscous component ($\tau_{Iv}$) and elastic component ($\tau_{Ie}$). $\eta_{Iv}$ and $\eta_{Ie}$ are the viscosity of melt for the viscous component, and elastic component, respectively. $\lambda$ is the relaxation time. $\alpha$ is the parameters of melt controlling the ratio between the first normal stress and the second normal stress difference. $D_I$ is the deformation rate tension of melt.

For two layers of assisted gases, they can be all regarded as the iso-thermal and Newtonian fluid, the numerical equations of assisted gases are shown as follows,
where $\delta_{ij}$ is the second-order unit tensor. $D_{ij}$ is the strain-rate of the tensor of gas. $\eta_{ij}$ is the viscosity of gases. $\tau_{ij}$ is the inelastic stress tensor of gases.

2.3. Boundary conditions

① Inlet: In Figure 1(a), JK is the inlet boundary of melt. IJ and KL are the inlet boundaries of assisted gases. Supposed that the flows of melt and assisted gases are all full-developed when melt and gases flow into the forming section of die channel, the boundary conditions of inlets can be satisfied the following relationships, i.e., $v_x=0$, $\partial v_y/\partial y=0$. where $v_x$, and $v_y$ are the flow velocities of melt and gases at the direction of $x$, and $y$ coordination, respectively. In the simulations, the inlet boundaries of melt and gases were set to the boundary condition of volume flow rate.

② Exit: FH is the exit boundary of melt. EF and PQ are the exit boundaries of inner and outer assisted gases, respectively. Supposed that no any normal traction forces and tangential velocities were imposed on the exits, the following relationship can be satisfied, i.e., $f_n=v_s=0$. where $f_n$ is the shear stress at the normal direction. $v_s$ is the flow velocities at the tangential direction.

③ Wall: LQ and IE are the inner wall of die channel and the outer wall of mandrel. The no-slip condition was used, i.e., $v_n=v_s=0$. where $v_n$ is the flow velocities at the normal direction.

④ Free boundary: PH is the free boundary of melt. The following kinetic relationship should be satisfied, i.e., $f_n=f_t=0$, and $v_n=0$. where $f_t$ is the shear stress at the tangential direction.

2.4. Constitutive parameters

In the simulations, the parameters of Giesekus constitutive model [11] are given in Table 1.

| Parameters | $\eta_0$ | $\eta_e$ | $\lambda$ | $\alpha$ |
|-----------|---------|---------|---------|---------|
| Value (unit) | 22 | 536 | 0.019 | 0.1 |

For the assisted gases, the viscosity constant of $2.6\times10^{-5}$ was used because gases were looked as the Newtonian fluid.

3. Numerical results and analysis

3.1. Effect of flow rate of inner assisted gas on the extrusion deformation of plastic micro-tubes

In the simulations, the inlet volume flow rate of melt was set to $1\times10^{-12}\text{m}^3/\text{s}$. At the same time, the flow rate of outer assisted gas was also set to $1\times10^{-12}\text{m}^3/\text{s}$. Then, the flow rate of inner assisted gas was increased from $1\times10^{-12}\text{m}^3/\text{s}$ to $8\times10^{-11}\text{m}^3/\text{s}$, the influence of inner assisted gas’s flow rate on the profile change of plastic micro-tubes was gotten, which are shown in Figure 2(a)-(d).

![Figure 2](image)

Figure 2. Profile changes of plastic micro-tubes under different flow rates of inner assisted gas. (a) $1\times10^{-12}\text{m}^3/\text{s}$; (b) $2\times10^{-11}\text{m}^3/\text{s}$; (c) $4\times10^{-11}\text{m}^3/\text{s}$; (d) $8\times10^{-11}\text{m}^3/\text{s}$

The effect of inner assisted gas’s flow rate on the inner and outer diameter of plastic micro-tube at
the cross-section of exit face was obtained, which are shown in Figure 3.

![Figure 3. Effect of inner assisted gas’s flow rate on the inner and outer diameter of plastic micro-tube at the cross-section of exit face](image)

From Figure 2, we can see that, there is no any deformation phenomenon for the gas-assisted extruded plastic micro-tube when the flow rate of inner assisted gas is about $1 \times 10^{-12} \text{m}^3/\text{s}$. With the increase of the flow rate for inner assisted gas, the inner cavity becomes bigger and bigger, which results in the blow swell phenomenon of inner cavity. When the flow rate of inner assisted gas continues to increase, the numerical computing is not converged, which demonstrates that the inner cavity of plastic micro-tube is blew and broken. From Figure 3, it can be seen that the inner and outer diameters of plastic micro-tubes all increase with the flow rates of the inner assisted gas in the exponential function form. Therefore, with the increase of flow rate of inner assisted gas, the gas-assisted extrusion deformation of inner cavity swell will be serious. On the premise of guaranteeing the stable establishment of internal gas-assisted layer, the flow rate of inner assisted gas should be as small as possible.

3.2. Effect of flow rate of outer assisted gas on the extrusion deformation of plastic micro-tubes

Then, the inlet volume flow rate of melt was also set to $1 \times 10^{-12} \text{m}^3/\text{s}$. At the same time, the flow rate of inner assisted gas was also set to $1 \times 10^{-12} \text{m}^3/\text{s}$. The flow rate of outer assisted gas was increased from $1 \times 10^{-12} \text{m}^3/\text{s}$ to $2 \times 10^{-10} \text{m}^3/\text{s}$, the influence of outer assisted gas’s flow rate on the profile change of plastic micro-tubes was gotten, which are shown in Figure 4(a)-(d).

![Figure 4. Profile changes of plastic micro-tubes under different flow rates of outer assisted gas. (a) $1 \times 10^{-12} \text{m}^3/\text{s}$; (b) $1 \times 10^{-11} \text{m}^3/\text{s}$; (c) $1 \times 10^{-10} \text{m}^3/\text{s}$; (d) $2 \times 10^{-10} \text{m}^3/\text{s}$](image)

From Figure 4, it can be seen that the extrusion inward depression phenomenon of plastic micro-tube become more and more serious with the increase of the outer assisted gas’s flow rate. Moreover, with the increase of flow rate of outer assisted gas, the gas channel of outer assisted gas become wider, which squeezes the annual melt to occupy the gas channel of inner assisted gas. When the flow rate of outer assisted gas increase to about $1 \times 10^{-9} \text{m}^3/\text{s}$, the numerical computing is not converged, which demonstrates that the inner gas-assisted extrusion failure induced by the excessive flow rate of outer assisted gas.

The effect of outer assisted gas’s flow rate on the profile size of plastic micro-tubes was also studied. The width of inner cavity of plastic micro-tube was used, i.e., RR’ (See Figure 4). The effects of outer assisted gas’s flow rate on the width of inner cavity of plastic micro-tubes were obtained,
which are shown in Figure 5.

From Figure 5, it can be seen that, with the increase of outer assisted gas’s flow rate, the inner diameter of plastic micro-tube at the outlet of die decreases, which demonstrates that the larger flow rate of outer assisted gas results in the shrinkage of inner cavity and generates the inward depression phenomenon.

4. Conclusion
In this paper, the effects of flow rate of assisted gases on the extrusion deformation of plastic micro-tubes were numerically studied by using the finite element method. For the inner assisted gas, with the increase of the flow rate, the inner cavity of plastic micro-tube becomes bigger and bigger. When the excessive flow rate was imposed on the inlet of inner assisted gas layer, the inner cavity will be broken. For the outer assisted gas, with the increase of flow rate, the inner cavity of plastic micro-tube will be shrunk. When the excessive flow rate was imposed on the inlet of outer assisted gas layers, the inner gas-assisted extrusion will fail. Therefore, the reasonable flow rates of assisted gases are very important process parameters during the gas-assisted extrusion of plastic micro-tube.

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