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Effect of Viscous Flow Activation Energy on the Gas-Assisted Extrusion Forming of Plastic Micro-Tube

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Abstract. In this paper, the effect of viscous flow activation energy on the gas-assisted extrusion (GAE) forming of the plastic micro-tube was investigated by numerical method. The three-phase fluids geometric model was built and same boundary conditions were imposed in the model. Under different viscous flow activation energies (VFAE), the influence of VFAE on the size changes of plastic micro-tube in the GAE were obtained. Moreover, the flow velocities, pressure, temperature, and viscosity distributions of melt were also gotten and analyzed. Results show that with the increase of viscous flow activation energy, the inner and outer radiuses all synchronously increase due to the increase of radial velocity and axial velocity. In addition, the temperature distribution slightly increases, which results in the decrease of the pressure and viscosity of melt.

1. Introduction

Plastic micro-tube is a kind of important diagnosis tool used in the clinical interventional diagnosis and treatment, e.g., interventional medical catheter, such as venography catheter, coronary artery catheter and urinary catheter. Usually, plastic micro-tube is produced via the extrusion forming method [1] for the polymeric melt. However, some extrusion problems, such as extrusion swell [2], melt rupture [3], and extrusion distortion [4] are easily produced by the traditional extrusion method. In order to overcome these extrusion problems, the GAE forming method [5, 6] has already been studied by some scholars. In this work, the GAE forming method was also used to manufacture the plastic micro-tube. For the material of plastic micro-tube, there are lots of polymers can be used to generate the plastic micro-tube. However, the different polymers have different material parameters, such as, viscosity, relaxation time, flow index, density, and melt index. The effects of melt's rheological properties on the GAE forming of plastic micro-tube have already been studied in past researches. In this paper, the effect of viscous flow activation energy on the GAE forming of plastic micro-tube was numerically studied. Under same geometric model, boundary conditions, and rheological parameters, the effects of viscous flow activation energy on the size changes, flow velocities distributions, pressure distributions, temperature distributions, and viscosity distributions of melt were all obtained. The mechanism about the effect of viscous flow activation energy on gas-assisted extrusion forming of plastic micro-tube was studied and analyzed.

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2. Simulations

2.1. Model

The geometric model and finite element mesh model of the GAE forming of plastic micro-tube is shown in Figure 1(a), and (b), respectively. The inner and outer radiuses of plastic micro-tube are 1.0 and 1.5mm, respectively. The widths of two assisted gas layers are all 0.2mm. The lengths of melt internal die and external die are all 6mm. In Figure 1(b), in order to improve the precision of numerical computing, the finite element meshes were denser near all boundaries including interfaces between melt and both of assisted gases. The finite element mesh was 1360.

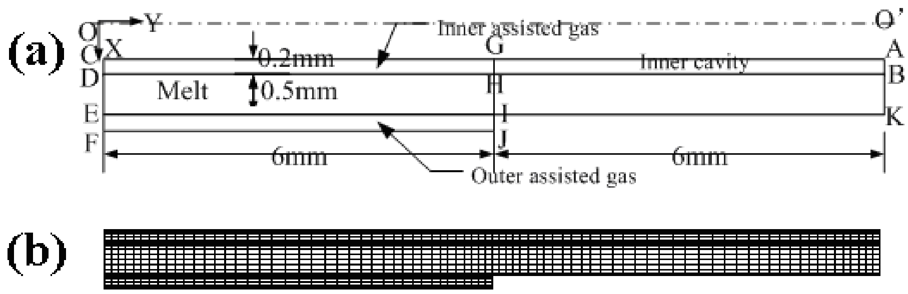

Figure 1. Model of GAE of plastic micro-tube

2.2. Governing Equations

Governing equations in the finite element computing of GAE of plastic micro-tube are present as follows,

$$\nabla \cdot \rho_k v_k = 0 \tag{1}$$

$$\rho_k v_k \cdot \nabla v_k + \nabla p_k - \nabla \cdot \tau_k = 0 \tag{2}$$

$$\rho_k C_{pk} v_k \cdot \nabla T_k + k_k \nabla^2 T_k - \tau_k : \nabla v_k = 0 \tag{3}$$

where, ρ_k is density constant of fluids, v_k is flow velocity vector, p_k is pressure vector, τ_k is partial stress tensor. C_{pk} is specific heat capacity constant, T_k is the temperature. k_k is the heat conductivity. $\tau_k : \nabla v_k$ is the viscous dissipation term. ∇ is Hamilton operator. The subscript *k*=*I* and *II*, which denotes melt and assisted gases, respectively.

In the numerical simulations, we used Bird-Carreau constitutive model [7] to reflect the rhyological properties of molten polymer, i.e.,

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)\left[1 + (\lambda\dot{\gamma})^2\right]^{\frac{n-1}{2}} \tag{4}$$

where η is the viscosity, η_0 is melt's viscosity at the zero shear rate, η_∞ is melt's viscosity at the infinite shear rate. λ is melt's relaxation time. $\dot{\gamma}$ is shear rate. *n* is melt's flow index.

Since the viscosity is depended on the temperature, the Arrhenius relationship [8] between the viscosity and the temperature was used in this paper, i.e.,

$$\eta' = \eta \cdot H(T) \tag{5}$$

$$H(T) = \exp\left[\frac{E_{\dot{\gamma}}}{R}\left(\frac{1}{T - T_0} - \frac{1}{T_\alpha - T_0}\right)\right] \tag{6}$$

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where $H(T)$ is the Arrhenius function. T is temperature variant. T_α is the reference temperature(473K). T_0 was set to 0. R is equal to 8.314. $E_{\dot{\gamma}}$ is the VFAE of melt, which should be changed according to the aims of this paper.

2.3. Boundary Set Conditions

a) Inlets: In Figure 1(a), DE is melt's inlet boundary. CD and EF are the inlet boundaries of inner and outer assisted gases, respectively. Supposed that melt and two assisted gases are full-developed in the shaping section of die's channel, the following kinetic conditions can be obeyed, 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 *x* and *y* direction, respectively. The temperature of 473K and 500K were respectively imposed on the inlets of melt and two assisted gases.
b) Walls: XA and FJ are the inner and outer walls of plastic micro-tube. In this paper, the no-slip condition was imposed on the walls. i.e., v_s=v_n=0. where v_s ,v_n are the flow velocities of melt at the tangential and normal directions. The constant temperature of 473K was imposed on the walls.
c) Interfaces: DB and EI are the interfaces between the annual melt and two assisted gases, respectively. The following kinetic boundary conditions are satisfied, i.e., f_n=v_n=0, and v_s=0. At the same time, the heat flux equation was used to reflect the heat transfer effect between the annual melt and two assisted gases, i.e., dq=α(T-T_α), where T is the actual temperature, T_α is the reference temperatures. α is the heat transfer coefficient, which was set to 10.
d) Free boundary: IK is free boundary of melt. The following kinetic conditions are satisfied, i.e., f_n=f_s=0, and v_n=0. where f_n, f_s are respectively shear stress of melt at the normal and tangential direction. In addition, the heat exchange effect between melt and ambient air was considered, the heat transfer equation was also used, where α was set to 5. T_α was set to 300K.
e) Exit: BK is the exit of melt. AB and IJ are respectively the exits of inner and outer assisted gases. In this work, there are no any tangential velocities and normal traction forces imposed on the exits of melt and assisted gases, the kinetic relationship, i.e., f_n=v_s=0 is satisfied. The heat boundary condition of outflow was used on the exits.

2.4. Parameters Setting

The constitutive and thermal parameters of polymer melt and gases are given in Table 1.

Table 1. Constitutive and thermal parameters of polymer melt and gases

Parameters	*η* (Pa.s)	*λ* (s)	*n*	ρ	C_p	*k*
Melt	2700	0.2	0.5	900	1883	0.22
Gases	2.6×10^{-5}	0	1	1	1026	0.037

3. Results and Analyses

3.1. Effect of VFAE on the Size of Plastic Micro-Tube

Four different VFAEs of melt were used, i.e., 8000, 20000, 60000, and 100000 J/mol. Firstly, the effect of VFAE on the size of plastic micro-tube was studied, the inner radius, outer radius and wall thickness changes of plastic micro-tube under different VFAEs were obtained, which are shown in Figure 2.

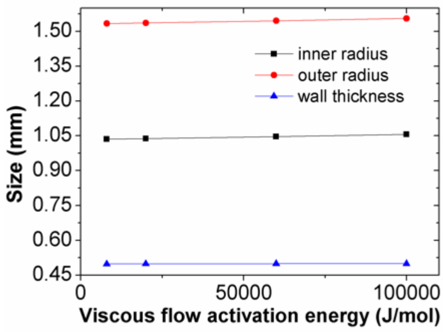

Figure 2. Effect of VFAE on the size of plastic micro-tube

In Figure 2, the inner and outer radiuses increase with the VFAE. However, for the wall thickness, it nearly doesn't change because the changes of inner and outer radiuses are nearly synchronous.

3.2. Effect of VFAE on the Flow Velocities of Melt

Then, the radial and axial flow velocities of melt under the different VFAEs are gotten, which are presented in Figure 3(a), and (b), respectively.

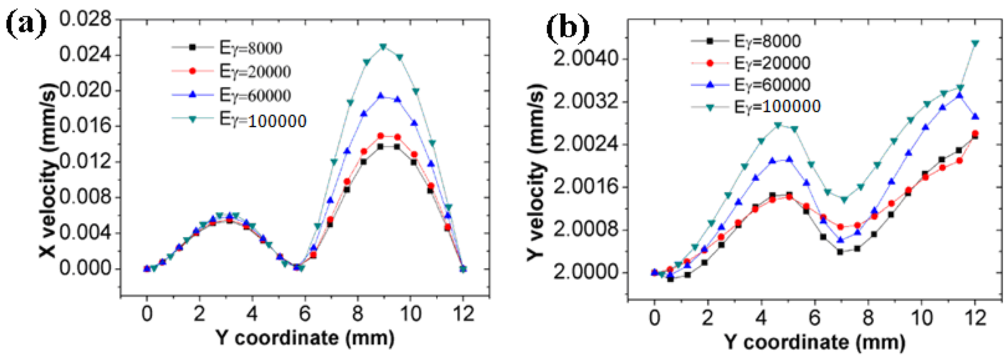

Figure 3. Effect of VFAE on the flow velocities of melt at the axial direction of channel. (a) radial velocity distributions; (b) Axial velocity distributions

In Figure 3(a), and (b), the radial velocity and axial velocity of melt all increase with the VFAE, which demonstrates that the flowability of melt becomes better when the VFAE of melt increases.

3.3. Effect of VFAE on the Pressure of Melt

The pressure distributions of melt at the axial direction under different VFAEs are shown in Figure 4.

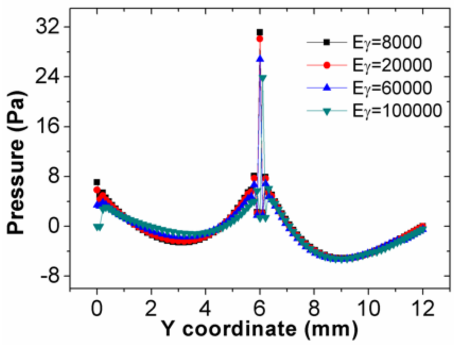

Figure 4. Effect of VFAE on the pressure of melt

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In Figure 4, the pressure of melt decrease with the increase of VFAE. The reason is that the flowability of melt is better by the increase of VFAE.

3.4. Effect of VFAE on the Temperature Distribution of Melt
Then, the temperature distributions of melt at the axial direction under different VFAEs were also obtained, which are shown in Figure 5.

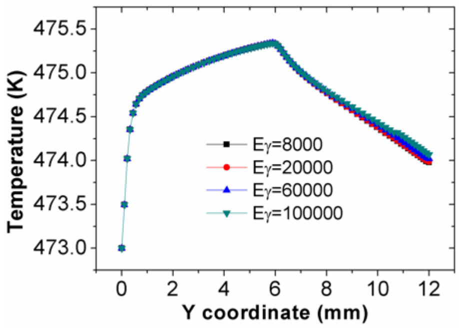

Figure 5. Effect of VFAE on the temperature distribution of melt

In Figure 5, the temperature slightly increase with the VFAE. Because the VFAE is the represent of material properties dependent on the temperature, the more VFAE, the more the melt is sensitive to temperature, which results in the increase of heat transfer and viscous heating generation for the melt.

3.5. Effect of VFAE on the Viscosity Distribution of Melt
Since the viscosity of melt is function of temperature, and is dependent on the VFAE. Therefore, the effect of VFAE on the viscosity of melt was also studied, the viscosity changes of melt under different VFAEs are shown in Figure 6.

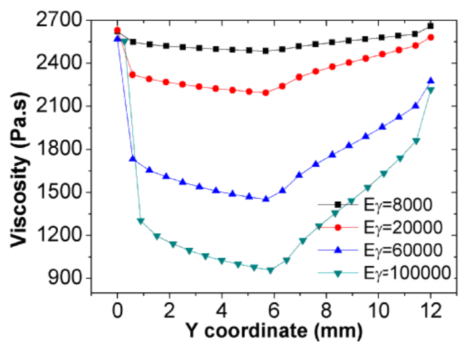

Figure 6. Effect of VFAE on the viscosity distribution of melt

In Figure 6, the viscosity of melt decreases with the increase of VFAE. The reason is that the temperature increase is induced by the increase of VFAE, at the viscosity of melt is inversely proportion to the temperature, which finally results in the decrease of the viscosity.

4. Conclusion
The VFAE is one of most important material parameter connected with the temperature. The larger VFAE, the more sensitive to the temperature for the melt. The effect of VFAE on the GAE forming of plastic micro-tube was numerically studied in this paper. Numerical results show that with the increase of VFAE, the radiuses of plastic micro-tube increase due to the increase of temperature, which results in the increase of flow velocities. At the same time, the pressure and viscosity distributions of melt decrease. Therefore, the reasonable choosing of VFAE is very important during the GAE of plastic micro-tube.

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