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Numerical studies of temperature effect on the extrusion fracture and swell of plastic micro-pipe

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Abstract. Temperature is a key factor that impacts extrusion forming quality of plastic micro-pipe. In this study, the effect of temperature on extrusion fracture and swell of plastic micro-pipe was investigated by numerical method. Under a certain of the melt's flow volume, the extrusion pattern, extrusion swelling ratio of melt are obtained under different temperatures. Results show that the extrusion swelling ratio of plastic micro-pipe decreases with increasing of temperature. In order to study the reason of temperature effect, the physical distributions of plastic micro-pipe are gotten. Numerical results show that the viscosity, pressure, stress value of melt are all decreased with the increasing of temperature, which leads to decrease the extrusion swell and fracture phenomenon for the plastic micro-pipe.

1. Introduction

Up to now, the plastic micro-pipes have been widely applied into some fields, e.g., the medical diagnosis [1], automobile oil circuits, optical fiber [2], and precision instruments etc. The plastic micro-pipes are usually manufactured by using the extrusion forming technique [3-5]. After a kind of polymer material is loaded into the extruder, it is heated to become the viscous flow state and under the push force of the screw the melt is extruded into the die channel, then it is extruded out from the outlet of the die with a kind of cross section shape, finally it is cooled to form the plastic micro-pipes. During the extrusion forming of the plastic micro-pipes, many factors will impact the flow behaviors and the forming results of molten polymer, for example, the screw rotation speed, temperature, polymer properties, and the geometric structure of die, etc. Among these factors, the temperature is a key process parameter, which not only impact whether the extrusion is successful or not, but also impact the qualities of the extruded plastic micro-pipes. In order to investigate the effect of temperature on extrusion fracture and swell of plastic micro-pipes, the numerical simulation of the plastic micro-pipes was performed by means of finite element numerical method. In the simulations, the non-isothermal viscoelastic flow behaviors and extrusion forming of the plastic micro-pipes were considered. Moreover, to guarantee the stability and convergence of the finite element compute of the numerical simulation, the Galerkin coupled streamline upwind (US) algorithm [6], evolution method [7], and the elastic viscous splitting stress (EVSS) algorithm [8] were used. The physical field distributions of the plastic micro-pipes were gotten and analyzed to explain the effect of temperature on the extrusion fracture and swell of the plastic micro-pipes.

2. Simulation

2.1. Numerical model
The model of the plastic micro-pipe is given in Figure1. where Figure1(a) is the cross-section of plastic micro-pipe, Figure 1(b) is the 2D axial geometric model of the plastic micro-pipe. Only 1/2 part of Figure 1(b) can be used because the geometric model of plastic micro-pipe is axis-symmetric model. Figure1(c) is the 1/2 part of mesh model for the plastic micro-pipe.

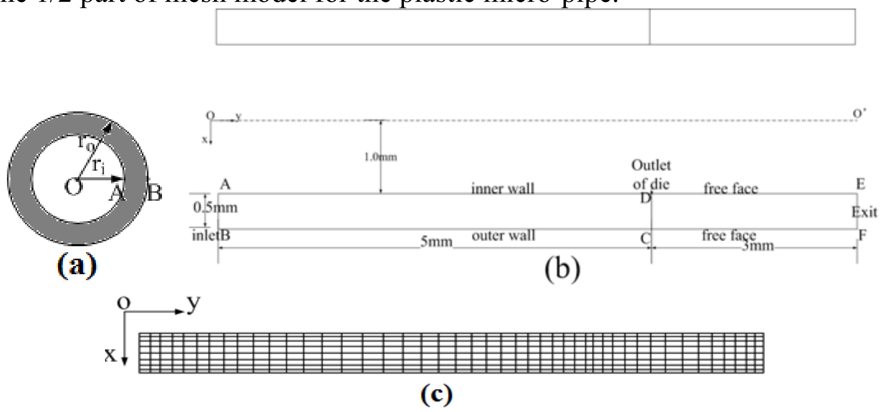

Figure 1. The model of the plastic micro-pipes. (a) cross-section; (b) 2D axial geometric model; (c) mesh model.

In Figure 1, the inner radius and outer radius of plastic micro-pipe are 1mm and 1.5mm, respectively. ABCD and CDEF are sections of the inside and outside of the die, respectively. The wall thickness (AB) of the plastic micro-pipe is 0.5mm. The length of the plastic micro-pipe inside of the die is 5mm, the length of the plastic micro-pipe outside of the die is 3mm. The mesh number of Figure 1(c) is about 600.

2.2. Numerical equations
In numerical computing of extrusion forming for plastic micro-pipe, the plastic's melt flow was looked to the steady, non-isothermal, laminar, non-Newtonian flow. The gravity force, thermal radiation effect and the surface tension of the melt are neglected due to the little volume and the strong viscosity.

Three governing equations are given,

$$\nabla \cdot (\rho v) = 0 \tag{1}$$

$$\rho v \cdot \nabla v + \nabla p - \nabla \cdot \tau = 0 \tag{2}$$

$$\rho C_p v \cdot \nabla T - k \cdot \nabla^2 T = \tau : \nabla v \tag{3}$$

In Eq.(1-3), ρ denotes the melt's density vector, v denotes the melt's flow velocity vector, p denotes the melt's pressure drop vector, τ denotes the melt's extra stress tension, k denotes melt's thermal coefficient, C_p denotes melt's specific heat capacity, T denotes melt's absolute temperature, ∇ denotes the Hamilton operator.

Because PTT model can well describe the visco-elastic properties of polymer melt, the PTT model [9] was chosen to used as the plastic melt's constitutive model,

$$\exp\left[\frac{\varepsilon\lambda}{(1-\eta_r)} tr(\tau)\right]\tau + \lambda\left[\left(1-\frac{\xi}{2}\right)\overset{\nabla}{\tau} + \frac{\xi}{2}\overset{\Delta}{\tau}\right] = 2(1-\eta_r)\eta D \tag{4}$$

In Eq.(4), the parameter of D is the rate of deformation tensor, which equals to $\dot{\gamma} = \sqrt{2(D^2)}$. η_r is the viscosity ratio, which equals to η_2 / η. The parameter of η is the melt's total viscosity, which equals to $\eta = \eta_1 + \eta_2$. The parameters of η_1 and η_2 are the Newtonian and Non-Newtonian viscosity components, respectively. In addition, the parameters of ε and ξ are the parameters connected with the tensile and shear properties of melt, respectively. $\overset{\nabla}{\tau}$ and $\overset{\Delta}{\tau}$ are the upper and lower convected derivative of τ. The parameters of λ is the melt's relaxation time.

Since the melt's viscosity closely depends on the temperature, Arrhenius equation [10] was used to describe the relationship between the viscosity and the temperature in this study, which is shown as follows,

$$\eta = \eta_0 \exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{5}$$

where η_0 is the viscosity of the melt at the reference temperature (T_0), α is the viscous activation energy of melt.

2.3. Boundary conditions

In the study, f_n and f_s are used to express the normal stress and tangential stress, v_n and v_s are used to express the normal velocity and tangential velocity of melt.

1) inlet boundary: In case of the melt flow is already steady and fully developed when the melt flows into the channel of die,

$$\partial v_y / \partial y = 0, v_x = 0 \tag{6}$$

In Eq.(6), the radius and axial velocities of melt are denoted as v_x and v_y.

2) free boundary: The free boundary should satisfy the following relationships,

$$f_n = 0, f_s = 0 \text{ and } v_n = 0 \tag{7}$$

3) wall boundary: Since the melt was adhered on the wall of die, no slip boundary condition are used,

$$v_n = v_s = 0 \tag{8}$$

4) exit boundary: There are no any traction forces and tangential velocities are acted on the melt's exit boundary,

$$f_n = 0,\ v_s = 0 \tag{9}$$

2.4. Material parameters

Table 1 gives the material parameters of plastic micro-pipe's melt used in the simulations.

Table 1. Parameter values of PTT model

Parameter	η	λ	η_r	k	C_p	ε	ξ	ρ
Value	2700 Pa.s	0.2 s	0.12	0.22W/(m^2·K)	1883(J/Kg*K)	0.23	0.18	900(kg/m^3)

3. Simulation results

3.1. Extrusion swelling result

Figure 2(a) is the extrusion profile change of the plastic micro-pipe inside and outside of die. In Figure 2(a), extrusion swelling phenomenon of plastic micro-pipe take place when the melt is extruded out. To obtain the effect of temperature on extrusion swelling situation of plastic micro-pipe, the extrusion swelling ratios of plastic micro-pipe at different temperatures are presented in Figure 2(b).

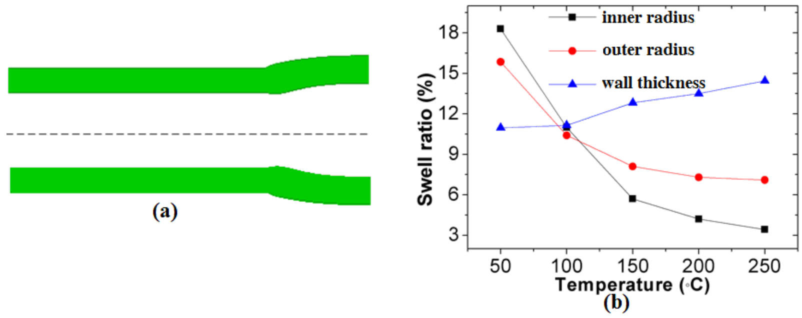

Figure 2. Extrusion swelling result of plastic micro-pipe. (a) extrusion profile; (b) extrusion swelling ratios at different temperatures.

In Figure 2(b), when the temperature rises, inner radius and outer radius is shrinked. However, the wall thickness of plastic micro-pipe is swelled because the inner radius's shrinkage degree is larger than that of outer radius when temperature is over 100ºC.

3.2. *Temperature field distributions*

To find the reasons of temperature acted on extrusion forming of plastic micro-pipe, the physical distributions including temperature, pressure, stresses distributions are obtained. The temperature field conditions of the plastic micro-pipe at four temperatures are given in Figure 3.

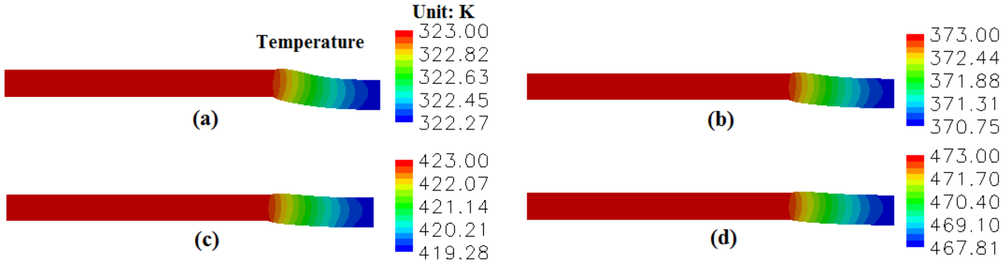

Figure 3. Temperature distributions of plastic micro-pipes. (a) 50 ºC; (b)100 ºC; (c)150 ºC; (d) 200ºC.

In Figure 3, the temperatures of melt are mostly unique in the inner channel of die when temperature imposed on the inlet is similar to that of the walls. However, at the time that the melt is extruded from the metal die, melt's temperatures gradually decrease due to the thermal transmission effect between melt and natural air.

3.3. *Viscosity field distributions*

Figure 4 is the viscosity distributions of melt in the channel of die at the radial direction under different temperatures. In Figure 4, we can find that when the temperature rises, the melt's apparent viscosity decreases. According to the Eq.(5), we can know that the viscosity of melt is inverse proportion to temperature. Therefore, the viscosity dependent to temperature is satisfied to the relationship of Arrhenius equation.

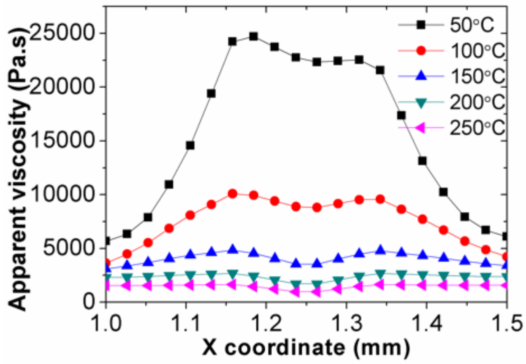

Figure 4. Viscosity distributions of melt at different temperatures

Moreover, the viscoelastic energy of melt will decrease with the decreasing of viscosity induced by temperature, which will decrease the extrudate swell effect of plastic micro-pipe.

3.4. Pressure drop distributions
Figure 5 is the plastic micro-pipe's pressure drop distributions at four different temperatures. In Figure 5, we found that the melt's pressure drop gradually decreased along the metal die's channel direction. Moreover, the melt's pressure drop value decreases when the temperature increases. Because the melt 's extrusion swelling situation depended on the pressure value. Therefore, the melt's pressure drop value's decreasing induced by temperature will decrease the extrudate swell phenomenon of plastic micro-pipe decreases.

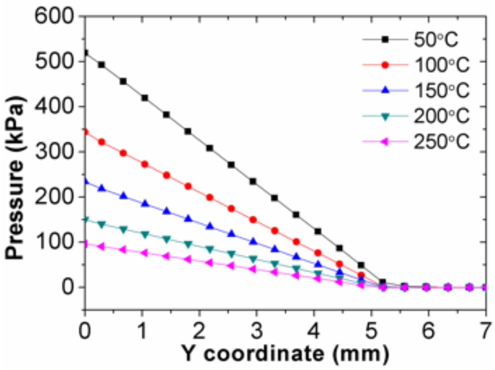

Figure 5. Pressure distributions at the different temperatures.

3.5. Stresses field distributions
Then, the shear stress situations of plastic micro-pipe at four different temperatures are obtained in Figure 6. where figure 6(a) is the shear stress distributions at the radial direction of die channel, Figure 6(b) is the shear stress distributions at the axial direction on the outer wall of die. According to Figure 6, we can know that when temperature rises, the shear stress of melt decreases. Since the melt 's viscoelastic store energy is connected to the stresses of melt generated between melt and die's wall. Therefore, the decreasing of stress value induced by temperature rise will decrease the viscoelastic store energy of melt, which will decrease the extrudate swell effect. Especially at the outlet of die, the stress value of melt decreases with the increase of temperature, which will also decrease the extrudate fracture phenomenon of plastic micro-pipe.

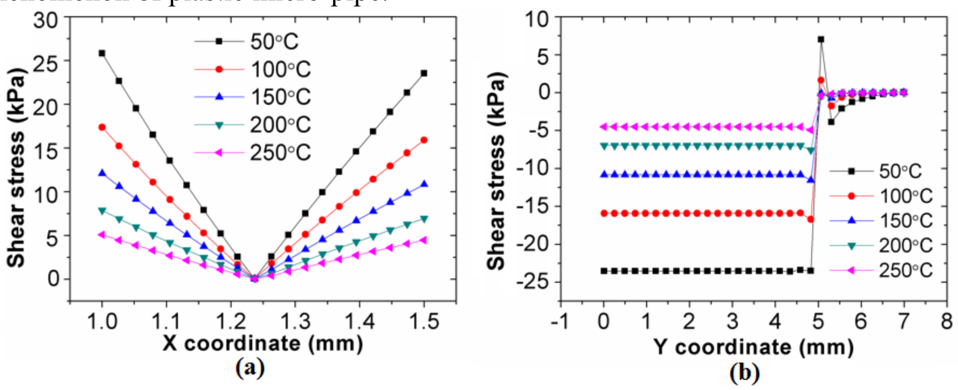

Figure 6. Stress distributions at different temperatures. (a) shear stress distributions; (b) first normal stress difference distributions.

4. Conclusion
The temperature effect on the extrusion forming of the plastic micro-pipe was investigated by the finite element numerical method. Under some reasonable hypotheses, boundary conditions, material parameters, the numerical results of the extrusion forming and physical distributions of plastic micro-pipe are obtained. Results show that when the temperature rises, the extrusion fracture and extrusion

swelling phenomenon can be greatly decreased because the viscoelastic store energy, viscosity, pressure drop, and stress values of polymer melt are all reduced.

Acknowledgments

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