Transient numerical simulation on the surface deformation for GAE forming of plastic micro-pipe

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Abstract: To ascertain the mechanism of gas-assisted extrusion (GAE) deformation for the plastic micro-pipe (PMP), the transient simulation was done. The geometric model based on three phase fluids and finite element mesh were established. To get the converge solutions, the Crank-Nicolson integration, the interpolation method of elastic-viscous split-stress finite element method combined with streamline-upwind scheme were used. At the reasonable boundary and material conditions, the GAE forming of PMP for different gases flow rates were numerically studied. Moreover, the extrusion profiles of PMP under different transient times were also obtained. To explain the reason of surface deformation for the GAE forming of PMP, the radial and axial velocity, and stress difference of melt under larger gases flow rates at different transient times were all obtained. The transient numerical results can better interpret the mechanism of surface deformation of PMP.

1. Introduction

PMP is usually manufactured via extrusion technique[1]. During the manufacture process of PMP, the molten melt is sustained large stresses in the die channel, which will results in the molecular oriental effect and elastic storage energy effect of melt, finally lead to generate some extrusion problems, for example, die swell[2], melt rupture[3], and extrusion deformation[4], etc. Some studies show that the reduction of stresses for the melt in channel weak the extrusion problems [5]. There are some useful methods studied by some scholars, for example, surface coating on the surface of channel[6], modification of melt[7], vibration extrusion[8], GAE[9-11], etc. The GAE method was used in the paper. However, in the GAE of PMP, some new extrusion problems will be generated when the gas-assisted processes are not reasonable, for example, the gas-assisted failure, surface waves, even inner cavity breaking. Although these GAE problems have been already studied by some scholar, the detail situations of the GAE problems, especially the melt deformation in the die channel can't be observed, which results in the limitation of ascertaining the mechanism for the GAE deformation of the PMP. The main aim is to further ascertain the GAE deformation of PMP, the GAE forming of the PMP was investigated by the transient finite element method. The extrusion results at the different transient times were obtained to explain the deformation process of PMP.
2. Simulations

2.1 Numerical model

Figure 1(a) is numerical model of GAE forming of PMP, the finite element mesh of numerical model is given in Figure 1(b). The finite mesh numbers are 1200.

2.2 Equations

Transient continuous and monument equations should be used,

\[ \frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \bar{u}_k) = 0 \]  \hspace{1cm} (1)

\[ \rho_k (\frac{\partial \bar{u}_k}{\partial t} + \bar{u}_k \cdot \nabla \bar{u}_k) = -\nabla p_k + \nabla \cdot \tau_k \]  \hspace{1cm} (2)

Where \( \nabla \) is Hamilton operator, \( \rho_k \) is density. \( \bar{u}_k = (\bar{u}_x, \bar{u}_y, \bar{u}_z) \) is flow velocity. \( p_k \) is pressure, \( \tau_k \) is extra stress tensor. \( k = I, II \) respectively denotes melt and gases. The first terms in Eq.(1) and Eq.(2) are all the transient terms, which reflects the change situations of fluids with time dependent.

The differential viscoelastic constitutive model of Phan-Thien-Tanner [12] was used in here to describe the visco-elastic properties of melt with high viscosity and elasticity,

\[ \exp \left[ \frac{\epsilon \lambda}{(1 - \eta_\lambda) \eta} \right] \tau_1 + \lambda \left[ \left( 1 - \frac{\epsilon \lambda}{2} \right) \tau_1 + \frac{\epsilon \lambda}{2} \tau_1 \right] = 2(1 - \eta_\lambda) \eta D \]  \hspace{1cm} (3)

\[ \tau_1 = \frac{D \tau_1}{Dt} - \eta_1 \cdot \dot{v}_y - \dot{v}_y \cdot \eta_1 \]  \hspace{1cm} (4)

\[ \tau_1 = \frac{D \tau_1}{Dt} - \eta_1 \cdot \dot{v}_y - \dot{v}_y \cdot \eta_1 \]  \hspace{1cm} (5)

where \( \eta_\lambda \) is viscosity ratio, which is equal to \( \eta_2 / \eta. \) \( \eta \) is whole viscosity, \( \eta_1 \) is non-Newtonian viscosity, \( \eta_2 \) is pure viscosity part of extra stress tensor; \( \lambda \) is melt relaxation time; \( \epsilon \) and \( \xi \) are the parameters corrected with materials; \( \tau_1 \) and \( \tau_1 \) are respectively upper and lower adjoint derivatives of \( \tau_1. \) \( D \) is deformation rate tensor.

Double gas layers were regarded as the Newtonian fluids, the gas’s constitutive equations are given as follows,

\[ \tau_\| = 2\eta_{\|} D_\| \]  \hspace{1cm} (6)

\[ D_\| = \frac{1}{2} (\nabla \nu_{\|} + \nabla^T \nu_{\|}) - \frac{1}{3} \nabla \nu_{\|} \delta_{\|} \]  \hspace{1cm} (7)

Where \( \tau_\| \) is the gas’s inelastic stress tensor, \( D_\| \) is the gas’s deformation rate tensor, \( \eta_{\|} \) is the gas’s viscosity.

2.3 Boundaries setting

(1) inlet: BC was set as the melt’s inlet boundary, AB and CD were set as the inlet boundaries of gases. In the simulations, all fluids were all looked full-developed fluids, i.e., \( \nu_x = 0, \nu_y / \partial y = 0. \)

(2) walls: AE and DH were set as the walls. The no slip condition was used, \( \nu_n = \nu_s = 0. \)
(3) interfaces: BF and CG were set as the interfaces between double gas layers and melt, \( f_s = v_n = 0 \).

(4) freedom surface boundaries: FI and GJ were set as the freedom surface boundaries of melt, i.e., \( f_n = f_s = 0 \).

(5) outlets: IJ was set as the outlet of melt. EF and GH were set as the outlets of gas layers. In the simulations, no any normal forces and tangential velocities were inserted at the outlets, i.e., \( f_n = v_s = 0 \).

2.4 Materials and Numerical method

In the work, the properties of fluids are presented in Table 1.

| Properties | \( \eta \) | \( \lambda \) | \( \varepsilon \) | \( \xi \) | \( \rho \) |
|------------|---------|---------|---------|--------|----------|
| Melt       | 2700 Pa.s | 0.2 s   | 0.23    | 0.18   | 900 kg/m³ |
| Gases      | \( 2.6 \times 10^{-5} \) | 0 | 0 | 0 | 1 |

In the simulations, the evolution scheme for transient inlet flow rate was used. The Crank-Nicolson integration method was used to ensure the converge of numerical computing. In addition, the interpolation of EVSS finite element method incorporating SU scheme method was used.

3. Simulational results

3.1 Effect of gases’ flow rate

The melt’s flow rate was set to 0.1 mm³/s in simulations. Four different flow rates of gases (i.e., \( 1 \times 10^2 \) mm³/s, \( 1 \times 10^3 \) mm³/s, \( 1 \times 10^4 \) mm³/s, and \( 1 \times 10^5 \) mm³/s) were respectively inserted on the inlet boundaries of assisted-gases. The different results for the GAE forming of PMP were gotten and shown in Figure 2.

Figure 2. GAE forming of PMP under different flow rates of gases. (a) \( Q_g = 1 \times 10^2 \) mm³/s; (b) \( Q_g = 1 \times 10^3 \) mm³/s; (c) \( Q_g = 1 \times 10^4 \) mm³/s; (d) \( Q_g = 1 \times 10^5 \) mm³/s

In Figure 2, when the assisted gases’ flow rates increase, the axial flow velocity of gases increases, and results in the decrease of wall thickness of PMP. Moreover, the surface quality of PMP, i.e., surface roughness and bump phenomenon was also decreased.

3.2 Transient numerical results at different times

In order to further know about the extrusion deformation of GAE for PMP when the flow rate of gases are larger (i.e., \( Q_g = 1 \times 10^5 \) mm³/s), the transient numerical results of GAE forming of PMP at different times were obtained and represetned in Figure 3(a), (b), (c), and (d).

Figure 3. Transient numerical results for the GAE forming of PMP. (a) 0.4s, (b) 0.6s, (c) 0.8s, (d) 1s

From Figure 3, it can be seen that at different transient times, not only the flow rate of gases are different, but also the profiles of PMP are different, i.e., the surface quality was become worse and worse with the time. The quality roughness was aggravated with the gradually increase of time, finally the wall thickness decreases, as well as the surface bump phenomenon was generated under the larger flow rates of assisted gases.
3.3 Transient velocities

To know the GAE deformation of PMP under the larger flow rates of gases, the flow distributions of melt were shown in Figure 4. Figure 4(a) shows the radial velocity distributions of melt at different transient times. Figure 4(b) gives the melt’s axial velocity distributions at different transient times.

![Figure 4. Melt’s velocities at different times. (a) radial velocity; (b) axial velocity](image)

In Figure 4(a), with the increase of transient time, not only the radial flow velocity amplitude increases, but also the radial flow instability, i.e., flow volatility aggravates, and results in the flow instability of melt in the die channel with the role of assisted gas layers in larger flow rates, finally which leads to generate the surface bump phenomenon. According to Figure 4(b), the melt’s axial velocity gradually increases with the increase of transient time.

3.4 Transient stress distributions of melt

To ascertain the GAE deformation of PMP with the larger assisted gases’ flow rate, the stresses distributions of melt inserted by the assisted-gases were analyzed. The first normal stress differences ($N_1$) of melt at different transient times are presented in Figure 5.

![Figure 5. $N_1$ of melt at different times](image)

In Figure 5, $N_1$ value of melt is largest near the inlet of die channel, then gradually decreases to zero, which demonstrates that the GAE deformation of PMP mainly occurs at the inlet of die channel for the melt impacted by the larger flow rates of assisted gases. Moreover, $N_1$ value of melt increases with the transient time. Therefore, the GAE deformation of PMP gradually aggravates over time.

4. Conclusion

In this paper, the GAE forming of PMP was numerical investigated by the transient finite element simulation method. The numerical results of GAE forming of PMP at different flow rates of gasses were gotten and analyzed. Moreover, to clear the mechanism of larger flow rates of gasses on the surface deformation of PMP, the profiles, flow velocities, stresses of melt at different transient times are all obtained and analyzed. Results show that with the flow rates of assisted gases, the extrusion deformation of GAE for PMP was generated. Moreover, with the increase of transient time, the radial flow velocity amplitude in the die channel and $N_1$ value of melt at the inlet of die channel all increase, especially the instability radial flow velocity, which is the main reason that generating the surface deformation of GAE forming of PMP.
5. Acknowledgments

We thank to the assistance of the China National Natural Science Fund (51763011), Jiangxi Province Natural Science Outstanding Youth Fund (2018ACB21006), JXSTNU Doctor start-up Fund (2017BSQD021), the Natural and Science Fund of Jiangxi Province (20192BAB206016), Key Lab. of Optic-electronic Detection and Information Processing of Nanchang City(2019-NCZDSY-008), and 2019 Innovation of Outstanding Young Personnel Training Program (20192BCBL23015).

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