Numerical Simulation of GAEM for Asymmetric Double-Lumen Plastic Micro-Catheter

Zhong Ren$^{1,2,*}$

$^1$Key Laboratory of Optic-Electronic and Communication, Jiangxi Science and Technology Normal University, Nanchang, 330038, China
$^2$Key Laboratory of Optic-Electronic Detection and Information Processing of Nanchang City, Jiangxi Science and Technology Normal University, Nanchang, 330038, China
Email: renzhong0921@163.com

Abstract: In the study, the numerical simulations of gas-assisted extrusion molding (GAEM) of double-lumen micro-catheter (DLMC) with asymmetric structure were performed via the finite element software package Polyflow. At the same time, the numerical results of traditional extrusion were also obtained. The numerical extrusion profile, deformation, and the die swell ratios of DLMC based on the traditional and GAEM were all gotten, and compared with each other. In addition, to analyze the effect of gas-assisted on the elimination of the extrusion problems, the physical field distributions of melt for both extrusions were also compared and analyzed. Numerical results show that the obvious die swell and large extrusion deformation of DLMC generated by the traditional method were all eliminated by using the GAEM.

1. Introduction
Medical micro-catheter has already been widely used in the fields of medical interventional diagnosis and treatment. DLMC is one types of medical catheters, which is usually used as the venous catheter, urinary catheter, and angiographic catheter etc. Moreover, among the DLMC, there is a kind of asymmetric double-lumen typed catheter, i.e., the profile and size are not same between dual lumen. In general, the DLMC is manufactured by using the continuous extrusion process. Since the micro-catheter is made by the polymers with high visco-elasticity, and the molten polymer suffers from the large stresses, some extrusion problems include die swell[1, 2], deformation [3, 4] and surface fracture [5] etc were seriously generated during the process production. The quality and efficiency of production are impacted by these extrusion problems. To solve the problems, the GAEM technique [6-9] was introduced and used in the study. By means of the assisted gas layers formed between the walls and mandrels, the visco-elastic storage energy, and the flow nonuniform of melt can be greatly eliminated in the channel of extrusion die. In this paper, the numerical simulations of GAEM forming of asymmetric double-lumen plastic micro-catheter were performed by using the computed fluid dynamics (CFD) method. To analyze the mechanism of the extrusion problems of double-lumen micro-catheter can be removed by the multiple-layers GAEM, the simulations of tradition extrusion forming of double-lumen micro-catheter were also performed and compared.

2. Model
The geometric model of DLMC is given in Figure 1. Figure 1(a) is the cross section. The wall thickness is 0.3mm, the thickness of intra-cavity rib is also 0.3mm, the outer diameter of large cavity is 3mm, the inner diameter of small cavity is 0.9mm. Figure 1(b) is the axial section. The lengths of melt
inside die and outside die are all 10mm. Figure 1(c) is the finite element mesh. Since the symmetric
structure in the vertical-axial direction, the half part of geometric model was used in the simulations.
The hexahedral mesh and tetrahedral mesh were used in the numerical mesh, and the meshes were
refined to improve the numerical precision. The mesh number is 2040.

![Figure 1. cross-section(a); 1/2 part of numerical model (b); finite element mesh(c)](image)

3. Simulation
The continuity and momentum equations are given as follows,

\[ \nabla \cdot \vec{v} = 0 \]  
\[ -\nabla p + \nabla \cdot \tau = 0 \]

where \( \nabla \) is the Hamilton operator. \( \vec{u} = (u_x, u_y, u_z) \) is the flow velocities of melt at \( x, y, \) and \( z \)
coordinates, respectively. \( p \) is the pressure. \( \tau \) is the extra stress tensor.

In the simulation, Phan-Thien-Tanner constitutive model [10] was used,

\[ \tau = \tau_1 + \tau_2 \]

\[ \exp \left[ \frac{\phi \xi}{(1 - \eta) \eta} \tau_1 \right] \tau_1 + \lambda \left[ \left( 1 - \frac{\xi}{2} \right) \tau_1 + \frac{\xi}{2} \dot{\tau}_1 \right] \]

\[ = 2(1 - \eta) \eta D \]

\[ \dot{\tau}_1 = 2\eta D \]

where \( \tau_1 \) and \( \tau_2 \) are the viscoelastic component and viscous component of \( \tau \), respectively. \( \eta \) is
the total viscosity of melt, \( \eta_1 \) and \( \eta_2 \) are respectively the Non-Newtonian viscosity component and the
Newtonian viscosity component of the melt, \( \eta_r = \eta_2 / \eta \) is the viscosity ratio. \( \lambda \) is the relaxation time
of melt. \( \varepsilon \) and \( \xi \) are the parameters controlling the shear viscosity and elongational behavior of melt,
respectively. \( D \) is the melt rate-of-deformation tensor. \( \nabla \tau_1 \) and \( \nabla \dot{\tau}_1 \) are the upper convected derivative
and below convected derivative of viscoelastic extra stress tensor component( \( \tau_1 \)).

4. Boundaries and Material Parameters
In Figure 1(b), ABCDEF: the inlet face of DLMC.
AGLF: outer wall of DLMC.
BUVH: inner wall of large cavity.
CUVI: outer wall of small cavity.
DEKJ is the inner wall of small cavity. For the traditional extrusion, the boundary condition of walls is set as. For the multiple-layer GAEM, the simple full-slip boundary condition was used.
GMSL, HNWV, IPWV, and JQRK: the free faces.
ABNM, CDQP, EFSR: symmetric faces.
MNWPQRS: the exit face.
In the simulations, the material parameters of melt are shown in Table 1.

Table 1. Material parameters of melt

| η (Pa.s) | λ (s) | ε | ξ | μ |
|---------|------|---|---|---|
| 8823    | 0.1  | 0.15 | 0.44 | 0.12 |

5. Numerical Results and Discussion

5.1 Extrusion Profiles
In the simulation, inlet flow rate was set to 0.01 mm$^3$/s. The extrusion profiles of DLMC based on the both extrusions were obtained, which are shown in Figure 2.

Figure 2. Extrusion profiles of DLMC. (a) inlet and outlet faces of traditional extrusion; (b) axial profile of traditional extrusion; (c) inlet and outlet faces of GAEM; (d) axial profile of GAEM.

Figure 2(a) and (b) are the inlet and outlet faces of DLMC based on the traditional extrusion. From the results, it can be seen that the extrusion deformation and die swell problems are very serious. Not only the position large deviation generated between the inlet face and exit face, but also the profile deformation of whole body was generated outside die. Moreover, the die swell, i.e., the diameter and thickness swells of DLMC are all generated. However, for the GAEM, from Figure 2(c) and (d), the extrusion deformation, die swell problems were all eliminated. The profile of DLMC is uniform between the melt inside die and outside die.

5.2 Deformation Analysis
Then, to further compared the extrusion deformation of DLMC, the positions shift condition of the exit face and inlet face of DLMC based on the traditional extrusion and GAEM were respectively shown in Figure 3(a), and (b)
From figure 3(a), we can see that under the traditional extrusion, the large vertical shift of melt was generated between the exit face and the inlet face due to the large position change of points F, A, and C. At the same time, the obvious horizontal shift was also generated, which results in the generation of the large extrusion deformation. However, in figure 3(b), the vertical and horizontal shifts of melt are very few for the GAEM. Then, to compare the die swell and deformation of DLMC between the traditional extrusion and the GAEM, the swell ratios of wall thickness and profile between the exit face and the inlet face were computed, which are shown in Figure 4(a), and (b), respectively.

From Figure 4(a), and (b), we can see that the die swell of wall thickness and the diameter for the traditional extrusion of DLMC are very large. However, for the GAEM, the die swell of melt is very little.

5.3 Physical Field Distributions
To analysis the effect of gas-assisted on the elimination of die swell and deformation of DLMC, several physical field distributions (flow velocity, pressure, shear stress, first normal stress difference) were compared and analyzed between the GAEM and the traditional extrusion. Firstly, the radial and axial flow velocity distributions of melt for two different extrusions were gotten, which are shown in Figure 5(a)-(d), respectively.
Figure 5. Flow velocity distributions. (a) radial velocity of traditional; (b) radial velocity of gas-assisted; (c) axial velocity of traditional; (d) axial velocity of gas-assisted.

For the traditional extrusion of DLMC, in Figure 5(a), there is large positive radial velocity of melt near the die outlet, which results in the radial flow and radial deformation. Figure 5(c) is the axial flow velocity distribution of melt at the cross-section of die outlet for the traditional extrusion. In figure 5(c), the axial velocity distribution is non-uniform, the large axial velocity focuses at the junction of dual cavity, and the axial velocity is zero at the walls. This non-uniform axial velocity leads to generate the extrusion deformation. However, for the GAEM, the radial and axial velocity distribution deviations of melt are all small, so the extrusion deformation of DLMC can be better eliminated.

Figure 6. Pressure and stress distributions. (a) axial pressure distribution of traditional; (b) axial pressure distribution of gas-assisted; (c) shear stress distribution of traditional; (d) shear stress distribution of gas-assisted; (e) first normal stress difference distribution of traditional; (f) first normal stress difference distribution of gas-assisted.

Figure 6(a), (c), and (e) are the axial pressure, shear stress, and first normal stress difference of melt for the traditional extrusion for DLMC. We can see that the melt has large axial pressure, and shear stress in channel of die. The strong elastic energy storage of melt and the orientation effect of molecular chain initiate the large die swell, which is one of main reason why the die swell problem of DLMC was generated in the traditional extrusion. At the same time, the large first normal stress difference was also generated at the outlet of die, which also initiate the die swell and deformation problems in the radial and axial direction. However, for the GAEM, the axial pressure, shear stress and the first normal stress difference are very small. So the extrusion problems can be greatly removed.
6. Conclusion
The DLMC is one of most important device used in the medical interventional diagnosis and treatment. DLMC is usually manufactured via the traditional extrusion in the factory. However, the quality and efficiency of DLMC products can be impacted by the series of extrusion problems. To eliminate the extrusion problems, the gas-assisted method can be used in the extrusion of DLMC. To analyze the effect of gas-assisted on the elimination of the extrusion problems, the numerical simulations were performed and compared with the traditional extrusion. Numerical results that the vertical and horizontal shifts of melt outside die generated by the traditional extrusion were eliminated by the GAEM. At the same time, the pressure, shear stress and the first normal stress difference were all reduced. These results finally remove the die swell and the extrusion deformation. Therefore, the GAEM has the potential value in the manufacture of the DLMC.

7. Acknowledgments
This paper was supported by 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 (2019BCBL23015).

8. References
[1] L. Pauli, M. Behr, S. Elgeti, J. Non-Newton. Fluid Mech. 200, (2013) 79-87.
[2] G. Luis, E. William, Inter. J. Numer. Meth. Fl. 29, (2015) 1-18.
[3] V. G. Shibakov, D. L. Pankratov, A. P. Andreev, et al., IOP Conf. Ser. Mater. Sci. Eng. 86, (2015) 1-6
[4] S. Parasiz, B. Kinsey, N. Krishnan, et al., J. Manuf. Sci. E.-T. ASME 129, (2007) 690-697
[5] M. Seth, S. G. Hatzikiriakos, T. M. Clere, Polym. Eng. Sci. 42, (2002) 743-752.
[6] Z. Ren, X. Y. Huang, H. S. Liu, et al, J. Appl. Polym. Sci. 132, (2015) 1-12
[7] Z. Ren, X. Y. Huang, Z. H. Xiong, Inter. J. Mater. Forming, (2019) 1-22
[8] Z. Ren, X. Y. Huang. Mater. Sci. Forum 956, (2019) 253-259.
[9] Z. Ren, X. Y. Huang, Liu Hesheng et al. CIESC J. 4(2015) 1615-1623.
[10] M. A. Alves, F. T. Pinho, P. J. Oliveira, J. Non-Newton. Fluid Mech. 101, (2001) 55-76.