Effect of gas inlet angle on the gas-assisted extrusion forming of polymer melt

Z Ren¹,²,³ and X Y Huang²

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

E-mail: renzhong0921@163.com

Abstract. In this paper, the effect of gas inlet angle on the gas-assisted extrusion (GAE) forming of polymer melt was studied by means of numerical simulation method. The geometric models and the corresponding finite element meshes of four different gas inlet angles (0°, 30°, 60°, and 90°) were established. The computed fluid dynamic software package Polyflow was used. The shear stress, normal stress, and first normal stress difference of melt at the gas/melt interface were obtained. The results show that the influence of gas inlet angle at 30° on the gas-assisted extrusion forming of melt is lest, which can provide the technique guidance for the optimal designing of the gas-assisted die for the polymer melt.

1. Introduction

In the polymer process, the extrusion forming [1] is one of important method in the plastic manufacturing field, such as plastic bar, tube, profiled bar, etc. Since the polymer melt has the characteristic of high viscoelasticity, some serious extrusion problems, e.g., extrudate swell [2], melt fracture [3], extrudate distortion [4], will be generated under the large shear rate or shear stress. The mechanisms of generating the above mentioned problems were the elastic energy storage recovery mechanism, large first normal stress, and the shear stress focuses at outlet of metal die. In order to overcome these problems, some methods have been studied by many scholars, such as, material modification [5], fluoride coating on the surface of die [6], vibration extrusion [7], GAE [8], etc.

Among these methods, the GAE method is a well-established, most-promising, and green environmental method of extrusion forming. The GAE forming have been proved to greatly decrease the shear stress of melt on the channel of die by using stable gas thin-layers formed between melts and die’s wall. Many studies showed that the gas process parameters (e.g., gas pressure [9], gas flow [10], gas temperature, etc) have the great influences on the extrusion effect of polymer melt. However, the study about the effect of gas layer’s inlet angle on extrusion forming of polymer melt is very few. In this paper, the influence of gas layer’s inlet angle on extrusion forming of polymer melt was numerically investigated. Studies results show that the influence of gas layer’s inlet angle on the extrusion forming of polymer melt is significant. The study results can provide the good guidance for the GAE forming of polymer melt in practice.

2. Numerical simulations
2.1. Numerical model

The geometric models of GAE forming for melt with different gas layer’s inlet angles are shown in Figure 1.

![Figure 1](image)

**Figure 1.** Geometric model of GAE forming for melt with different gas layer’s inlet angles. (a) 0 angle, (b) 30 angle, (c) 60 angle, (d) 90 angle.

In Figure 1, AEMF is the region of the melt, where ADKF is the melt in the inner part of the die, DEMK is the melt outer part of the die. GKLH is the region of the gas channel in the inner die. Since the symmetric characteristic of geometric model, the half of geometric model was used in the numerical simulation. The width of AF is 3mm, the width of gas layer is 0.2mm, the length of AB, BC and CD is 10mm, 5mm, and 20mm, respectively. The length of DE is 10mm. The length of gas layer is also 20mm. In this paper, four different gas inlet angles were considered, which are 0°, 30°, 60°, and 90°, which are given in Figure 1(a-d), respectively.

2.2. Controlling equations

In the finite element numerical computing, the following basic hypotheses should be satisfied: 1) the melt’s flow behavior is looked as steady, isothermal, and laminar flow. 2) The melt is looked as the incompressible and viscoelastic fluid. 3) The flow of gas layer is also laminar, and the turbulence effect was neglected. 4) The inertia, thermal dissipation, and the gravity effects of melt and gas are all neglected.

According to the above mentioned hypotheses, the controlling equations are given as follows,

**Continuity equation:** \( \nabla \cdot v_k = 0 \quad k = I, II \)  \( (1) \)

**Momentum equation:** \( \nabla p_k - \nabla \cdot \tau_k = 0 \)  \( (2) \)

where \( k = I, II \) denote melt and assisted gas, respectively. \( \nabla \) denotes flow velocity vector. \( \nabla \) denotes Hamilton operator. \( \rho \) denotes melt’s and gas’s pressure. \( \tau \) denotes extra stress tension.

PTT constitutive equation [11] was used to describe the viscoelasticity and rheology of melt, i.e.,

\[
\exp \left[ \frac{\frac{\partial}{1 - \eta_1} \eta \tau (\alpha_{\tau})}{\frac{\partial}{(1 - \eta_1)\eta}} \right] \tau_1 + \lambda \left( \frac{1 - \varepsilon}{2} \right) \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \tau_1 \right] = 2(1 - \eta_1)\eta D
\]

where \( \eta \) denotes melt’s total viscosity. \( \eta_1 \) denotes Non-Newtonian component viscosity, \( \eta_2 \) denotes the Newtonian component viscosity, \( \eta_1 = \eta_2 / \eta \) denotes the viscosity ratio. \( \lambda \) denotes the melt’s relaxing time. The parameters of \( \varepsilon \) and \( \xi \) correlate with melt’s tensile and shear. \( D \) denotes strain-
rate of tensor. $\tau_1$ and $\tau_1$ are the lower and upper convected derivative of the extra stress tensor $\tau_1$, respectively.

PTT model’s parameters are given in Table 1.

| Parameter | $\eta$ (Pa.s) | $\lambda$ (s) | $\epsilon$ | $\xi$ | $\eta_r$ |
|-----------|---------------|---------------|-------------|------|---------|
| Value     | 2700          | 0.2           | 0.18        | 0.23 | 0.12    |

2.3. Boundaries setting condition
1) inlet: Supposing that the flow behaviors of melt and gas are full developed, which satisfies the following relationship,

$$\frac{\partial \nu_y}{\partial y} = 0, \nu_x = 0$$

(4)

where $\nu_x$ and $\nu_y$ are the melt’s and gas’s flow velocities at radial and axial direction, respectively.

2) wall: No-slip condition is imposed on the die’s wall, which is satisfied as follows,

$$\nu_n = \nu_s = 0$$

(5)

where $n$ and $s$ are the normal and tangential direction, respectively.

3) gas/melt interface: The flow and thermal transmitting of melt and gas at the melt/gas interface is continuous, and the relative slip between the melt and the gas is neglected. The following conditions should be satisfied,

$$\nu_n = 0, f_n = 0, f_s = 0$$

(6)

4) symmetric boundary: On the symmetric boundary, the flow and thermal transmitting of melt and gas at the melt/gas interface is also continuous. The relationship is similar to the gas/melt interface boundary.

5) free boundary: The relationships should be obeyed as follows,

$$f_n = 0, f_s = 0 \text{ and } \nu_n = 0$$

(7)

6) outlet: Supposing there are no any trances and entangle velocities on the outlet of melt, i.e.,

$$f_n = 0, \nu_s = 0$$

(8)

3. Results and analyses

3.1. Shear stress distribution
To analysis the effect of gas layer’s inlet angle on GAE of melt, the melt’s shearing stress distribution at four gas layer’s inlet angles were obtained, which are given in Figure 2(a-d), respectively.
3.2. Normal stress distribution
To further investigate the effect of gas layer’s inlet angle on the extrusion forming of melt, normal stress of melt distributions were obtained, which are shown in Figure 3(a-d), respectively.

In Figure 3, the melt’s normal stress with gas layer’s inlet angle of 90° is largest, but the normal stress of melt at the angle of 0° and 30° are lest.

3.3. First normal stress difference distribution
Then, the melt’s first normal-stress different at four kinds of gas layer’s inlet angles were gotten, which are presented in Figure 4 (a)-(d), respectively.
In Figure 4, the melt’s first normal-stress difference at angle of 30° are less than that of others. Moreover, the first normal-stress difference value at the angle of 90° is largest, which indicates the influence of gas layer’s inlet angle at 90° is largest but the influence of gas inlet angle at 30° is lest. Based on the above mentioned analyses and results, it can be seen that the effect of gas layer’s inlet angle of 30° is best, which can be used to design the gas inlet angle for the die of GAE forming.

4. Conclusion
In the GAE forming of melt, optimal design of GAE die is very key work. To optimally design the GAE die, the effect of gas layer’s inlet angle on the extrusion forming of melt was investigated in this work, the finite element simulations based on Polyflow software was used. Shear stress, normal stress, and first normal-stress differences of melt based on four kinds of gas layer’s inlet angles (0°, 30°, 60°, and 90°) were obtained. The results show that the effect of gas inlet angles at 30° on the melt’s GAE forming is best.

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References
[1] Ren Z, Huang X Y and Liu H S 2016 IOP Conf. Series: Mater. Sci. Eng. 137 012007
[2] White J L and Huang D 2010 Polym. Eng. Sci. 21 1101
[3] Vlachopoulos J and Alam M 2010 Polym. Eng. Sci. 12 184
[4] Jallouli I, Kallel T, Ayadi A and Halouani F 2010 Phys. Chem. News 53 22
[5] Rungruangsuparat S, Patcharaphun S and Sombatsompop N 2016 Polym. Testing 57 184
[6] Zagrebaev S A, Orlova E A, Alekseev V V, Zhmurin V G, Orlov M A, Shirshov Y N, Torbenkova I Y and Tychinskii P I 2015 Russ. Phys. J. 57 1283
[7] Chen J, Chen Y, Li H, Lai S Y and Jow J 2010 Ultrason. Sonochem. 17 66
[8] Ren Z, Huang X Y, Liu H S, Deng X Z and He J T 2015 J. Appl. Polym. Sci. 132 12365
[9] Ren Z, Huang X Y and Liu H S J 2016 Sichuan Univ. (Eng.Sci. Ed.) 48 200
[10] Yu Z, Huang Y B, Zhang K, Dong T W and Li T 2016 Polym. Mater. Sci. Eng. 32 113
[11] Thien N P and Tanner R I 1997 J. Non-Newtonian Fluid Mech. 2 353