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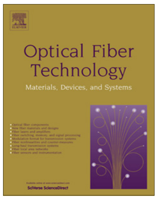

Regular Articles

Finite element simulation of extrusion of optical fiber preforms: Effects of wall slip

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ABSTRACT

Extrusion has been successfully used to fabricate optical fiber preforms, especially microstructured ones. Although simplified mathematical model has been used to calculate the extrusion pressure or speed, more frequently die design and extrusion process optimization depend on trial and error, which is especially true for complex die and preform design. This paper employs the finite element method (FEM) to simulate the billet extrusion process to investigate the relationship between the extruding pressure, the billet viscosity, the wall slip condition and the extruding speed for extrusion of rod preforms. The slipping wall boundary condition is taken into account of the finite element model, and the simulated extruding pressure agrees with the one experimental value reported preciously. Then the dependence of the extruding speed on the extruding pressure, billet viscosity and the slip speed is systematically simulated. Simulated data is fitted to a second order polynomial model to describe their relationship, and the terms of the model are reduced from nine to five by using a statistical method while maintaining the fitting accuracy. The FEM simulation and the fitted model provide a convenient and dependable way to calculate the extrusion pressure, speed or other process parameters, which could be used to guide experimental design for future preform extrusion. Furthermore, the same simulation could be used to optimize die design and extrusion process to improve quality of extruded preforms.

1. Introduction

Microstructured optical fibers (MOFs) have been extensively studied and found many applications in the past two decades due to their special properties that are not attainable by conventional optical fibers [1–4], for example, the high nonlinearity, which makes MOFs promising for supercontinuum generation [5]. At present, fabrication of MOFs with irregular and complicated profiles however is still a major challenge despite that there are a few methods available including the stack and draw [6,7], drilling and draw [8] and casting [9].

Extruding structured fiber preforms is a relatively new and preferred method [10], which is particularly suitable to make complex preforms with large number of transverse features within different material types [11]. It has been mainly used to fabricate soft glass based MOFs as well as polymer based ones up to now [12,13]. To extrude high-quality MOF preforms, it is necessary to calculate and optimize various conditions involved during extrusion, including extrusion force, temperature, speed, as well as extrusion die design [14–16]. Previously an analytical model based on the Poiseuille law has been developed for the extrusion of MOF preforms [17,18], which is suitable for glass flowing through a circular die channel. Recently, the model is expanded to include the boundary slip and multiple channel effects, which has been shown to agree with experimental data. However, the analytical method ignores contributions from barrel and assumes laminar flow and circular channels with the same length in the die, which are not suitable for complex MOFs, for example, irregular microstructures for MOF research like suspended core fibers [19].

The finite element method (FEM) is an ideal solution to such complicated process modeling. FEM have been extensively used in many aspects of engineering problems including extrusion of metals, polymers and glasses [20–23]. For example, the dynamic mesh approach of the commercial computational fluid dynamics (CFD) software, ANSYS CFX, has been shown to be able to simulate a glass-stack co-extrusion process, and the simulated core/cladding dimensions of the extrudate are in good agreement with experimental results [24]. In another instance, stress distribution of the glass flowing through a die with inner mandrel for extrusion of suspended core fiber preforms has been investigated by FEM [25]. Slip boundary is a common phenomenon in extrusion process and is an important factor that influence the melt extrusion

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process and resultant extruded products [26,27], which can be readily incorporated into the finite element model [28,29]. For example, taking account of slip boundary, Trabelssi et al. used FEM to study the die well and the hole distortion in extruded microstructured optical fiber glass preforms [30,31].

The main objective of this paper is to employ FEM approach to provide an explicit model of extrusion process for rod preform, which could be easily modified to microstructured optical fiber preform extrusion to evaluate process parameters including extrusion pressure, billet viscosity, wall slip and extruding speed.

2. Finite element model

Finite element simulation is done by using the computational fluidic dynamic (CFD) module of ANSYS suite – CFX 14.5. Drawing 3D model and meshing are completed by use of ANSYS Workbench 14.5. By taking advantage of the symmetry of the 3D model, only one quarter of the extrusion die and the billet is simulated to shorten computation time. The billet flow is assumed to be laminar because of the low flow speed involved in the extrusion.

2.1. Geometry and mesh

In order to compare with experimental results reported in literature [18], the die and barrel geometry in it is adopted for the present study (Fig. 1). The die and the barrel are assumed to be a single body. The glass billet in diameter of 30 mm is extruded into a rod in diameter of 10 mm. The diameter and the length of the die channel are 10 mm and 5 mm respectively. The barrel is 30 mm in height and the tapered part (45°) is 10 mm in height. The model is meshed by the mesh module of the ANSYS Workbench (Fig. 2). The only size control on meshing is the size of the interface between the die and the billet which is set to 2×10^{-4} m. The mesh is refined until it has no effects on the simulation result. For the calculation of all results, the billet has 193616 nodes and 1060862 elements while the die has 158508 nodes and 144686 elements. Totally, there are 352124 nodes and 1205548 elements.

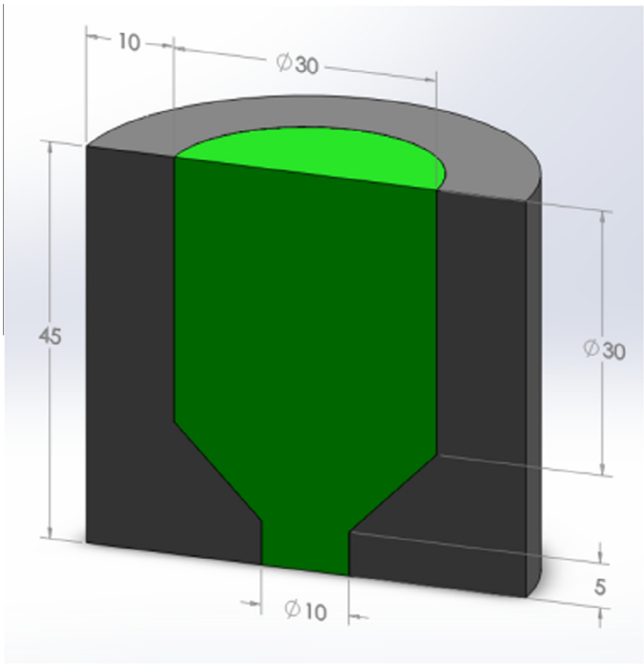

Fig. 1. Half view of the 3D model for the finite element analysis. The black represents the extrusion barrel and the die while the green is the billet. Dimensions are in unit of millimeter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Boundary conditions

Default simulation conditions are listed in Table 1 unless otherwise specified. To include the slip wall condition into the finite element model, the slip model in the ANSYS CFX is used. It uses a moving wall with a speed of U_w calculated by the following equation to simulate the slip

$$U_w = \begin{cases} 0, & \tau < \tau_c \\ U_s\left(\frac{\tau-\tau_c}{\tau_n}\right)^m \exp\left(-\frac{BP}{\tau_n}\right), & \tau > \tau_n \end{cases} \tag{1}$$

where U_s is the slip speed, τ_n and τ_c are the normalizing and the critical stresses respectively, m is a positive power, B is a pressure coefficient and P is pressure. In most cases, the influence of the pressure is found minimal and can be ignored, such as in extrusion and lubrication flows of viscoplastic fluids [32] and extrusion of polyethylene [33]. So the pressure coefficient B is set to be 0 for the simulation in this paper. The exponent m could be 1 or larger [32,33]. Based on these experimental results and also to simplify the model, the positive power m is set to be 1 and the pressure coefficient B is set to be 0, both τ_n and τ_c are set to be 1 Pa. The value of U_s is changed to simulate different magnitudes of slip. After simplification, the wall slip speed is proportional to the shear stress between the billet surface and the die wall.

3. Results and discussion

3.1. Analytical calculation

For comparison, the analytical method proposed in literature [18] is firstly used to estimate the extrusion pressure and force. This method, originally developed by Roeder for the capillary flow [17], assumes (1) the melt glass to extrude is Newtonian fluid; (2) flow of the melt glass during extrusion follows the Hagen–Poiseuille Law; (3) there is no slip between the interface of the glass and the die. The extrusion pressure at the steady state is given by the equation

$$P = \frac{128L}{\pi D^4} A\eta v \tag{2}$$

where P is the steady-state extruding press in Pa; L is length of the die channel in meter; D is diameter of die channel in meter; η is viscosity of the fluid in Pa s; A is the cross section area of the billet in m^2; v is the extruding speed (punch speed) in m/s. For the model in Fig. 1, the cross section area A is 7.07×10^{-4} m^2, D is 10 mm and L is 5 mm. The constant part of Eq. (2) can be calculated as a constant K_1 with unit of m^{-1}

$$K_1 = \frac{128L}{\pi D^4} A = 1.44 \times 10^4 \tag{3}$$

and Eq. (2) becomes

$$P = K_1 \eta v \tag{4}$$

where K_1 is 1.44×10^4 m^{-1}, η is in unit of Pa s, v in m/s and P in Pa.

However, Eq. (4) only includes the contribution of the die channel. In order to include the contribution from the barrel and the tapered funnel part, the constant part with the unit of m^{-1} should be

$$K_2 = \left(\frac{10}{30^4} + \int_0^{10} \frac{dh}{(30-2h)^4} + \frac{5}{10^4}\right) \times 10^9 \cdot \frac{128}{\pi} A = 1.94 \times 10^4 \tag{5}$$

And the final result is