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Hole distortion and drift in extruded microstructured optical fiber glass preforms: Part I – Sensitivity analysis

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ABSTRACT

Computational simulation of the extrusion of a glass preform for drawing microstructured optical fibers was used to study processing induced distortion and drift of the holes within the preform. Such distortion is the primary weakness of the extrusion approach. The validated model from a previous study for a preform with 36 holes is used herein for a sensitivity analysis. Symmetry of the cross section allows analysis of a thirty-degree subdomain, which contains five holes. Scalar variables are introduced to quantify preform deformation, hole distortion and hole drift. The manuscript describes and compares data sets and normalizing procedures for these variables, in order to choose a suitable set that facilitates the interpretation of the deformation, as well as the comparison between the outputs of different die designs. For two related die inserts, the sensitivity of these variables with respect to the level of friction ranging from no friction to no-slip, was studied in detail for the five holes. Such a study is required to identify ways to optimize the die insert geometry that creates the lattice of holes in the preform. Optimization is addressed in Part II, which is a companion study.

1. Introduction

Photonic crystal fibers (PCFs), which belong to a class of microstructured optical fibers (MOFs), are a promising development in the progress of fiber optic technology. In order to realize its theoretical potential, this technology requires a level of accuracy of the shapes and locations of the internal features, such as the holes within the cross section of the fiber in the present case [1–3]. Fiber processing starts with a preform containing the features in the cross section. This preform is then drawn into a fiber, which essentially preserves the geometry in spite of the drastic reduction in cross section. Since optical performance is dependent on a precise geometry, it is essential to create a preform with a precise geometry. The different processing approaches used to create the glass preforms include stacking [4,5], drilling [6–8], casting [9,10] and extrusion [11,12]. The latter approach, which is the focus of the current study, has the advantages of surface quality and geometric versatility [11,13–23]. In this process, a soft glass billet is gradually forced though a die structure. Extrusion is performed above the glass transition temperature at a viscosity range of 10^6–10^{10} Pa·s, where the glass is soft enough to flow through the die structure, yet stiff enough to resist the influences of gravity and surface tension. Low ram speeds of 0.02–0.2 mm/min are generally employed to maintain good optical quality [24–26], and to avoid material damage, die surface abrasion [27,28], or die breakage [29].

Extrusion is a computer controlled single step process, which therefore allows a great level of reproducibility and robustness. This in turn enhances the flexibility of the process, and enables the fabrication of any structure within the limits of current process parameters [11,13–23]. Nevertheless, it also has the disadvantage that distortions occur during processing. The die swell phenomenon, for example, limits the precise control over the shape of the preform [11]. Hence, repeated trials are usually conducted to obtain the desired geometry [20]. While there are a few adjustments that can be made in the drawing process to correct for inaccuracies in the preform geometry, these corrections are limited [29,30].

The recent use of 3D printed dies [24,31] gives promise to a high level of geometric control of the die, well beyond what is practical using more standard methods of machining. Furthermore, computational mechanics can be used to predict preform shape knowing the die shape and processing parameters [32]. Therefore, understanding and controlling the mechanics of the flow through the die during extrusion becomes a necessity to fully exploit the potential of 3D printing and to further improve the robustness of the process.

In the study by Trabelssi et al. [32], a computational approach for

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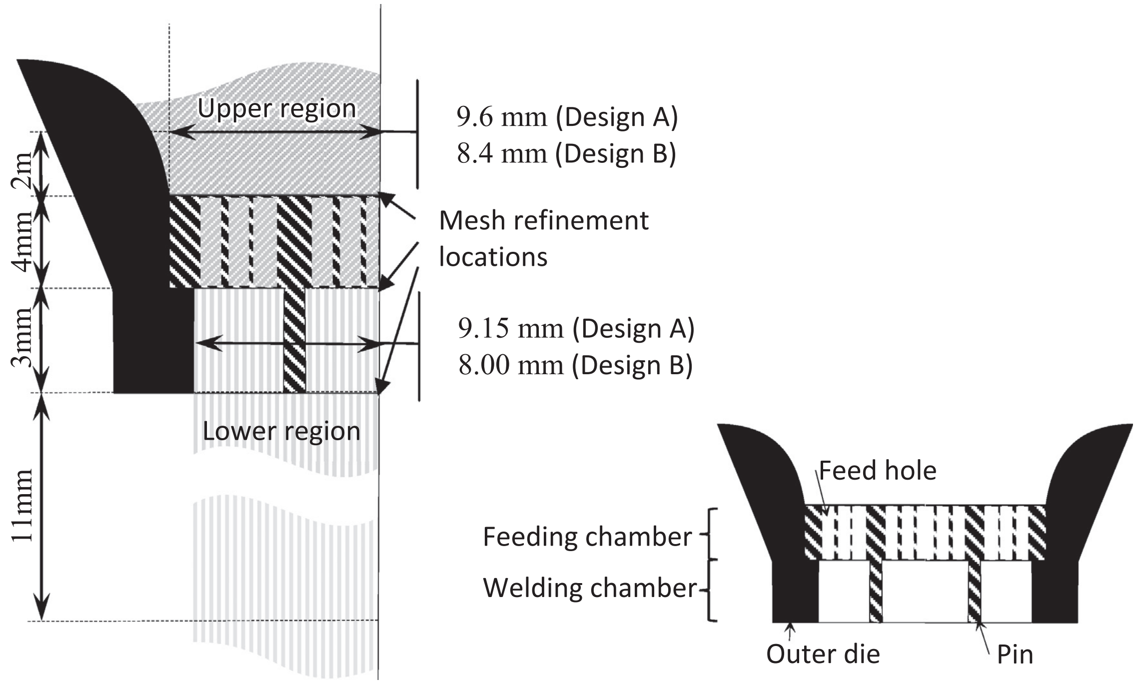

Fig. 1. Schematic of the die insert chambers and the modeling domains used to extrude an MOF preform.

the prediction of the distorted shape and drift of the holes was validated for a case of an MOF with 36 holes [8,33]. This study accounted for flow through the feed holes, flow over the pins used to create the holes in the preform, flow exiting from the die, and the development of the steady state cross section. The study revealed the importance of interface friction on distortion and drift. The current study, which consists of both the current Part I and its companion Part II [34], makes use of this validated model to provide the computational tools necessary to guide the design of the die insert used to create the holes in the cross section of the preform. Two similar MOF configurations to that used in [32] are used. After introducing these configurations, some preliminary results are presented that show the distortion and drift, and reveal the complexity of the flow. Scalar parameters are defined that quantify the degrees of distortion, allowing for a detailed presentation of the sensitivity results. Optimization through feed hole and pin adjustment is the topic of Part II.

2. Die geometry

Following Trabelssi et al. [32], the goal of the computational model is to predict the final arrangement of the holes within a glass preform that result from glass flow through a complex die consisting of feed holes and pins. The feed holes allow the glass to flow through the die into a welding chamber that contains the pins that form the holes. The objective is to determine the difference between the shapes and locations of the pins, and the final arrangement of the holes that are formed in the preform. In this study two slightly different die inserts will be used to add to the understanding of what creates this difference. A schematic of the die outer and insert is shown in Fig. 1, along with dimensions. The pins and the feed holes have been organized in the two different designs, which are presented in Fig. 2, and are referred to as Design A and Design B. The designs in this figure are drawn to scale. Besides the differences in the number of feed holes (Fig. 2) and welding chamber diameter (Fig. 1), the position of the pins relative to the feed holes is different in the two designs. As an example of the latter difference, the symmetry plane that intersects three pins in Design A also intersects four feed holes, while the same plane in Design B does not intersect any feed holes.

The insert geometries in Fig. 2 reveal how 30 degree portions are sufficient to analyze the entire cross-section when symmetry is taken into account. Fig. 2 also provides the numerical reference system for identifying the feed holes and pins. While taking advantage of symmetry provides a simplification of the complete model, the remaining structure is still fairly complicated due to the presence of either 17 or 13 feed holes, the free surface of the preform, a free surface for each of the 5 holes and the intersection of free surfaces with the two symmetry planes.

3. Computational model of MOF preform extrusion

This section is a summary of that given by Trabelssi et al. [32] since the only change is the geometry presented in Figs. 1 and 2. In that study all the details of modeling assumptions, boundary conditions and convergence were presented. Here only the key points are stated.

Following Trabelssi et al. [32], steady state, isothermal extrusion of an incompressible Newtonian fluid is assumed. Furthermore, inertia forces are neglected due to high viscosity extrusion ($> 10^7$ Pa·s) and low ram speed (< 0.5 mm/min for a 30 mm billet diameter), both of which are required to achieve optical quality. For these assumptions the continuity and conservation of momentum equations reduce to

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\nabla \cdot (\eta \nabla \mathbf{u}) - \nabla p = 0. \tag{2}$$

where $\mathbf{u}$ is the velocity vector, p is the pressure, and η is the shear viscosity. Extrusion with high viscosity also minimizes the effect of surface tension, which is neglected. However, high viscosity introduces the complication of interface slip. Following Trabelssi et al. [26] and Trabelssi and Joseph [35], the linear form of the Navier friction model is used to describe the interface behavior between the glass and the die. In this model the interface friction stress, τ_{wall}, is related to the relative sliding speed between the die and the glass, u_{wall}, by

$$\tau_{wall} = k u_{wall}, \tag{3}$$

where k is the Navier friction coefficient.

The boundary conditions and the handling of the inflow are identical to what was presented in [32]. To summarize, boundary