The dynamic process of laser drawing germanium core optical fiber

Wei Zhang, Na Chen*, Zhenyi Chen, Ziwen Zhao, Qiang Guo, Fufei Pang and Tingyun Wang

Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, 149 Yanchang Road, Shanghai 200072, China

*E-mail: na.chen@shu.edu.cn

Abstract. The Laser drawing process of germanium core optical fiber is studied numerically and experimentally in this paper. We analysed the changes in the maximum temperature, maximum velocity and surface profile over time. The final profile of dynamic simulation is in good agreement with the experimental result.

1. Introduction

As a member of semiconductor core fibers, germanium core optical fiber is attracting more and more attention due to its mid-wave infrared transparency and high third-order nonlinear coefficients. It has been reported that the germanium core fiber preform can be fabricated by the molten-core method [1], high-pressure chemical vapor deposition [2], and so on. After that, the prepared preform was drawn into a fiber with a graphite furnace. However, because of the long heating zone of the graphite furnace, the semiconductor core is easily oxidized during the drawing process, and the molten core material is easily deposited under the action of gravity at the bottom of the softened area before the drawing process.

Laser drawing has many advantages such as short heating time and small action area, and the neck-down region of the preform during the drawing process is totally observable in real time. It appears to be a better solution. Here we present a numerical model to study the dynamic changes in the laser drawing process, and then we studied the change in temperature and velocity, at the end we compared the final profile obtained by the experiment and the simulation.

2. Models and experimental conditions

2.1. Simulation conditions

Optical fiber drawing process involves heat transfer, mass transfer, and laminar flow phenomena. This problem is generally considered to be axisymmetric, so a 2-D numerical model was used to reduce the scale of the model. The intersection of the preform bottom line and the axis is the origin of the coordinate, the axis of symmetry is set to z axis, and the germanium core is at the top of the center of the preform.

Softened silica and molten germanium are treated as Newton's incompressible fluids, which are governed by Navier-Stokes equations:
\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}
\]

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mathbf{\tau}] + \mathbf{F}, \tag{2}
\]

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = -\nabla \cdot (q) + \mathbf{\tau} : \mathbf{S} - \frac{T}{\rho} \frac{\partial \rho}{\partial t} \mathbf{p} \left( \frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p \right) + Q, \tag{3}
\]

where \( \mathbf{u} \) is the velocity vector, \( p \) is pressure, \( \rho \) is density, \( \mathbf{\tau} \) is the viscous stress tensor, \( \mathbf{F} \) is the volume force vector, \( C_p \) is the specific heat capacity at constant pressure, \( T \) is the absolute temperature, \( q \) is the heat flux vector, \( \mathbf{S} \) is the strain-rate tensor, \( \mathbf{I} \) is unit matrix, \( Q \) is heat sources. This is an intuitive formulation that facilitates boundary condition specifications. Equ. (1) is the continuity equation and represents conservation of mass. Equ. (2) is a vector equation which represents conservation of momentum. Equ. (3) describes the conservation of energy, formulated in terms of temperature. Besides that, \( a : b \) stands for \( \sum \sum a_{nm} b_{mn} \). In this paper, we set the feed speed as 1 mm/min, the same as experimental condition.

The heat transfer process can be expressed by the following equation:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (q + q_r) = Q, \tag{4}
\]

where \( q \) is the heat flux by conduction, \( q_r \) is the heat flux by radiation, we use a homemade CO\(_2\) laser (10.6 \( \mu \)m) drawing instrument to heat the preform. The schematic of the laser heating path is shown in Fig. 1. The laser will be absorbed in a very short distance on the surface of the preform, so we can treat it as a boundary heat source.

![Fig. 1. Optical paths of CO\(_2\) laser drawing instrument.](image1)

The power of laser is initially a Gaussian distribution. After the conversion of the optical paths, it reaches the preform all around with a near half-Gaussian distribution. When the total power is 320 W, the power distribution obtained by Zemax simulation is shown in the Fig. 2.

![Fig. 2. Power distribution on the surface of preform.](image2)

In reality, the power density increase as the radius of the preform decrease, so the laser power function must multiply a scale factor \( r/r_0 \), where the \( r_0 \) equals to the initial radius of the preform. The
preform is cooled by radiation and air convection of the surface. The air convection can be simplified as a boundary convective heat flux. It can describe as follows:

\[
\textbf{q} = h(T_{\text{ext}} - T) \tag{5}
\]

where \(h\) is heat transfer coefficient, and \(T_{\text{ext}}\) is external temperature. The radiation heat flux can be described as:

\[
-\textbf{n} \cdot \textbf{q}_r = \varepsilon \sigma (T_{\text{ext}}^4 - T^4) \tag{6}
\]

where \(\varepsilon\) is the surface emissivity, \(\sigma\) is the Stefan-Boltzmann constant, and \(\textbf{n}\) is the normal vector on the boundary. In this model, the surface and the bottom of the preform have suffered both radiation heat flux and air convection, the external temperature is set as 20 centigrade. The material parameters involved here can be found in [3-6]. The equations are solved numerically with Comsol Multiphysics using a finite-element method, and the free surface is solved with an Arbitrary Lagrangian-Eulerian formulation.

2.2. Experiment conditions

In addition to theoretical simulation, we also experimentally validated this process. The fiber preform was prepared by putting a single crystal Ge-rod with OD around 220 \(\mu\)m into a silica tube with OD around 8 mm. The whole drawing process could be divided into three states: heating state, unstable drawing state, and stable drawing state. In the first state, the preform has been heated by the \(CO_2\) laser. After being well heated, the preform starts to deform under the effect of gravity. The preform is tapering and eventually forming a neck-down shape. In the final state, the shape of preform stop changing, and the drawing process becomes steady under a fixed preform feed speed and a fixed fiber drawing speed.

During the drawing process, we set the initial feed speed to 1 \(mm/min\) and initial power to approximately 100 W, gradually increasing the power until the preform starts to deform. By tuning the laser power, the preform feeding and fiber drawing speeds, the steady drawing condition can be finally reached. After the part containing the germanium core is completely drawn, the laser is turned off and the entire drawing process ends.

3. Result and discussion

For comparison, the preform parameters and the drawing conditions in the simulation are set as the same with the experiment. When laser power reaches 320 W, the preform is tapering and eventually forms a neck-down shape. The maximum temperature and maximum velocity vary with time, as shown in Fig. 3.

![Fig. 3. Variation of maximum temperature and velocity with time.](image)

It can be seen from the temperature curve that the position at the peak of laser power is rapidly heated to higher than 2500 K just in a few seconds because of the high absorption of the silica material.
at the wavelength of 10.6 μm. As time goes on, heat conduction and accumulation let more and more silica material soften, and the preform begins to deform with the decreasing of silica’s viscosity. The maximum velocity increases greatly after 300 s, which denotes the increasing deformed rate. This will lead to a rapid temperature increase, and finally causes an increasing velocity. At the last 25 s, the deformation rate is so large that the preform is quickly falling down just like free falling.

Fig. 4 shows the preform profile changes with the laser heating time. In the first 50 s, the deformation is not obvious. Starting from 100 s, the deformation speed increases as time passed by. From 345 s to 349.13 s, the rapidly falling happens and a necked-down profile forms at 349.13 s.

![Variation of preform surface profile with time.](image)

In the experiment, the feed speed of preform and the power of laser were adjusted to make sure that the preform is fully softened but not vaporized. In this way, we successfully reached the steady drawing state, and the part containing the germanium core was fully drawn into Ge-core optical fiber in the end. Both the picture of the drawn preform and the neck-down profile from above simulation are shown in Fig. 5. We can see from the figure that the simulation result has a good agreement with experiment results.

![The final neck-down profile of the fiber preform obtained by the experiment and the simulation.](image)

4. Conclusion
A model to simulate the dynamic process of laser drawing pure Ge-core fiber is presented. The variation curves of the temperature, the velocity, and the surface profile of the preform with time were
calculated and discussed. The final profile of the preform has a good agreement with the profile obtained by the experiment.

Acknowledgment
This work is supported by the National Natural Science Foundation of China (Project Nos: 61227012, 61575120, 61422507, 61475095, and 61635006).

References
[1] Ballato J, Hawkins T, Foy P, et al. 2011 Silica-clad crystalline germanium core optical fibers. Optics Lett. 36: 687-688.
[2] Mehta P, Krishnamurthi M, Healy N, et al. 2010 Mid-infrared transmission properties of amorphous germanium optical fibers. Appl. Phys. Lett. 97: 071117.
[3] Doremus R H. 2002 Viscosity of silica. Journal of Applied Physics 92: 7619-7629.
[4] Rhim W K, Ishikawa T. 2000 Thermophysical Properties of Molten Germanium Measured by a High-Temperature Electrostatic Levitator1. International Journal of Thermophysics 21: 429-443.
[5] Brückner R. 1970 Properties and structure of vitreous silica. I. Journal of non-crystalline solids 5: 123-175.
[6] Sato Y, Nishizuka T, Tachikawa T, et al. 2000 Viscosity and density of molten germanium. High Temperatures High Pressures(UK) 32: 253-260.