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3D VISCOELASTIC FINITE ELEMENT MODELLING OF POLYMER FLOW IN THE FIBER DRAWING PROCESS FOR MICROSTRUCTURED POLYMER OPTICAL FIBER FABRICATION

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Abstract: The process of drawing an optical fiber from a polymer preform is still not completely understood, although it represents one of the most critical steps in the process chain for the fabrication of microstructured polymer optical fibers (mPOFs). Here we present a new approach for the numerical modelling of the fiber drawing process using a fully three-dimensional and time-dependent finite element method, giving significant insight into this widely spread mPOF production technique. Our computational predictions are physically based on the viscoelastic fluid dynamics of polymers. Until now the numerical modelling of mPOF drawing has mainly been based on principles, such as generalized Newtonian fluid dynamics, which are not able to cope with the elastic component in polymer flow. In the present work, we employ the K-BKZ constitutive equation, a non-linear single-integral model that combines both elastic and viscous ideas and can appropriately describe the physics of polymers under processing.

Key words: Fiber drawing, numerical simulation, finite element method, microstructured polymer optical fiber, polymers.

1. Introduction

A critical step in the process chain for microstructured polymer optical fiber fabrication [1] is the drawing of polymer fibers, that may deviate from the specific design outlined in the initial preform. The process of drawing an optical fiber from a polymer preform is still not understood, although it represents one of the most critical steps in the process chain for microstructured polymer optical fiber manufacturing. In particular, the modelling of this process represents a challenging task from both theoretical and computational points of view. In fiber drawing, as well as in most polymer processing operations such as injection molding and extrusion, the dynamic behavior of polymers is generally complex and multifaceted. It therefore needs to be modelled as a 3-D time-dependent flow problem, in which the presence of interfaces or any moving surface must be taken into account [2-3].

The aim of this paper is to propose a new approach for the numerical modelling of the fiber drawing process using a fully three-dimensional (3D) and time-dependent finite element method (FEM) to provide new insight into this widely spread mPOF fabrication technique. The computational predictions in this work are physically based on the viscoelastic structured fluid dynamics of polymers. Until now the numerical modelling of mPOF drawing has mainly been based on viscous principles, such as Newtonian and generalized Newtonian fluid dynamics [4-7]. Except for the limit of vanishing elasticity, where the Newtonian model is correct, viscous models do not represent the physics of polymer flow. To correctly model and simulate the flow of polymer melts, it is thus important to consider the polymer as a complex viscoelastic material and choose an appropriate constitutive model. The particular model used in our simulations is the factorized K-BKZ constitutive equation [8-9], a non-linear single-integral constitutive equation which is based on the transformation of a non-linear expression for the stress tensor $\boldsymbol{\tau}$ of an ideal elastic solid in large deformations into a model for a fluid combining both viscous and elastic components [8]. K-BKZ model have shown great potential in predicting the behavior of plastics for complex flow situations of industrial importance [3,9].

We think that the use of a time-dependent description in 3D is important for a thorough investigation of polymer flow during the fiber drawing process. Albeit several problems may ideally be described using 2D or 1D geometry, the presence of any disturbance or irregularity will affect the flow of plastics and may turn the problem into 3D. Moreover, a steady-state flow might have a limited range of stability, the extent of which can be appropriately investigated using a time-dependent approach [10].

2. Three-dimensional viscoelastic flow of plastic in fiber drawing

2.1. *Finite element formulation*

The approach follows the method developed by J.M.R. Marín *et al.* [2]. A Lagrangian kinematics approach, where the spatial coordinate system is attached to the particles, is used. The particle position $\boldsymbol{x} = (x_1, x_2, x_3)$ is calculated starting from t_0 (when time is equal to 0) and applying an appropriate set of boundary conditions for the present time, t, higher than t_0.

The total stress tensor $\boldsymbol{\pi}$ for the considered system can then be calculated as:

$$\boldsymbol{\pi} = p\boldsymbol{\delta} + \boldsymbol{\tau} \tag{1}$$

Here $\boldsymbol{\delta}$ is the unit tensor, and p denotes the pressure. The factorized K-BKZ model for the stress tensor $\boldsymbol{\tau}$ can be written as follows [2]:

$$\boldsymbol{\tau} = \int_{-\infty}^{t} M(t-t')\boldsymbol{S}\,(\boldsymbol{x}, t, t')dt' \tag{2}$$

in which t' denotes some past time, $M(t-t')$ represents the memory function [8], and $\boldsymbol{S}$ is known as the isotropic strain tensor:

$$\boldsymbol{S}(\boldsymbol{x}, t, t') = \psi_1(t-t', I_1, I_2)\boldsymbol{\gamma}_{[0]} + \psi_2(t-t', I_1, I_2)\boldsymbol{\gamma}^{[0]} \tag{3}$$

In Eq. (3), ψ_1 and ψ_2 denote two scalar functions of the elapsed time $(t-t')$, and I_1 and I_2, which are the first and the second invariants of the Finger strain tensor [2-3,8], respectively. Here $\boldsymbol{\gamma}_{[\mathbf{0}]}$ and $\boldsymbol{\gamma}^{[\mathbf{0}]}$ represent the relative finite strain tensors and their definition can be found elsewhere [8,11].

The discretization of momentum balance and continuity equation is performed using a mixed Galerkin FEM with third order accuracy in time and space. Second order tetrahedral finite elements are adopted to describe the flow in a Lagrangian framework (i.e., following the particle movement). A complete description of the algorithm is published in [2-3,10].

2.2. *Model implementation*

The mPOF consists of a 3-ring hexagonal lattice of air holes in the initial preform, as shown in Figure 1(a). This kind of hole arrangement is rather common for microstructured optical fibers [12]. Length and diameter of the preform are 100 mm and 60 mm, respectively (for an aspect ratio diameter/length of 0.6). The 3-ring hexagonal structure is made of 36 holes with a diameter of 2.5 mm, whereas the hole pitch is equilateral triangular. Furthermore, the spacing between adjacent holes is chosen to be 6 mm.

Both CAD design and 3D meshing of the mPOF preform are performed with GMSH software by C. Geuzaine *et al.* [13]. For the microstructured polymer preform a non-uniform structured mesh (with tetrahedral elements) is generated using Delaunay triangulation (Figure 1(b)). Furthermore, exploiting the presence of symmetry planes in the hexagonal hole structure it is possible to considerably reduce the computational domain. In particular, assuming a perfectly uniform heating in the hot zone, the considered three-dimensional domain is only 1/12 of the initial volume. As a result, the 3D viscoelastic fiber drawing simulations are efficient and much faster than those carried out considering the whole microstructured preform without symmetry.

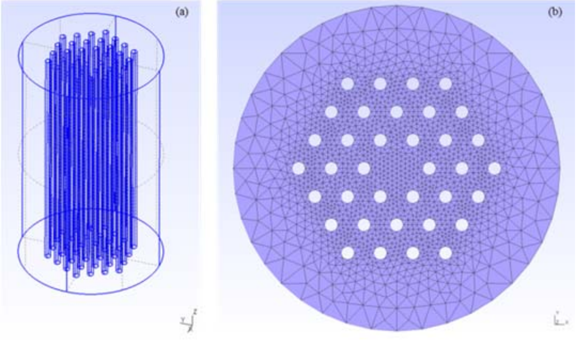

Fig. 1. (a) CAD model of the initial mPOF preform which has a 3-ring hexagonal lattice of air holes. b) Non-uniform and structured mesh generated using GMSH [13].

The preform is assumed to be placed in an oven, in a perfectly centered position for homogenous heating (origin at $x = 0$ and $y = 0$), and the lower part of it is heated up to temperature higher than the glass transition temperature of the polymer. The bottom of the preform is then drawn down at a constant speed. The fiber drawing process is handled as a pseudo-isothermal flow as the polymer is considered insensitive to temperature change (except for melting). That is, the polymer relaxation spectrum remains the same during the simulation, whereas the 3D elements are slowly released with time according to the change in the axial coordinate of the melting zone. In this problem we do not consider the solidification of the polymer fiber. Therefore the diameter dimension may still change even when it is far from the neck-down region, but the strain hardening in the polymer fiber can somehow balance this effect.

2.3. Results

The simulation displays the typical behavior observed when pulling down polymer performs at the drawing tower, with the formation of a neck-down region in which a sudden change in diameter occurs [1] (Figure 2(a)). The final length is approximately 1.8 meters, whereas the correspondent diameter reduction is of around 90% (that is, it reduces up to one tenth of the initial diameter). Figure 2(b) illustrates the final fiber in a snapshot taken at the end of the simulation. Figure 2(c) and Figure 2(d) show that the designed hexagonal hole pattern is preserved throughout the drawing process and further display the final shape of the neck-down region at the end of the finite element computations. Note that here, due to symmetry, the simulation results are conveniently reported only for one twelfth of the original volume.

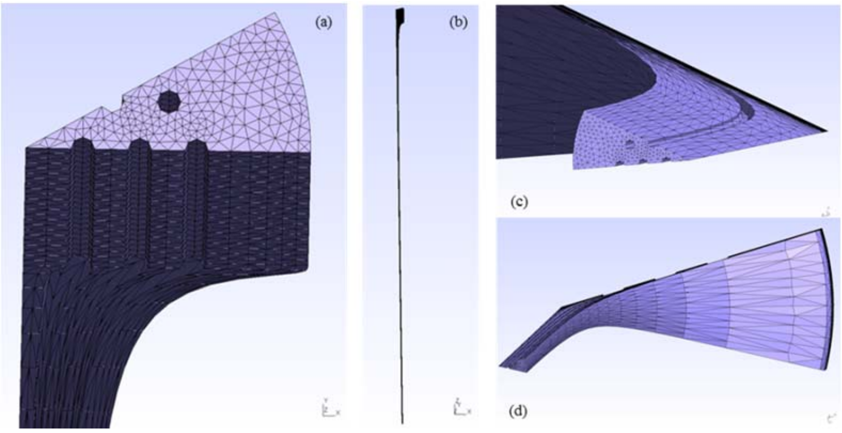

Fig. 2. (a) Neck-down region formation during the mPOF drawing process. (b) Final fiber after being drawn down. The final reduction in diameter is of ca. 90%. (c) The 3-ring hexagonal arrangement drilled/machined into the polymer preform is preserved in the optical fiber. (d) Final shape of neck-down region.

The air holes in the hexagonal structure are found to expand in the neck-down region, as shown in Figure 3(a) and Figure 3(b) below. This is agreement with what was observed by S.C. Xue *et al.* [4-6], who also explained the phenomenon [4]. Expansion is then followed by hole collapse as the polymer is stretched along z-axis to the desired fiber length.

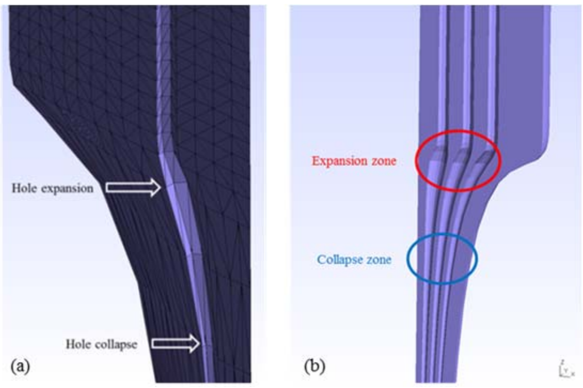

Fig. 3. (a) Expansion and collapse exhibited by the air holes in the neck-down region. (b) Hole expansion and collapse zones at the symmetry plane with three holes. Note the dependence of the enlargement of the holes on their radial position with respect to the center of the preform/fiber.

Interestingly, expansion-collapse phenomena take place at both symmetry planes with single hole and three holes, respectively. Regarding the latter, the extent of hole enlargement in the neck-down zone seems to be dependent on the radial position of the holes with respect to the center of the mPOF preform (the position of which, for symmetry reasons, is fixed at the origin of x-axis and y-axis). In particular, this expansion shows to be more pronounced for the hole in proximity to the center, as displayed in Figure 3(b). The higher increase in the hole diameter may be due to a greater suction of material needed by the polymer to increase its velocity in the neck-down region, in addition to the material taken from the reduction in the preform diameter observed therein.

3. Conclusions

In this paper, we have presented a new approach for the numerical modelling of the fiber drawing process with a time-dependent 3D finite element method. Our computational work has been based on the viscoelastic structured fluid dynamics of plastic materials, in particular using a K-BKZ constitutive model, which can properly describe the complex physics of plastics under flow in processing operations. Experimentally observed phenomena, such as hole expansion and retraction within the neck-down region, were seen in the computations.

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