Instabilities in the Fabrication of Polymer Optical Fibers

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Abstract

Polymer optical fibers (POFs) have drawn interest as high-bandwidth (or high-speed) data-transmission media for short distance communications as in local area networks or home networks. In spite of their higher attenuation (or loss of optical power) than glass optical fibers (GOFs), POFs are perceived to be more suitable for these applications due to their flexibility and durability. These properties make it possible for POFs to have a much larger core diameter in the order of 1 mm compared to 5 ~ 10 m of single-mode GOFs. In order for a POF to have high-bandwidth capability, it should have a special structure in that the refractive index of the fiber should vary smoothly in the radial direction. Such a fiber with a near-parabolic refractive index profile is called a graded-index polymer optical fiber (GI-POF). GI-POFs can be made by several different methods that may be classified into two main categories; coextrusion fiber spinning and thermal drawing of preforms. In all these fabrication methods, some kind of instabilities are encountered in that the fiber radius may fluctuate and/or the cylindricity of the fiber is lost depending on the processing conditions and the material properties. Besides draw resonance that is well known since mid 1960s as sustained periodic oscillation of radius, a long wave fluctuation of radius is found to be associated with a characteristic time of a fabrication process. Non-cylindrical shapes of the fiber cross-section, that are quite regular as elliptical, triangular or pentagonal, seem to be associated with the material properties especially the molecular weight of the polymer.

Introduction

POFs can be classified into step-index (SI) and graded-index (GI) fibers depending their structural characteristics and utility, and these fibers are fabricated mostly by extrusion methods or preform methods. While the continuous extrusion is the dominant method for the manufacture of SI-POF, the preform method appears to be the preferred approach for the GI-POF. In the following sections, these methods are described for the fabrication of SI-POFs and GI-POFs, respectively.

Extrusion Methods

One of the most well-developed method for the production of SI-POF is the continuous extrusion method that is described schematically in Figure 1 (1). In this method, a purified monomer (e.g., methyl methacrylate) along with an initiator and a chain transfer agent is fed into the polymerization reactor where polymerization reaction takes place. The polymer, which is for the core of the SI-POF, is then fed into an extruder by a gear pump. The extruder is capable of devolatilization to remove monomer residues and to return them back to the polymerization reactor. The core material then proceeds into a coextrusion die (or a spinning block) where the concentric core-cladding structure of an SI-POF is formed along with a cladding material fed by a separate extruder. Although the description of this process may appear to be simple, numerous variables including the purity of the monomer, the reaction

temperature, the degree of polymerization, amount of the initiator and the chain transfer agent, extrusion conditions play an important role in determining the optical and physical properties of the fiber. (2)

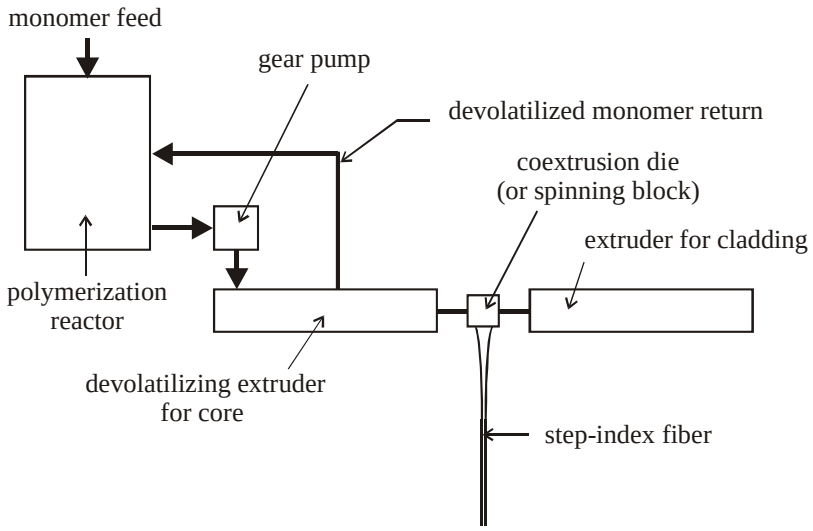

Figure 1. Schematic of a continuous extrusion process

Although the extrusion method is used most preferably to produce SI-POF, it has been also used for the manufacture of GI-POF (3-5). In order to achieve a gradient index profile, a dopant (or monomer) has to be added to the core material that diffuses radially to the cladding layer. Thus, a heated diffusion zone is needed prior to take-up of the fiber. Molecular diffusion is a very slow process and it may limit the high production rate of the extrusion method (6, 7).

Preform Method with Thermal Drawing

Preform method is a batch process where a polymeric preform (or rod) is made first followed by thermal drawing of the preform into a fiber. The preform method is most preferably used for the manufacture of GI-POF. In fact, a GI-POF was first fabricated by the thermal drawing of a graded-index rod that was made by photo-copolymerization in 1976 (8). Later in 1988, the most well-known method of interfacial-gel polymerization was introduced by Koike et al. (9). In mid 80's, another method was introduced by Dahl et al. (10). In this method, a cylindrical reactor is partially filled with a monomer mixture that is polymerized (Figure 2). As the polymerization reaction proceeds, monomer mixtures of varying composition are fed continuously into the reactor. Because of the centrifugal force of the rotating cylindrical reactor, the reaction takes place at the inner wall of the reactor and proceeds radially inward. Unlike the interfacial-gel polymerization method, material diffusion does not play a role in this method. Thus, a preform with a large diameter can be made and the refractive index profile can be adjusted by varying the mixture composition. Recently several researchers adopted the similar approach for the fabrication of GI-POF. Although various methods taken by different researchers may have their own peculiar features of proprietary in nature, there exist many similarities and appear to the share the same basic principle (11).

The Dahl's method involves many variables that influence various properties of the preform to a very large extent (12). The variables include mixture composition, additive

(initiator and/or chain transfer agent) concentration, reaction temperature (and/or UV-radiation intensity), rotational speed, and the feed rate the reactant mixture with varying composition. The properties that are influenced by these variables include the optical properties such as the refractive index profile and attenuation, and the mechanical properties such as tensile and bending strength. The mechanical properties are mainly determined by the molecular weight distribution and its spatial variation (especially in the radial direction). The molecular weight distribution also determines the drawing characteristics of the preform when it is drawn thermally to a fiber. Therefore, although similar approaches were taken by several different researchers, their respective results may be significantly different depending on the materials used and the conditions adopted.

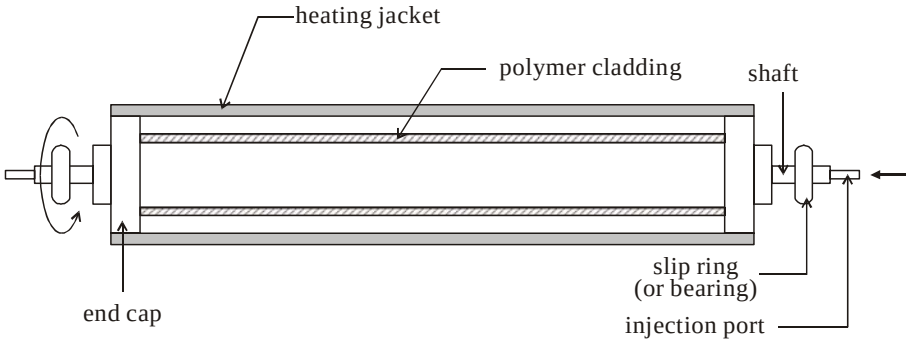

Figure 2. Schematic of a preform-making process by Dahl et al.

The preforms made by various methods are drawn into fibers by a thermal drawing process described schematically in Figure 3. The preform is fed continuously into a furnace where heat is provided by convection and/or radiation, and the molten preform in the furnace is drawn into a fiber by a nip roll. The diameter is measured by a micrometer (typically a laser meter) and controlled by adjusting the speed of the nip roll. The optical and mechanical properties of the fiber depend not only on the properties of the preform itself but also on numerous variables involved in the thermal drawing process. These variables include feed rate of the preform, furnace temperature, length of the furnace and draw span. The structure of the furnace (e.g., relative diameter, upper and lower iris) and cooling of the fiber also have significant influence.

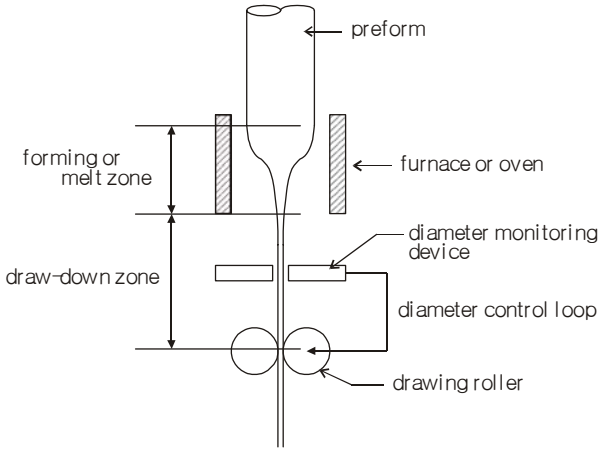

Figure 3. Schematic of a thermal drawing process

Instabilities

Depending on the processing condition, various instabilities are also encountered that are associated with the diameter fluctuation and the cylindricity of the fiber. Some instability phenomena are known theoretically and some are known only empirically yet.

Draw Resonance

Draw resonance is an instability that represents sustained period oscillation of radius when a fiber is drawn by the extrusion process or the thermal drawing process. It has been well studied since it was first reported in early 60's (13-16). It has been also known that this instability can be suppressed by controlling the processing condition, especially the drawing tension or the thermal condition. A non-Newtonian property, especially the extensional viscosity, of the fluid is known to have strong influence on this instability in that linear polymers are more prone to draw resonance (17-20).

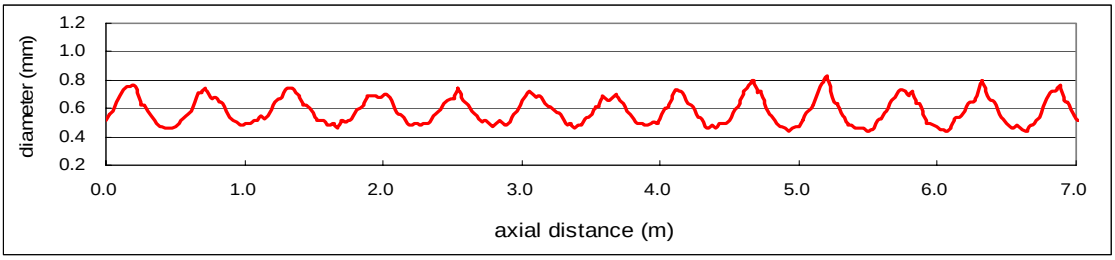

Figure 4. Draw resonance encountered in the extrusion of polyethylene (19)

Instability in the Circumferential Direction

When a polymer optical fiber was drawn from a preform by the thermal drawing process, non-circular shapes of the fiber were observed sometimes in that the cross-sectional shape of the fiber took on elliptical, triangular, pentagonal or hexagonal shapes as shown schematically in Figure 5.

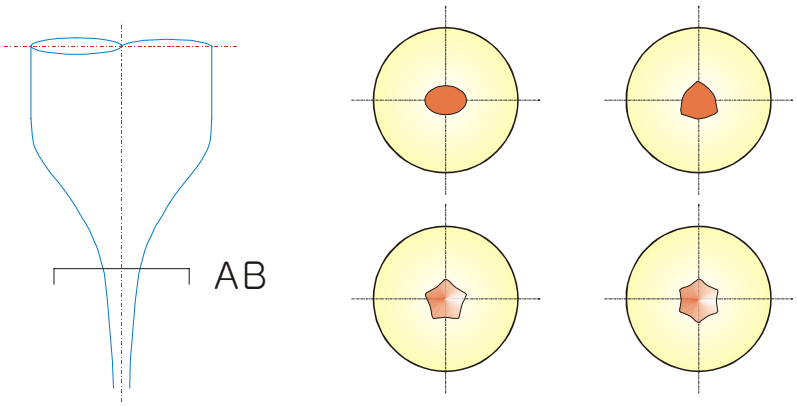

Figure 5. Polygonal shape of the fiber observed at the cross-section AB of the neck-down region of the preform

The polygonal shapes of the fiber cross-section have been observed to be preserved through the thermal drawing process, and it seems that the shape is mainly determined by the molecular weight of the preform and the drawing temperature has little influence. Apparently, the peculiar shapes.appeared only when the weight averaged molecular weight of the preform was larger than about 120,000. Although the number of sides of the polygons may have be closely related with the molecular weight, its correlation is not yet known.

Random Fluctuation of Radius

Either in the extrusion or the thermal drawing process, the radius of the fiber shows a random fluctuation to a certain extent as shown in Figure 6.

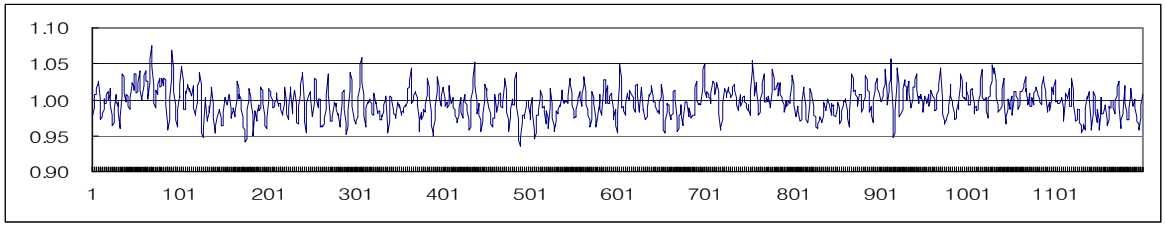

Figure 6. Random fluctuation of the fiber made by the thermal drawing process (Avg. diameter of the fiber is 1.0 mm, and the x-axis represents the data point taken every second.)

A Fourier analysis of the data given in Figure 6 indicates that the radius fluctuation is random and the standard deviation is smaller than 25 μm for the fiber with an average diameter of 1mm.

In the thermal drawing process, the radius fluctuation is also strongly influenced by various processing conditions such oblique angle of the preform relative to the direction of gravity (Figure 7).

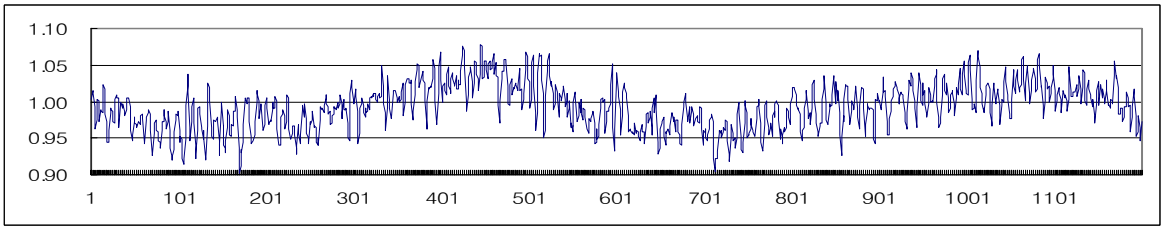

Figure 7. Long wave instability induced by the oblique angle of the preform relative to the direction of gravity.

Fourier analysis of the data in Figure 7 indicates a long wave with temporal period of about 10 minutes. When the preform is heated in the oven to be drawn into a fiber, it is rotated to ensure uniform heating in the circumferential direction. The period of rotation matches with the long wave period indicating that the long wave instability may be associated with the rotation of the preform.

Acknowledgement

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