Stress Measurements on Fibers and Preforms

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Abstract—**During the study of loss reduction on trapezoidal core 1.55-μm dispersion-shifted MCVD fibers, measurements of the axial stress distribution on preform and optical fibers have been investigated.**

It has been shown that the internal stress profile of MCVD or SPCVD preforms is related to the expansion coefficients of different materials. However, the results show that the level of fiber stress is linearly dependent on drawing tension and that the stress profile is related to the glass transition temperature T_g of the different materials.

I. Introduction

MEASUREMENTS of the axial stress distribution in preform and optical fibers have been achieved as some preform preparation process and fiber drawing conditions have shown nonexplained phenomena such as index profile modification from preform to fiber, the need to change standard fiber cutting conditions, and the higher influence of fiber mechanical properties to defects enhanced by drawing tension.

These observations were made during the study of loss reduction on trapezoidal core 1.55-μm dispersion-shifted fibers, manufactured by the MCVD technique. These phenomena are related to the low temperatures and relatively high drawing tensions used [1]. The aim of the present study is to point out the formation mechanism of axial stress, to describe the method and the apparatus used for the measurements, and to present the results.

II. Stress Origin

During the deposition, collapse, sleeving, and drawing steps, the preform or the fiber is heated and rapidly cooled down. They are made through concentric layers of materials having different physical properties, natural or synthetic silica for the deposit or sleeving tubes, doped silica for the cladding or the core. Each shows a different expansion coefficient or glass transition temperature.

The origin of the axial stresses is due to the relatively high drawing tension used with glass materials having different softening temperatures in the fiber cross section (Fig. 1). The connection of internal stresses with material viscosity is illustrated in Fig. 2 which shows a fiber with

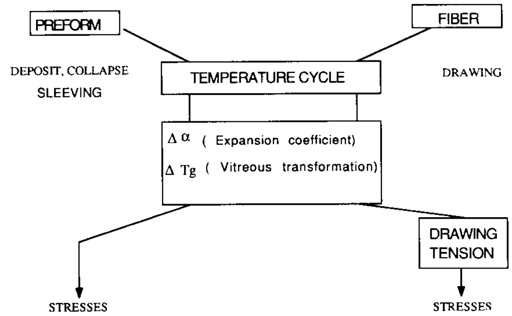

Fig. 1. Origin of the internal stresses.

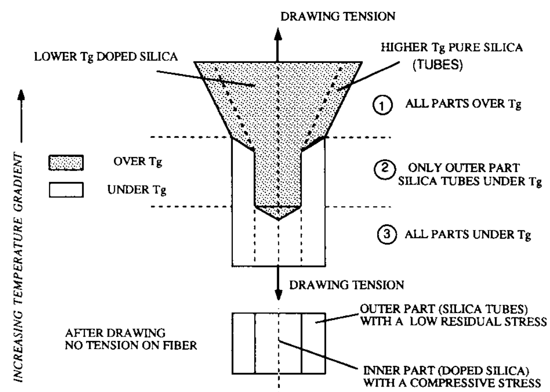

Fig. 2. Internal stresses are related to the viscosity difference.

a pure silica tube and doped silica central part. The preform drawing neck-down is close to the furnace temperature gradient. In the upper part both outside (silica tubes) and inside (cladding and core doped silica) are over their glass transition temperature (T_g).

In the middle part at lower temperature, the tensile stress is applied only on outer silica tubes which are under their transition temperature. In the bottom part, at an even lower temperature, all the parts of the fiber are under their transition temperature, the same stress effect is kept, and the doped silica part of the fiber stays almost under zero stress.

When the drawing tension is released, after capstan, a new equilibrium of axial stresses effects appears. The inner parts (low T_g doped silica) stand a compressive axial stress and the outer part (high T_g silica tubes), a balancing stress effect.

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The levels of these stresses are directly dependent on the drawing tension and in inverse ratio on the relative cross sections of the different transition temperature parts of the fiber.

Complementary stress effects are induccd by expansion coefficient differences.

III. Theoretical Analysis of the Stress Distribution

The stress distributions in a cylinder under thermoelastic forces are described in [4], σr, $\sigma\theta$, σz are the diagonal components of the stress tensor following the cylindrical coordinates (Fig. 3). The axial stress is:

$$\sigma z(r) = \frac{E\Delta T}{1\nu}\left[\frac{2}{b^2}\int_0^b \alpha r \, d r\alpha\right] \tag{1}$$

where E = elasticity module, ν = Poisson coefficient, $\alpha(r)$ = expansion coefficient gradient along the radius r, b = external radius, and ΔT = temperature difference between the melting and the room temperature.

The above relationship is based on the following assumptions:

- stresses are relevant of the thermoelasticity,
- E and ν are supposed to be independent of the temperature or the chemical composition,
- external tensions are ignored, the fiber is supposed to be infinite and unloaded,
- ΔT is constant everywhere in the sample,
- σz is only function of r.

IV. Relationship Between Stress and Optical Delay

Through the effect of nonisotropic stresses, the glass, initially isotropic glass, becomes birefringent. A plane wave propagating along Oy (Fig. 3) can be split into two plane waves, one having the polarization vector parallel to Ox and the other following to Oz. The index difference along Ox and Oz is proportional to the difference between the stress component perpendicular to the propagation direction [3], i.e.:

$$n_x - n_z = C(\sigma_{xx} - \sigma_{zz}) \tag{2}$$

where n_x and n_z are the refraction indexes, σ_{xx} and σ_{zz} the stress components along x and z. C is the photoelastic constant or Brewster coefficient (for silica glass $C = 3.46 \times 10^{-4}\ (\text{MPa})^{-1}$).

After a travel dy in the material, the phase $d\delta$ between the two perpendicular waves is given by:

$$d\delta(x) = \frac{2\pi \, dy \, (n_x - n_z)}{\lambda} \tag{3}$$

where λ is the wavelength of the source.

This delay is related to the stress under the assumptions that the beam follows a straight line inside the fiber or the preform, and the Brewster coefficient is independent on the radius.

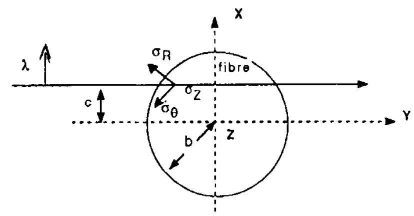

Fig. 3. Measurement conditions.

Under these conditions from (1) we obtain the axial stress:

$$\sigma_z(r) = \frac{1}{\pi C}\int_r^b \frac{\partial R(x)}{\partial x}\frac{dx}{(x^2 - r^2)^{1/2}} \tag{4}$$

where $R(x)$ is the retardation, and x is the position of the incident ray.

The computation of the stress distribution implies therefore the phase displacement profile measurement. It is determined by the quarter-wave method.

The straight vibration coming out the polarizer is bisector of the fiber neutral lines (Fig. 4(a)). At the output of the fiber (Fig. 4(b)), we collect an elliptical vibration E for which one of the axis is parallel to OP and the axis ratio b/a is related to the phase difference induced by the fiber. We have:

$$\frac{b}{a} = \tan\left(\frac{\varphi}{2}\right).$$

This wave is allowed through a quarter-wave plate for which a neutral line Ox is parallel to OP direction of the input wave (Fig. 4(c)). The plate introduces a new difference in phase $\pi/2$ and resets a straight vibration OR having an angle β with Ox. The extinction is then obtained again by rotating the analyzer of $\beta = \varphi/2$. The measurement of β is performed all across the fiber or the preform allowing to obtain the phase displacement profile.

V. Stress Measurements [4]

Stress measurements for fiber and preform are explained as follows.

A) The fiber, laid vertically in a cell filled with index matching liquid, is illuminated by a He–Ne horizontal laser beam (λ = 633 nm) which is polarized at 45° of rotation from the neutral axis of the fiber (Fig. 5). The median plan of the fiber is imaged on the detection plan and magnified by a set of low stress microscope objective and eyepiece. A quarter-wave plate is set with its optical axis oriented at 45° from the fiber neutral axis. Rotation of the analyzer to minimize the transmitted intensity points out the new polarization plan and then the relative retardation in the sample. A cylindrical lens is used to con-

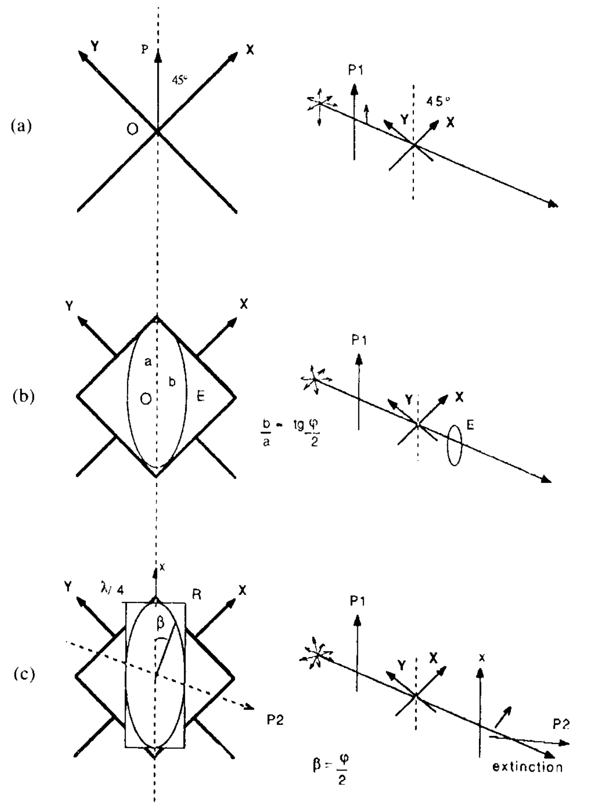

Fig. 4. Quarter-wave plate method. (a) At the fiber input. Fiber neutral lines: X, Y. (b) At the output of the fiber. (c) After the quarter-wave plate.

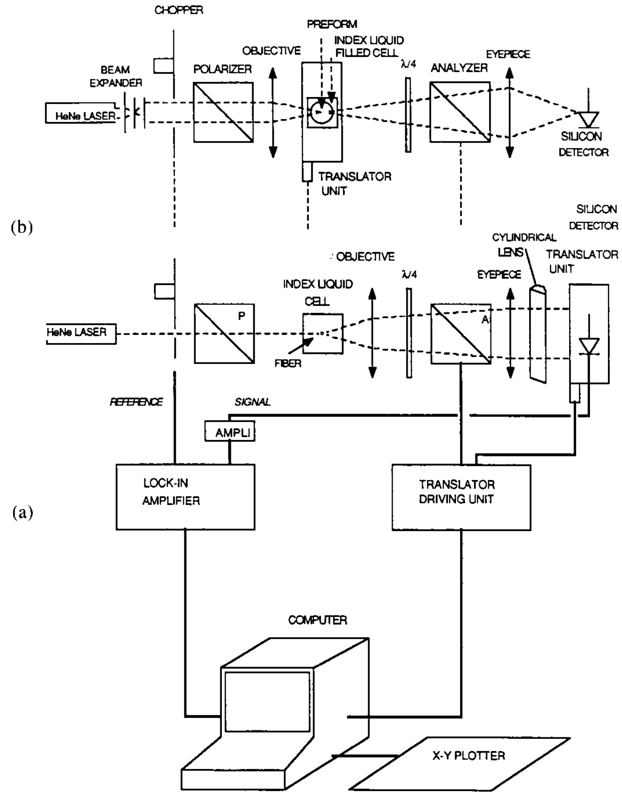

Fig. 5. Stress measurement setup: (a) fiber (b) preform.

centrate light power onto the silicon detector which is moved by a translator unit. Equivalent translation accuracy is $+1.1$ μm.

B) The preform is set horizontally, the laser beam is expanded to minimize the spot focused by a low stress objective onto the center of the preform. The beam is focused by a low stress objective onto the center of the preform. The beam is focused again on a fixed silicon detector after passing through the quarter-wave plate and analyzer as previously. The preform is moved vertically by a translator unit with 200-μm steps. Detailed information is given in Table I.

VI. Stress Profile Measurement

Stress profile measurements were performed on preforms manufactured by MCVD or surfaguide plasma assisted chemical vapor deposition (SPCVD) [5] techniques. Various index profiles were studied: step index, graded index, trapezoidal profile, and pure silica core optical fiber. The preform index was measured by P101 preform analyzer (York Technology) with an accuracy of ± 0.0001 on the index difference.

TABLE I

	PREFORM	FIBER
SAMPLING STEP	200 µm	1,7µm
MEASURING TIME	30 min	30 min
HIGHER ANGLE LIMIT	50°	4°
EXPERIMENTAL DISPERSION	5%	15%

The observations which can be made from the profiles shown in Fig. 6 are: the axial stress variations σ_z follow those of the index profile; σ_z is constant inside a homogeneous doped region; the GeO_2 doped part of the preform is in extension; the use of GeO_2 dopant increases the axial stress; and the fluorine doping decreases the axial stress.

A series of stress profiles is shown in the Fig. 7 for the trapezoidal core fiber drawing with increasing drawing tension on bare fiber (50, 80, 140 cN) but with the same drawing speed (60 m/min).

These fibers are made from preforms processed with Heralux WG deposit tube and Suprasil F[1] sleeving tube.

[1]Heralux WG and Suprasil F are the Heraeus trademarks for natural and synthetic silica tubes.

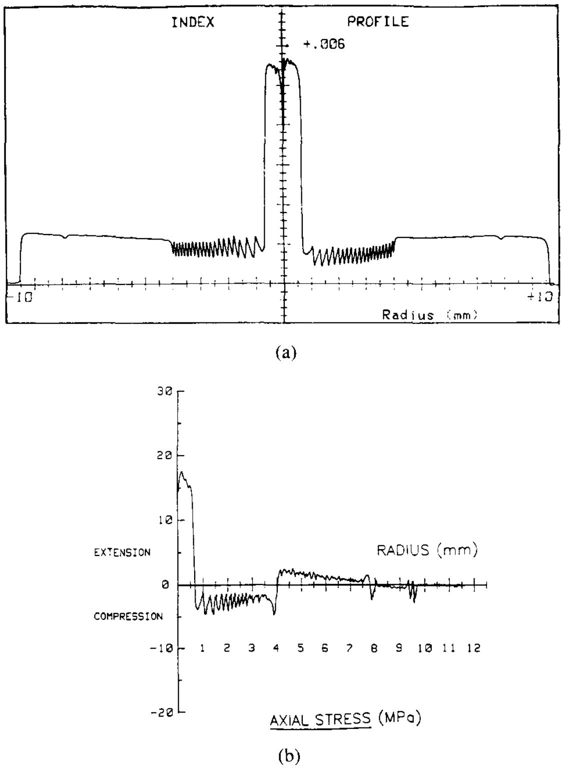

Fig. 6. (a) Actual preform step index profile (P101 preform analyzer). (b) Axial stress profile computed from relation (4).

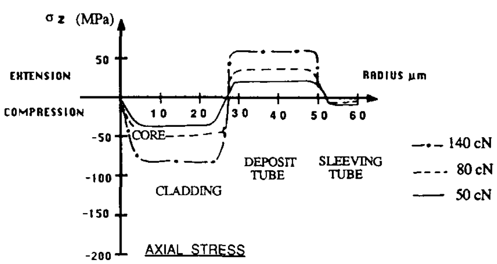

Fig. 7. Axial stress profile of fibers drawn with increasing drawing tension.

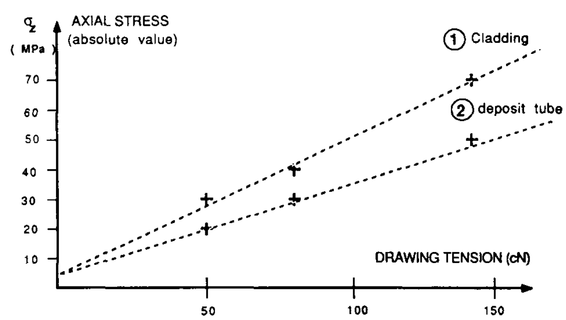

Fig. 8. Axial stress versus drawing tension in (*1*) optical cladding and (2) silica tube.

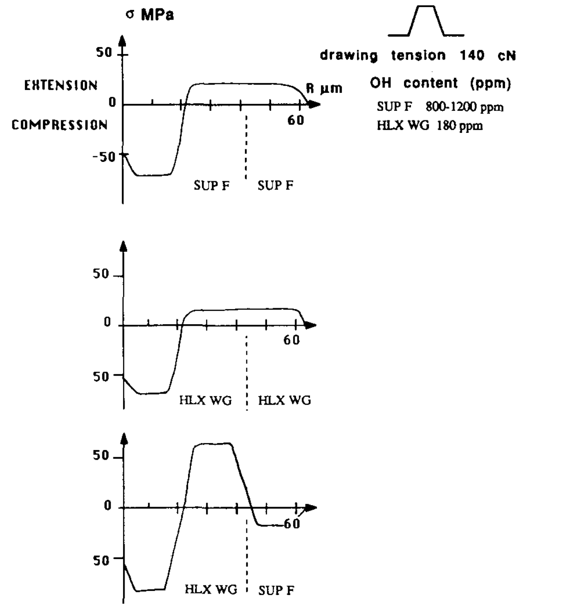

Fig. 9. Dependence of the axial stress with the nature of the deposit tube and the sleeving tube.

The following observations can be deduced from Fig. 7.

- The axial stress is in compression inside the cladding and the core region, and is in extension inside the deposit tube.
- The axial stress inside the sleeving tube is zero.
- The axial stress behavior in the deposit tube and the cladding is linear versus the drawing tension (Fig. 8). The extrapolation of both curves at zero stress corresponds to measured stress on preform.
- The axial stress profile is related to the transition temperatures of materials, even for different silica tube quality this may be related to OH content (Fig. 9).
- In the last example, by sleeving a Suprasil F tube to a Heralux tube made preform, surface tension of the fiber is slightly in compression, and this would increase failure strength of the fiber [6]. No fatigue test has been made and 1.5-percent elongation screen test showed no significant improvement on short-term fiber strength.

VII. Conclusion

The stress measurements on fiber are less accurate than those on preform (experimental dispersion reaches 15 percent instead of 5 percent). Precise manipulations are required. The various observations made from measurements on preform show that the axial stress is related to the index profile and that the core axial stress increases with the GeO_2 content. The same observation can be made whether the preforms are prepared by SPCVD or MCVD processes.

The measurements performed on fiber show that the level of stress is linearly dependent on the drawing tension, and that the stress profile stress is related to the glass transition temperature T_g of the different materials.

Furthermore, this method of stress measurement is complementary to the more standard index profile measurement on fiber (refracted near field) or on preform (P101 preform analyzer).

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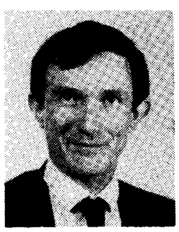

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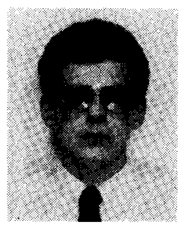

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