Observation of Azimuthal Cracking in the Core/Cladding Interface of the Fiber Preform during MCVD Process

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Abstract

We observed cracks propagated in azimuthal direction, at the core/cladding interface of a fiber preform for magneto-optical application during MCVD process. Since the core of the preform contained large amount of terbium oxide and alumina, the crack formation and propagation was attributed to the thermal expansion mismatch between the core and cladding. The stress in the preform was theoretically calculated by using well-known thermal stress equations with the physical properties of the glass for the core and cladding and the result was found to be in good agreement with the observation in the aspect of azimuthal crack propagation.

Keywords: Faraday effect, magneto-optic, thermal stress, crack, MCVD

1. Introduction

In order to implement additional active functionality other than simple propagation in an optical fiber, it is necessary to change core composition or to add dopants in the core of the fiber. There has been research work on developing optical fibers for magneto-optic application by adding large amount of rare earth oxides in the core of the fiber.[1] We have recently observed crack formation at the interface of the core and cladding of the fiber perform, in which the core was Tb_2O_3-Al_2O_3-SiO_2 glass whereas the cladding was pure silica glass. Numerous cracks were formed at the core/cladding interface and they propagated in azimuthal direction after collapsing of the perform prepared by use of the Modified Chemical Vapor Deposition (MCVD) process. The cracks might be due to thermal expansion coefficient mismatch between the core and the cladding.

In this paper, characterization based on stress analysis was performed theoretically and experimentally to investigate the observed crack formation and propagation in the fiber preform.

2. Experiments

2.1 Fabrication of a fiber preform.

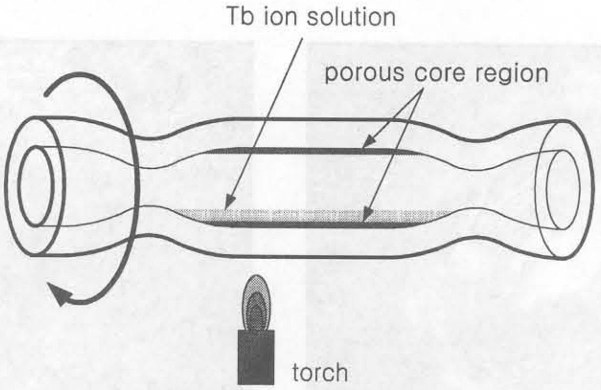


Fig. 1 Modified solution doping technique

To prepare a fiber preform, a porous core layer of pure silica was first deposited by the MCVD process. An aqueous solution of $TbCl_3$ and $AlCl_3$, with which composition of the core of the fiber was designated to be $25Tb_2O_3$-$30Al_2O_3$-$45SiO_2$, was injected in the porous core region shown in Fig. 1 to add a magneto-optical function.[2,3] Then the preform with the wet porous core layers was dried and followed by sintering process at 1890°C. After the sintering process, the tube was collapsed into a rod preform. The rod preform with cracks at the interface of the partially sintered core and cladding is shown in Fig. 2.

2.2 Examination of the cracks

The cracking was not observed when the preform was cooled slowly after collapsing. Ten minutes after the cooling, however, small cracks started to appear near the core region. The cracks continued to grow until the next day and then cracking slowed down and did not progress any more after several days.

The cracks might occur because of the large difference in thermal expansion coefficients. The cracks seemed to appear and develop spontaneously from the interface of the core and cladding, which might be in large tension due to high thermal expansion mismatch after cooling. Particularly, the cracks were round in shape as shown in Fig. 2.

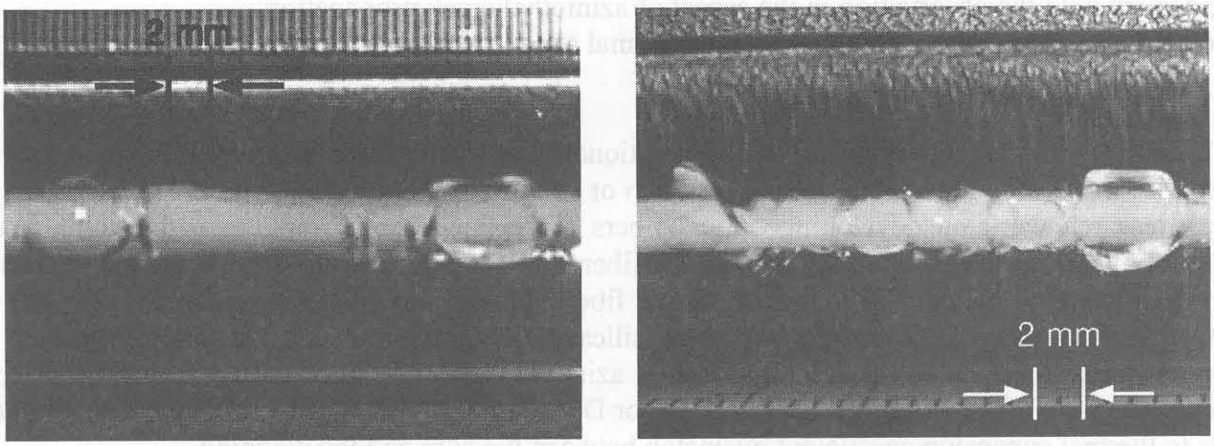
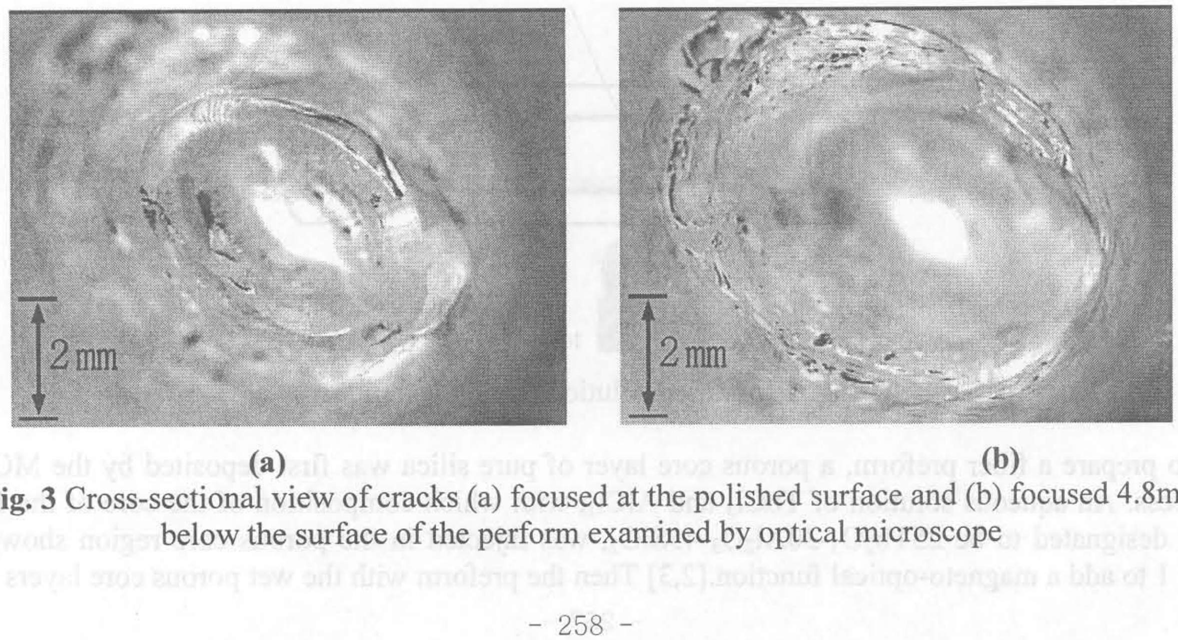


Fig. 2 Side view of cracks formed at the core and cladding interface

A part of the preform was carefully cut and polished and the cross-section area was examined using an optical microscope. Fig. 3 clearly shows that the crack has distinct round shape. As the focal point of the microscope became deeper into the glass, the circular crack became larger. This indicates that the crack has conical or helical shape.



(a) **(b)**

Fig. 3 Cross-sectional view of cracks (a) focused at the polished surface and (b) focused 4.8mm below the surface of the perform examined by optical microscope

3. Results and Discussion

Thermal expansion mismatch was regarded as a limit of rare-earth addition to the core composition by the MCVD process.[1] Thermal expansion coefficient of the core of the perform prepared in this study was estimated to be 62.6 × 10^{-7} K^{-1}, and that of the cladding was 5 × 10^{-7} K^{-1}. Large residual stress is expected to build from the large difference in the thermal expansion. In addition, the glass transition temperatures are different considerably as shown in Table 1. Thus hydrostatic stress above the transition temperature of the core glass, where the core is viscous, should be taken into account.

Equations of the stress in cylindrical coordinates from the thermal expansion mismatch are given as follows.[4-7]

$$\begin{aligned}
\sigma_{r1} &= \sigma_{\theta 1} = \sigma + \frac{\sigma'}{2}\left(\frac{b^2}{a^2} - 1\right) \\
\sigma_{z1} &= \sigma + \sigma'\left(\frac{b^2}{a^2} - 1\right) \\
\sigma_{r2} &= \left(\frac{a^2\sigma}{b^2 - a^2} + \frac{\sigma'}{2}\right)\left(\frac{b^2}{r^2} - 1\right) \qquad \text{, where} \begin{cases} \sigma = \dfrac{3(\alpha_2 - \alpha_1^*)(T_{g1} - T_{g2})}{\dfrac{1}{K_1^*} + \dfrac{3a^2(1 - 2\nu_2) + 2b^2(1 + \nu_2)}{E_2(b^2 - a^2)}} \\ \sigma' = -\dfrac{E(\alpha_2 - \alpha_1)(T_{g1} - T_R)a^2}{(1 - \nu_2)b^2} \end{cases} \qquad (1) \\
\sigma_{\theta 2} &= -\left(\frac{a^2\sigma}{b^2 - a^2} + \frac{\sigma'}{2}\right)\left(\frac{b^2}{r^2} + 1\right) \\
\sigma_{z2} &= -\left(\frac{a^2\sigma}{b^2 - a^2} + \sigma'\right)
\end{aligned}$$

Subscript 1 and 2 denotes the core and the cladding region, respectively and superscript * means viscous state where temperature is above glass transition temperature, T_g. E is Young's modulus, and K is Bulk modulus. ν is Poisson's ratio, and α is thermal expansion coefficient. T_R is room temperature. a and b is the radius of the core and cladding, respectively and r is the radial distance from fiber axis to the point of interest. Poritsky's convention was adopted, namely positive stress is tension.

Table 1 Physical properties of the core and cladding of the preform

	Core	Cladding
Glass composition	$25Tb_2O_3$-$30Al_2O_3$-$45SiO_2$	Pure Silica
Thermal expansion coeff.[8]	$\alpha_1 = 62.6 \text{ X } 10^{-7}$ °K^{-1}	$\alpha_2 = 5 \text{ X } 10^{-7}$ °K^{-1}
Glass transition temperature[8]	$T_{g1} = 891$ °C	$T_{g2} = 1140$ °C
Young's modulus[7]		$E_2 = 6.7 \text{ X } 10^{10}$ Pa
Bulk modulus*[7]	$K_1^* = 3.5 \text{ X } 10^{10}$ Pa	
Poisson's ratio[7]		$\nu_2 = 0.18$
Radius	a = 0.45mm	b = 7.45mm

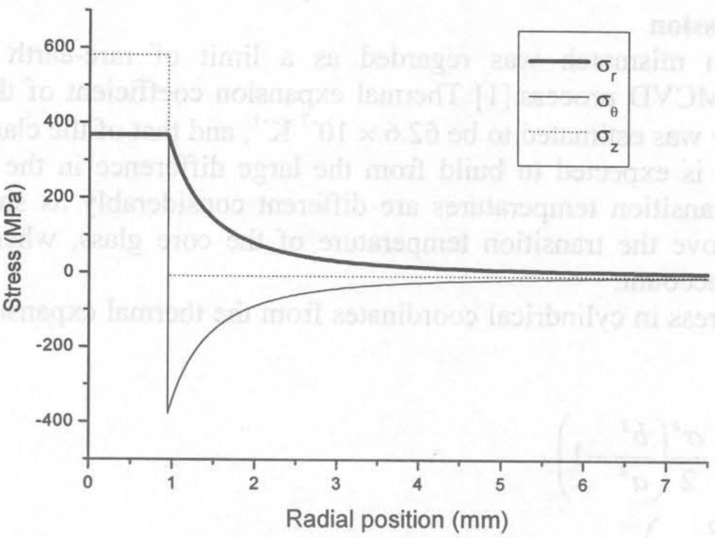


Fig. 4 Estimated thermal stress profile of the preform

Fig. 4 shows the calculated stress profile of the preform from Eq. 1 with the physical properties shown in Table 1. The preform was assumed to have a step index profile, and α^* was assumed to be three times of α.[7] In the core, three components of stress are all tensile and constant. In the cladding, σ_{z2} and $\sigma_{\theta 2}$ are compressive, but σ_{r2} is tensile. σ_{z2} is small constant value. σ_{r2} and $\sigma_{\theta 2}$ are large near the core and become small along radial direction.

The maximum stress is the axial stress in the core, σ_{z1} = 580 MPa. This tension is large but not enough to induce breaking of the tight glass structure. The core of the collapsed preform shown in Fig. 2 was white and opaque, which indicates that the porous layers were not fully sintered into a glass. Therefore, many micro-cracks may be initiated from the wall of the partially sintered core. The cracks initiated from the core can propagate from the interface into the cladding, since the tension smaller than 400 MPa existed even in the cladding. The cracks finally stop propagating in the cladding, because the tension decreases along radial direction. Because the stress in radial direction is only tension, the cracks are thought to propagate in azimuthal direction. Fig. 5 shows the schematic of the crack propagation at the core and cladding interface from the experimental results and the stress analysis.

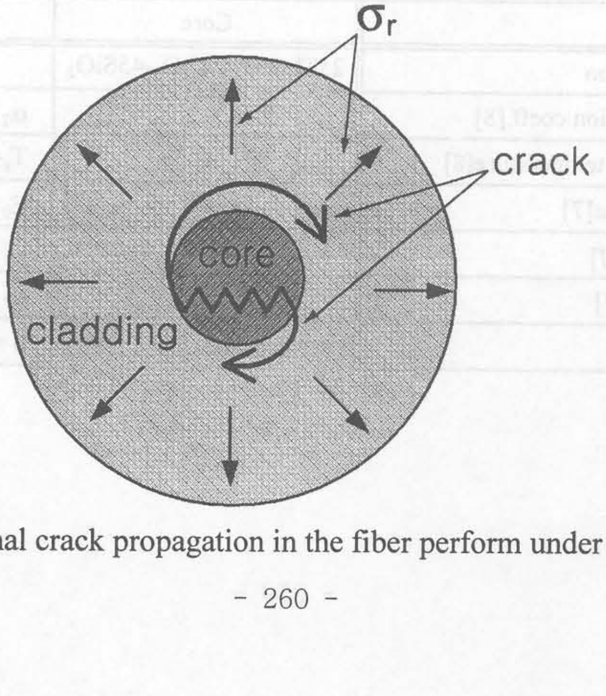


Fig. 5 Azimuthal crack propagation in the fiber perform under radial tension

4. Conclusion

We observed cracks appeared and propagated in azimuthal direction in a fiber preform during MCVD process. Micro-cracks were found to initiate from the incompletely sintered core/cladding interface under the tension about 600 MPa and propagate in azimuthal direction into the cladding. The crack formation and propagation was attributed to the thermal expansion mismatch between the core ($25Tb_2O_3$-$30Al_2O_3$-$45SiO_2$) and cladding (SiO_2) of the preform.

References

[1] J. Ballato and E. Snitzer, Appl. Opt. **34**, (1995) 6848.
[2] J.-S. Cho, U.-C. Paek, W.-T. Han, ThC4, OFC2001.
[3] S. R. Han, M. En. Thesis, Gwangju Institute of Science & Technology, 1997.
[4] Y. Park, M. En. Thesis, Gwangju Institute of Science & Technology, 1998.
[5] B. H. Kim, Y. Park, D. Y. Kim, U. C. Paek, and W.-T. Han, Opt. Lett. **27**, (2002) 806.
[6] G.W. Scherer and A. R. Cooper, J. Am. Ceram. Soc., **63**, (1980) 346.
[7] D. A. Krohn and A. R. Cooper, J. Am. Ceram. Soc., **52**, (1969) 661.
[8] O. V. Mazurin, M. V. Streltsina and T. P. Shvaiko-shvaikovskaya, Elsevier, 1983.