Tensile Behavior of photonic crystal fibres

C. Yan¹, ², H. Yu¹, L. Ye¹, J. Canning³ and B. Ashton³

¹Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering, J07, The University of Sydney, NSW2006, Australia
²School of Engineering Systems, Queensland University of Technology, Brisbane, QLD 4001, Australia, c2.yan@qut.edu.au
³Optical Fibre Technology Centre, The University of Sydney, 206 National Innovation Centre, ATP, Eveleigh, NSW 1430, Australia

Keywords: Optical Fibre, Deformation, Fracture, Tensile Test

Abstract. The mechanical strength and failure behavior of two photonic crystal silica optical fibers with different diameters were investigated using tensile test. The effect of polymer coating on the failure behavior was also studied. The results indicated that all fibers failed in a brittle manner and the failure normally initiated from fiber surfaces. The failure loads observed in the coated fibers are higher than that in bare fibers and the reason is explained by the apparent delamination between the fiber and the polymer coating when loaded on the fiber surfaces. The relationship between a characteristic parameter measured on the fracture surfaces and the failure stress was examined.

Introduction

Photonic crystal optical fibers (also referred as microstructured and holey fibers) are of interest since they offer a simple alternative to controlling the index profile of optical waveguides other than using expensive dopants [1-4]. They are also featured by some interesting characteristics, such as unique dispersion properties, as well as single-mode operation over an extended range of operating wavelengths [3]. The potential applications include gas-based nonlinear optics, sensing, lasers, high harmonic generation, ultrahigh nonlinearities and even guidance of atoms and particles [4]. On the other hand, the brittle nature, mechanical damage and failure of silica fibers, remain the key material issues. The flaws on the surface of fibers caused by processing, cleaving or subsequent assembling make the situation more complex. Very limited investigation has been directed to the strength of photonic crystal fiber as its development is still at the infancy stage. Without a basic understanding of mechanical reliability, it is difficult to imagine an extensive application of these novel fibers in telecommunication industry, even for a local network. In this work, the failure behavior of silica photonic crystal fibers was examined using tensile test.

Experimental Procedure

Two silica photonic crystal fibers with a similar holes arrangement but different diameters were fabricated using capillary stacking technique. The arrangements of air holes are shown in Fig. 1. The two fibres have diameters of 100 \( \mu \text{m} \) and 125 \( \mu \text{m} \), respectively, and are in-line coated with 60 \( \mu \text{m} \) acrylate polymer. The tensile test was carried out in accordance with the American Standard for Test and Measurement (ASTM) D 3379-75. An Instron 5567 with a load cell of 10 and 100 N and pneumatic grips was used. Samples were prepared by mounting a single fiber on a pre-prepared paper frame. The length of the cut-out is equal to the gauge length, i.e. the length over which the strain is measured. A 25 mm gauge length was used for the 125 \( \mu \text{m} \) fibre. The fiber was mounted on the paper frame using epoxy in two different ways, i.e., mounting on the coating directly and on the bare fiber after removing the coating by immersing the fibers into acetone for a few minutes. To investigate the effect of gauge length on failure behaviour, three gauge lengths, i.e., 10, 25 and 50 mm were applied to the fibre with 100 \( \mu \text{m} \) in diameter after removing the polymer coating. The failure process of the fibers during the tensile test was continuously monitored and recorded using a
CCD camera connected with a video recorder. The fracture surfaces of the fibers were observed using scanning electron microscopy (SEM).

Fig. 1 End face of the holey fibres.

Results and discussion

The average failure (maximum) loads for the 125 μm fibre with and without the polymer coating are 26.8 N and 6.1 N, respectively. A typical elastic load-displacement curve is observed in the bare fibre, indicating brittle failure behaviour. For the coated fibre, however, the load increases linearly until the peak value and then drops gradually, as shown in Fig. 2.

Fig. 2 Load-displacement curve of the 125 μm fibre with coating.

It is well known that glass may be strengthened by use of surface coatings. The possible mechanisms include reduction of residual stress and flaw healing. Recently, Hand et al [5] showed that closure stresses generated by thermal expansion mismatch within the flaws are a plausible reason of strengthening of glass with epoxy based coating. In this work, the failure of the fibers under tensile stress was continuously monitored. The failure of the bare fiber was dominated by brittle fracture but delamination occurred between the fiber and the coating in the coated fibers. The polymer coating was stripped out from the fiber. It is interesting to note that the locations of the delamination were very close to the gripping points and changed a little among the samples tested. Given that a delamination is normally caused by shear stress, the stress analysis of Nairn [6] on an embedded fiber is borrowed here. The maximum shear stress (τ) is located at a short distance to the loading points. This can be used to explain why the delamination normally initiates close to the gripping points. After the delamination, the coating may break due to load shift to the coating. Consequently, the coating is stripped out from the fiber while loading.
The consistency of coating failure indicates that no uniform deformation/strain can be established along the full length of the fiber/coating structure due to the weak interface strength between the coating and the fiber. This implies the sites close to anchoring points of optical fibers can be the potential failure sites in a photonic device.

Approximately, failure stress ($\sigma_f$) can be calculated using failure load divided by the section area of a fiber. Due to the brittle nature of these fibers, the data was scattered in the measurements of failure load, and a statistical analysis becomes necessary. The failure stress of the fibre with a diameter of 100 $\mu$m varies from 240 to 2900 MPa. Fig. 3 shows the Weibull distribution of the failure stress, where $P_f$ is the failure probability.

![Weibull plot of the failure stress of the 100 $\mu$m fibre.](image)

The failure stress decrease as the gauge length increases. This can be explained by the dependence of failure stress on the probability of the existence of a flaw in the fibre that is capable to initiate the failure. The probability depends on the sample size or volume; the larger the sample, the greater is this flaw existence probability, and the lower the failure stress. Fig. 4 gives the typical fracture surface of the fibers with a diameter of 100 $\mu$m, indicating that fracture normally initiates from the fibre surfaces. Therefore, it is expected that the presence of small surface defects or scratches generated by mechanical damage during fiber processing and handling will affect the tensile strength of these optical fibers.

![Typical fracture surface of the holey fibre.](image)

As shown in Fig. 4, the fracture surface consists of a crack initiation region featured by a semi-circular mirror area and a crack propagation region with larger radial ridges. It has been suggested
that the square roots of the radii of the mirror areas multiplied by the failure stresses are constants for a given material [7]. Fig. 5 shows the relationship between the mirror radius and the failure stress.

\[
\sigma_f = A \sqrt{r_m}
\]

where \( A \) is the constant and \( r_m \) is the radius of the mirror area. The data in Fig. 5 can be well fitted by an equation of \( A=\sigma_f r_m^{1/2} \) (\( A=1.65 \) MPa.m\(^{1/2}\)), where \( r_m \) is the radius of the mirror area. Therefore, it is possible to predict the failure stress or failure load by measuring the size of the mirror area on a fracture surface. Further work is much needed to establish a relationship between the size of these mirror areas and the size of surface defects, such as scratches and indents, so that the mechanical strength of a fibre can be estimated via simple visual inspection on the surfaces.

**Conclusions**

The failure behavior of photonic crystal optical fibers was investigated using tensile test. The results indicated that all fibers failed in a brittle manner and the failure initiated from the fiber surfaces. The gauge length had an apparent effect on the failure stress. Higher failure loads were observed in the coated fibers as compared to the bare fibers and the reason is attributed to the apparent delamination between the fiber and the polymer coating. The relationship between the failure stress and the size of mirror area measured on the fracture surfaces was confirmed.

**Acknowledgments**

C. Yan wishes to thank the Australian Research Council (ARC) for the continuing financial support of this project by two ARC Discovery Projects. J. Canning also acknowledges fibre fabrication funding from an ARC Discovery Project.

**References**