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Analysis of fracture damage in silica optical fibers

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ABSTRACT

Microstructured optical fibres (with a periodic transverse microstructure) are of interest since they offer a simple alternative to controlling the index profile of optical waveguides. Although many types of optical fibres and cables have been developed to meet the needs of communications service providers for long-term performance and reliable operation, the brittle nature, aging and fatigue of these fibres, remains to be the key materials issues. The flaws on the surface of fibres caused by processing (drawing) or subsequent assembling make the situation more complex. In this work, experimental investigation and fracture mechanics analysis have been conducted to understand the fracture behavior of these newly developed optical fibres. The results are believed to be useful for design, fabrication and evaluation of optical fibres for a variety of applications.

KEY WORDS: optical fibre, fracture, reliability, tensile test, fracture mechanics

1   INTRODUCTION

Optical fibres play a key role in global telecommunications. An optical fibre normally consists of a core and a cladding with different refractive indices so that the light can be forced to transmit within the core. 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. It is well known that the intrinsic strength of silica fiber is about 14 GPa. For commercial applications, a light guide fiber is required to pass the proof test at 0.7 GPa. Recent work on microstructured silica optical fibres indicated that they failed in a brittle manner and cracks initiated from the fiber surfaces [5]. Therefore, surface cracks and defects caused by processing, cleaving or subsequent assembling may play an important role in determining the mechanical strength of microstructured silica optical fibers. On the other hand, the effects of surface polymer coating have not been well understood although apparent increase of failure loads was observed in the coated fibres. The possible reasons were attributed to crack length reduction [6-7], Poisson's ratio effects [8] and the generation of

closure stresses [9]. Up to now, very limited investigation has been directed to the strength of microstructured optical 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 optical fibers was examined using tensile testing and fracture mechanics analysis.

2   EXPERIMENTAL

2.1   Optical fibres and tensile test

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. Here d and Λ are air hole diameter and pitch, respectively. The two fibres have diameters of 100 μm and 125 μm, respectively, and are in-line coated with 60 μm acrylate polymer. The tensile test was carried out in accordance with the American Standard for Test and Measurement (ASTM) D 3379-75. 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. 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 these fibres after removing the polymer coating. The fracture surfaces of the fibers were observed using scanning electron microscopy (SEM).
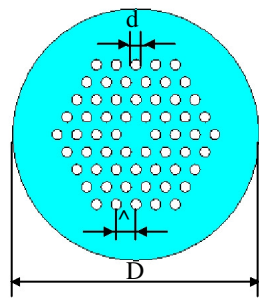

Fig. 1 Transverse section of the microstructured fibre.

3   EXPERIMENTAL RESULTS

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.
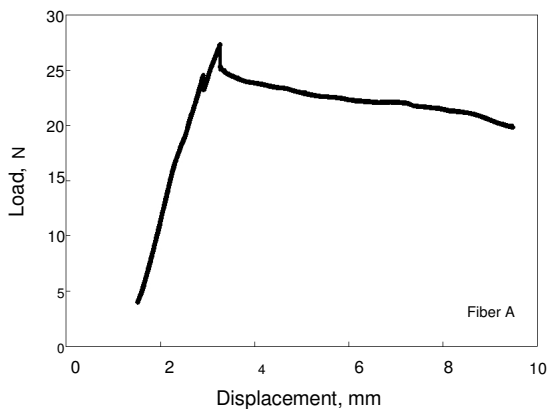

Fig. 2 Load-displacement curve of the 125 μm fibre with coating.

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. This is due to the fact that the maximum shear stress is located at a short distance to the loading 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. This implies the sites close to anchoring points of optical fibers can be the potential failure sites in a photonic device. Approximately, failure stress (σ_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. Fig. 3 shows the Weibull distribution of the failure stress of the 100 mm fibres, where P_f is the failure probability.
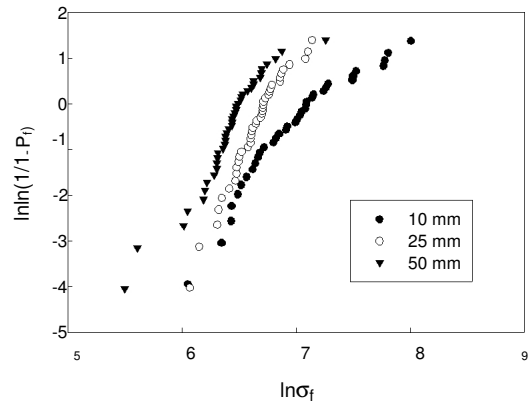

Fig. 3 Weibull plot of the failure stress

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. It is clear that fracture initiates from the fibre surfaces. This is very similar to the failure of solid silica fibres. 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.
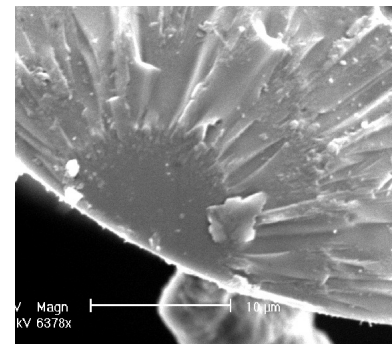

Fig. 4 Typical fracture surface of the fibre.

Skontorp [10] has observed a relationship between the radius of the mirror area and the failure stress, i.e.

$$\sigma_f \sqrt{c} = A , \tag{1}$$

where *c* is the radius of the mirror area and *A* a fitting constant. The testing data of the tensile test in this study can be well fitted by the above equation with *A*=1.65 MPa.m$^{1/2}$. Therefore, it is possible to predict the failure stress or failure load by measuring the size of the mirror area on a fracture surface. This implies that mechanical strength of a fibre can be estimated via simple visual inspection of the surfaces.

4 FRACTURE MECHANICS ANALYSIS

For the convenience of fracture mechanic analysis, an optical fibre with a surface (edge) crack is schematically illustrated in Fig. 5.
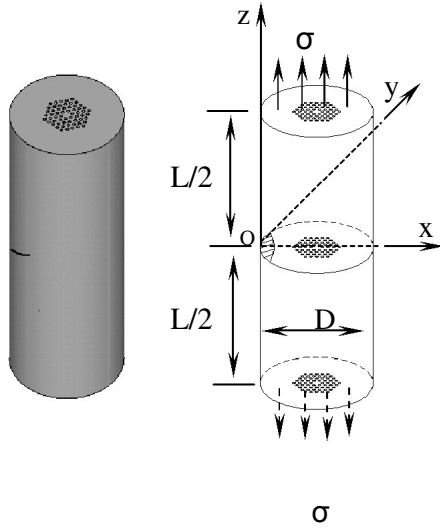

Fig. 5 Microstructured fibre with edge crack

The stress intensity factor can be evaluated by [11]

$$K_I = F\left(a/D, a/c, \theta\right)\sigma \frac{\sqrt{\pi a}}{\sqrt{Q}}, \qquad (2)$$

where $F(a/c, a/d, \theta)$ is the nondimensional stress intensity factor that can be obtained by numerical analysis. It is a function of a/c, a/d and θ, $\theta=arctg$ (y/x). Q is a geometric factor. For a coated optical holey fiber, based on the well-known rule-of-mixtures [12], the axial stress in glass and coating material can be estimated by

$$\sigma_g = PE^* \Big/ \left(\frac{\pi D^2 E^*}{4} + \pi(Dt + t^2)E_c \right) \qquad (3)$$

and

$$\sigma_c = PE_c \Big/ \left(\frac{\pi D^2 E^*}{4} + \pi(Dt + t^2)E_c \right) \qquad (4)$$

where P is the total failure load, E_c, E^* and t are the axial Young's modulus, effective modulus and the thickness of coating, respectively. Roach et al. [9] suggested that the coating (filling) material can bridge the surfaces of a crack via a closure stress, σ_{cl}, which resists the crack opening when subjected to a tension force. Hand and co-workers [13] explained the existence of closure stresses as a result of thermal expansion mismatch between the coating and glass. The strain in the polymer resin can be estimated as

$$\varepsilon_{resin} = \frac{1}{(1+\alpha_g \Delta T)(1-\alpha_c \Delta T)} - 1 \qquad (5)$$

where α_g and α_c are the thermal expansion coefficient of the glass and

epoxy, respectively. ΔT is the difference between the curing and room temperatures. Using the Young's modulus of epoxy, we can obtain the closure stress. The stress intensity factor caused by the tensile stress and closure stresses σ_g and σ_{cl} can be estimated by

$$K_I\left(\sigma_{cl} + \sigma_g\right) = F\left(a/D, a/c, \theta\right)\left(\sigma_g + \sigma_{cl}\right)\frac{\sqrt{\pi a}}{\sqrt{Q}} \qquad (6)$$

Here we assume the same geometric factor can be applied to the estimation of stress intensity factor caused by the closure stress. The correction on crack length a is required if the coating is partially fills into the crack. Using the materials constants of silica glass, i.e. Young's modulus=70.3GPa, Poisson's ratio=0.17, and K_{IC}=0.75MNm$^{-3/2}$, the geometric factor F can be estimated from a fibre without the coating. Then, the stress intensity factor and fracture toughness of the fibre with different crack configurations can be evaluated. The change of failure loads P_F with closure stress for a fibre with fully filled crack is shown in Fig. 5.
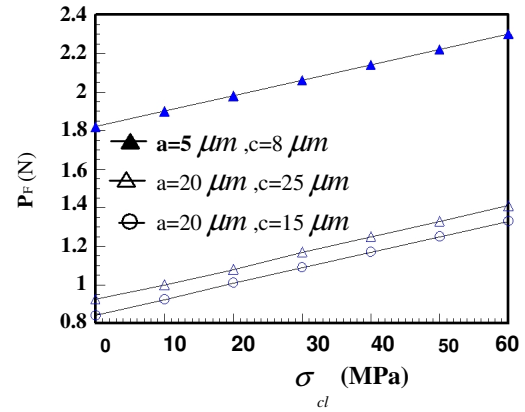

Fig. 5 Effect of closure stress on failure load

It can be seen that the failure load increases with the closure stress. If the closure stresses is completely generated by the thermal expansion mismatch of the polymer coating and silica glass, it is necessary to increase the thermal expansion coefficient α_c of the coating and the curing temperature (high ΔT) for a higher closure stress. Considering the situation where the crack is only partially filled by the coating, the effect of crack depth (unfilled) on the failure load is shown in Fig. 6.
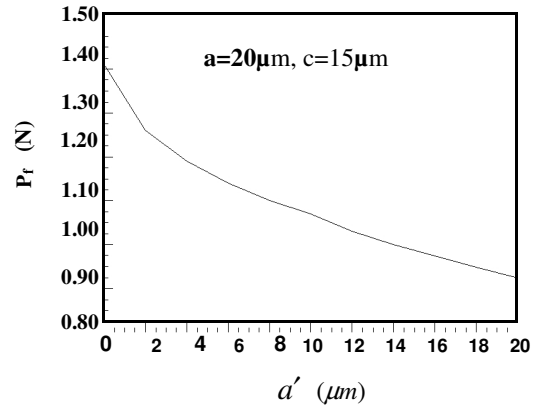

Fig. 6 effect of crack depth on failure load

In Fig. 6, the failure load decreases significantly with increase of the unfilled crack length, indicating the effect of coating on improvement of the load bearing capability of the silica fibres.

5   CONCLUSIONS

The failure behavior of microstructured silica optical fibers was investigated using tensile test and fracture mechanics analysis. 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. The relationship between the failure stress and the size of mirror area measured on the fracture surfaces was confirmed. The simplified 3D fracture mechanics analysis indicated the crack depth and size influenced the failure load of optical fibers without coating. Failure load increased with the closure stress that was created by the thermal expansion mismatch of the polymer coating and silica glass. Increase of thermal expansion coefficient of the coating and the curing temperature were considered to create a higher closure stress.

4   ACKNOWLEDGEMENTS

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