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Effects of surface cracks and coating on fracture behaviour of microstructured silica optical fibers

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Abstract: The fracture behavior of microstructured silica optical fibers containing surface cracks in tension was investigated using a simplified 3D analysis. Strengthening caused by the polymer coating was considered to be associated with the closure stresses uniformly applied to the crack surfaces, which were generally created by the thermal mismatch between the coating resin and the silica glass. The stress intensity factor of the surface cracks in tension was evaluated with considering the crack configurations and surface coating. The effects of crack configurations and closure stresses on the failure loads were also discussed.

Keywords: Microstructured optical fibres, Fracture mechanism, Surface crack, Surface coating

1 Introduction

Newly developed microstructured optical fibers have attracted increasing attention as they are cost efficient and can provide a wide variety of optical properties such as dispersion, birefringence and nonlinearity. However, strength and associated reliability are major technical concerns before they can reach the full potential for telecommunication industry. Mechanical properties and fracture mechanisms of conventional silica optical fibers have been investigated using experimental testing and 2D analytical analyses in which surface cracks were approximately treated as semi-circular cracks in an infinite medium [1-3]. For the microstructured optical fibers, unfortunately, very few investigations have been conducted on their mechanical and fracture behavior. It is well known that the intrinsic strength of silica fiber is about 14 GPa although the practically achievable strength is orders of magnitude less due to surface defects. For commercial applications, an optical fiber is required to pass the proof test at 0.7 GPa. Recent work on microstructured silica optical fibers indicated that they failed in a brittle manner and cracks initiated from the fiber surfaces [4]. Therefore, surface cracks and defects may play an important role in determining the mechanical strength of microstructured silica optical fibers. On the other hand, the effects of polymer surface coatings have not been well understood although apparent increase of failure loads was observed in the coated fibers. The possible reasons were attributed to crack length reduction [5-6], Poisson's ratio effects [7] and the generation of closure stresses [8]. The objectives of the current study are to investigate the tensile fracture behaviour of coated microstructured optical fibers containing surface cracks. Simplified 3D fracture analysis has been conducted to replace expensive 3D finite element analysis. The effects of crack configurations and closure stresses on the failure loads have also been investigated.

2 3D fracture analysis

2.1 Fiber without coating

For an optical fiber, the final failure is dominated by surface cracks. In this work, the analysis was simplified as a cylinder with finite size containing one crack, as shown in Figure 1. To account for the existence of hollow channels, an effective axial elastic modulus was introduced. For a fibre without coating, it can be estimated by

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$$E^{*} = E_{g}(1-\mathrm{y}) \,, \tag{1}$$

Where E_g is the elastic modulus of silica glass, y is the cross-sectional area fraction of the air holes. The axial stress in the fibre is

$$\mathrm{s} = \frac{4P}{D^{2}\mathrm{p}(1-\mathrm{y})} \,. \tag{2}$$

Neglecting the interaction between the crack and the air holes, the stress intensity factor can be evaluated by [9]

$$K_{I} = F(a/D, a/c, \mathrm{q})\mathrm{s}\frac{\sqrt{\mathrm{p}a}}{\sqrt{Q}} \,, \tag{3}$$

where $F(a/D, a/c, \mathrm{q})$ is a nondimensional function that can be obtained by numerical analysis. It is a function of a/c , a/D and q ; $\mathrm{q} = arctg(y/x)$. Q is the crack shape factor, which can be determined by

$$Q = 1 + 1.464(a/c)^{1.65} \tag{4}$$

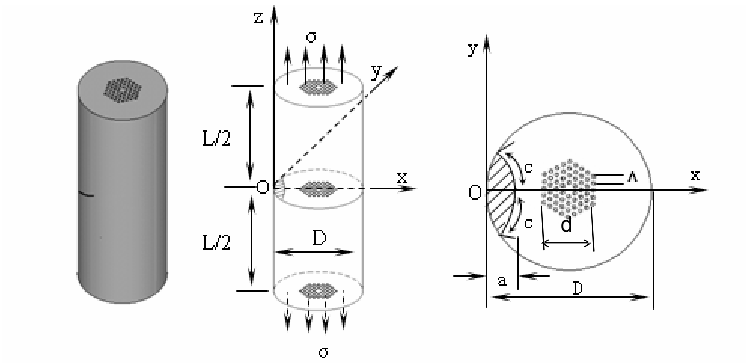


Figure 1 3D fracture model showing the surface crack and the central array of hollow channels

2.2 Coated fiber

For a coated optical fiber, based on the rule-of-mixtures [10], the axial stress in glass and coating material can be estimated by

$$\mathrm{s}_{g} = PE^{*} \Big/ \left(\frac{\mathrm{p}D^{2}E^{*}}{4} + \mathrm{p}(Dt + t^{2})E_{c} \right), \text{ and} \tag{5}$$

$$\mathrm{s}_{c} = PE_{c} \Big/ \left(\frac{\mathrm{p}D^{2}E^{*}}{4} + \mathrm{p}(Dt + t^{2})E_{c} \right), \tag{6}$$

where P is the tensile force, E_c and t are the axial Young's modulus and the thickness of coating, respectively.

Wang and co-workers [7] suggested that if a crack is fully filled by coating material it may respond in the same way as the bulk material when a load is applied. That is, the crack is healed by the coating material, shown in Figure 2(a).

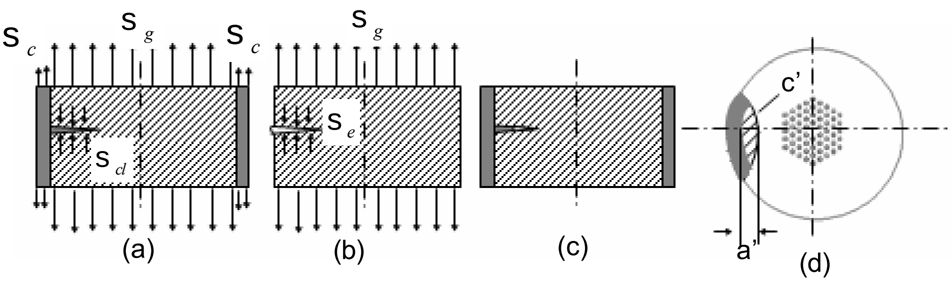


Figure 2 Sketch of coating effect

However, the Young's modulus of a polymer coating is significantly lower than that of silica glass. It is questionable whether the coating filled within a crack can completely respond in the same way as the bulk material (silica glass). Roach et al [8] suggested that the 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 [3] explained the existence of closure stresses as a result of thermal expansion mismatch between the coating and glass. The strain in the polymer coating can be estimated as

$$\varepsilon_c = \frac{1}{(1+\alpha_g \Delta T)(1-\alpha_c \Delta T)} - 1 , \tag{7}$$

Where α_g and α_c are the thermal expansion coefficients of the glass and epoxy, respectively. ΔT is the difference between the curing temperature and room temperature. The closure stress can be estimated if the Young's modulus of the coating is known. Assuming a rigid substrate and limited lateral strain in the coating, the effective modulus E_{eff} of the polymer is

$$E_{eff} = \frac{1-v}{(1+v)(1-2v)} E_c , \tag{8}$$

and the closure stress is

$$\sigma_c = \varepsilon_c E_{eff} . \tag{9}$$

Obviously, a higher closure stress can be obtained when the Poisson's ratio of the coating approaches to 0.5. For a well coated fiber, surface cracks can be considered to be completely filled with polymer. The segment of the fiber with one surface crack under uniform axial tension is shown in Figure 2(a), where the crack is far away from the fiber ends where the tension loads are applied. For simplicity, the contribution of surface coating and closure stress σ_{cl} to the propagation of a surface crack can be represented by an effective closure stress σ_e, uniformly distributed over the upper and lower surfaces of the crack, as shown in Figure 2(b). The stress intensity factor caused by the combination of the applied tensile stress σ_g and effective closure stress σ_e can expressed as

$$K_I(\sigma_g + \sigma_e) = K_I(\sigma_g) + K_I(\sigma_e) \tag{10}$$

The stress intensity factor caused by effective closure stress is

$$K_I(\sigma_e) = F_c(a/D, a/c, \theta)\sigma_e \frac{\sqrt{\pi a}}{\sqrt{Q}} , \tag{11}$$

where $F_c(a/D, a/c, \theta)$ is the geometry function. For a thin coating, the coating layer itself has a limited effect on the stress intensity factor and then we have $\sigma_e \approx \sigma_{cl}$. The stress intensity factor is reduced to zero when the magnitude of closure stress σ_{cl} approaches to σ_g. In other words, we have

$$K_I(\sigma_g) + K_I(\sigma_{cl}) \to 0 \quad (\sigma_{cl} \to \sigma_g) \tag{12}$$

Therefore, $K_I(\sigma_{cl})$ can be approximately evaluated using the same geometric factor for the applied stress, i.e.,

$$K_I(\sigma_{cl}) = F(a/D, a/c, \theta)\sigma_{cl}\frac{\sqrt{\pi a}}{\sqrt{Q}} \tag{13}$$

Then, the equation (9) can be reduced to

$$K_I(\sigma_{cl} + \sigma_g) = F(a/D, a/c, \theta)(\sigma_g + \sigma_{cl})\frac{\sqrt{\pi a}}{\sqrt{Q}} \tag{14}$$

Depending on the processing procedures, it is possible a surface crack is partially filled by the coating, as illustrated in Figure 2(c) and Figure 2(d). Similarly, the effect of partial filling on the stress intensity factor can be estimated by

$$K_I(\sigma_{cl}) = F(a/D, a/c, \theta)\frac{\sqrt{\pi}}{\sqrt{Q}}\sigma_{cl}\left(\sqrt{a} - \sqrt{a'}\right) \tag{15}$$

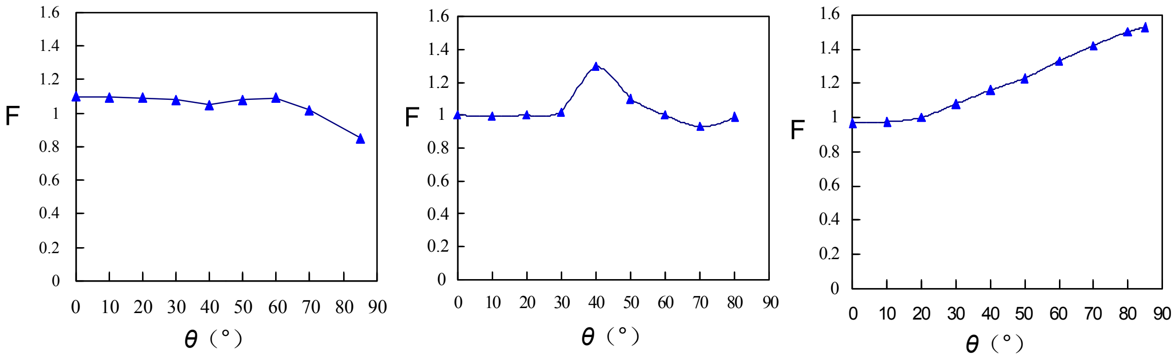
and then

$$K_I(\sigma_{cl} + \sigma_g) = F(a/D, a/c, \theta)\frac{\sqrt{\pi}}{\sqrt{Q}}\left(\sigma_g\sqrt{a} + \sigma_{cl}\sqrt{a} - \sigma_{cl}\sqrt{a'}\right) \tag{16}$$

3 Results and discussion

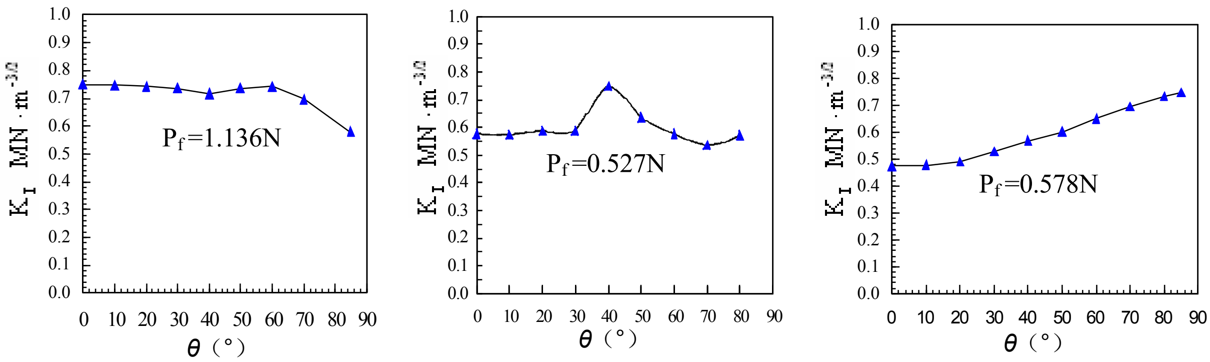
3.1 Stress intensity factor and failure loads of bare fiber

In the analysis, a silica fiber with a diameter of 100 μm was used, and the cross-sectional area fraction of the channels is 3.5%, the pitch Λ=6 μm, and then d=24 $\sqrt{3}$ μm. The coating thickness is 10 μm. The Young's modulus and Poisson's ratio of the silica glass were taken as 70.3GPa and 0.17, respectively. The fracture toughness was K_{IC} =0.75 MN $m^{-3/2}$. The Young's modulus and the Poisson's ratio of the polymer coating are 3.96 GPa and 0.39, respectively. Three different crack configurations were taken into account: 1) a=5 μm and c=8 μm, 2) a=20 μm and c=25 μm and 3) a=20 μm and c=15 μm. For the uncoated optical fibers without hollow channels, the geometry factor F, is shown in Figure 3. By using Eq. (3), Eq. (4) and F (Figure 3), the stress intensity factor for the uncoated fibers with hollow channels and different crack configurations can be obtained, as shown in Figure 4. In Figure 4, it can be seen that the stress intensity factors changes with a/D, a/c and θ, indicating the influence of finite lateral surface constraint. The failure load is defined as the value when the stress intensity factor equals to the fracture toughness, i.e., 0.75 $MNm^{-3/2}$. As shown in Figure 4, the failure loads are apparently dependent on the crack length.



(a) a=5 μ m, c=8 μ m (b) a=20 μ m, c=25 μ m (c) a=20 μ m, c=15 μ m

Figure3 Variation of geometry function F with crack configurations
(uncoated fibers without channels)



(a) a=5 μ m, c=8 μ m (b) a=20 μ m, c=25 μ m (c) a=20 μ m, c=15 μ m

Figure 4 Stress intensity factors for different crack configurations
(coated fibers with channels)

3.2 Failure loads of fully coated fibers

The variation of failure load P_f with closure stress in fully filled coated fibers is shown in Figure 5. It is clear that the failure load increases with the closure stress. To this end, it is necessary to explore the ways to increase the closure stresses, such as increasing the thermal mismatch (thermal expansion coefficient) between the fibre and coating and the curing temperature ΔT . However, attention should also be directed to the possible change of other physical and optical properties as a consequence of these methods. If the closure stress is ignored, the difference of failure loads between a bare fiber and a coated fiber can be only attributed to the load diverted to the coating material. On the other hand, a sufficiently high closure stress is expected to offset the effects of surface cracks. In fact, the magnitude of closure stresses is generally limited by the strength and ductility of coating materials. A premature failure of the coating layer is quite possible before a high closure stress can be established.

3.3 Failure loads of partially coated fibers

It is also worthwhile to consider the situation where a crack is partially filled (Figure 2(c)). Figure 6 shows the effect of unfilled crack depth on the failure loads. It can be seen that the failure load decreases with the increase of the unfilled crack depth. Note that the result shown in Figure 6 is an approximate estimation as for a partially filled crack, and the lateral strain in the thin coating layer can not be strictly constrained as in a fully filled case, which will result in a relatively lower closure stress.

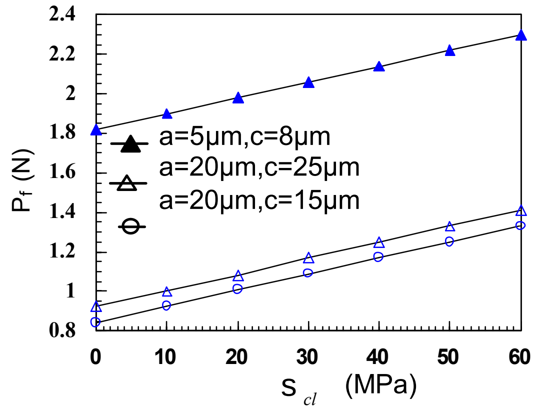


Figure 5 Failure load as a function of closure stress

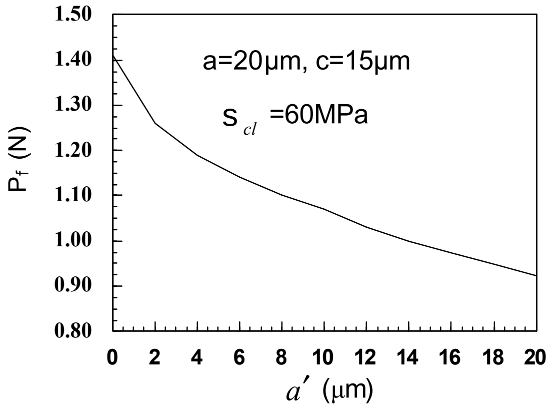


Figure 6 Variation of failure load with unfilled crack depth

4 Conclusions

A simplified 3D crack analysis was conducted to understand the failure behaviour of surface cracked optical fiber with and without polymer coating. The results showed that the stress intensity factor was strongly dependent on crack configurations, especially crack depth. The closure stresses caused by polymer coasting could significantly increase the failure load. It is therefore worthwhile to explore the ways to increase the closure stresses provided other properties will not be made worse. The situation of partially filled surface cracks was also investigated. The failure load decreased with increasing the length of the unfilled cracks.

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