A4.4   Reliability of Silica Fibres

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A   INTRODUCTION

The total length of silica optical fibre now installed around the world measures in the tens of Gm; the majority of it for telecommunications applications.   While the fibre has proved reliable so far, with most failures being caused by external factors such as 'dig-ups' [1], the huge capital investment involved requires that long term reliability be treated as a serious issue.

FIGURE 1 shows a Weibull probability plot of the strength distribution typical for silica fibre specimens that are several meters in length. The distribution shows a narrow high-strength mode that corresponds to the intrinsic strength of the material. For long enough specimens, a broad low-strength mode is observed which is caused by the presence of extrinsic defects that can be introduced at any stage during manufacture and deployment. Both parts of the distribution can impact reliability.
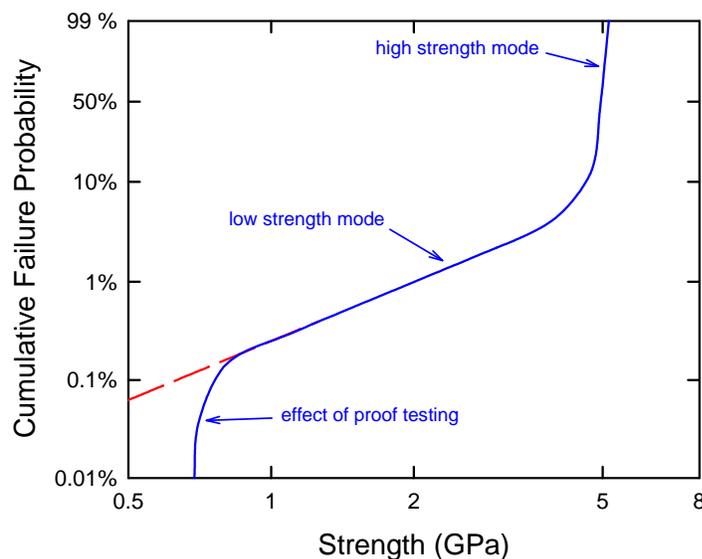
FIGURE 1 Weibull probability plot of the strength distribution typical of specimens several
meters in length, showing both the high and low strength modes and the effect
of truncation of the low strength mode by proof testing.

B   SUBCRITICAL CRACK GROWTH

The weakest flaws in the fibre can lead to delayed failure due to the phenomenon of subcritical crack growth, also known as fatigue. While such flaws do not fail instantaneously under load, they can slowly extend under the combined influence of applied stress and environmental moisture until they reach a critical size, causing failure. For a specimen of initial strength σ_i, the time to failure, t_f, under a static applied load, σ_a, is given by [2]:

$$t_f = B \frac{\sigma_i^{n-2}}{\sigma_a^n},$$

(1)

where B and n are fatigue parameters that are determined by accelerated laboratory testing. EQN (1) is then reinterpreted to make reliability predictions with t_f now representing the service life, σ_a the maximum service stress and σ_i the starting strength of the weakest expected flaw. The value of σ_i is controlled by proof testing which removes the weakest defects thus truncating the low strength mode of the strength distribution (see FIGURE 1). However, continued crack growth during unloading from the proof stress means that flaws weaker than the proof stress can survive though such flaws will be rare. Griffioen [3] examines several published models for reliability and proposes a unified model of which the earlier works are particular cases.

The accepted value for n is around 20 for the high strength material but there is considerable variability in the published values; especially for the low-strength material for which values of between 10 and 40 have been reported [4]. Reported values for B show even more variability with accepted values lying between about 10^{-8} and 10^{-5} GPa^2 s.

EQN (1) is derived assuming sharp, stress-free cracks that extend with a power law dependence on stress. These assumptions are hard to justify. In particular, weak defects can have residual thermal or mechanical stresses. "Real" weak defects are hard to study because of their low frequency and random positions. They have generally been modeled by inducing artificial defects by, for example, abrading the fibre (e.g. [5]) or deliberately applying particulate contaminants to the surface of the fibre preform (e.g. [6]). In general it is found that EQN (1) is conservative in that the weak defects often increase their strength with time [7,5], perhaps due to blunting of the crack tip. However, in a study of flaws induced by indentation, in a narrow region of behavior the residual stress discontinuously reduced the strength due to delayed nucleation of cracks [8].

Another difficulty with EQN (1) is its assumption of power law crack growth kinetics. A power law is used for mathematical convenience but more physically reasonable models that have an exponential dependence of growth rate on stress predict substantially shorter lifetimes [9,10]; the power law may therefore be unrealistically optimistic.

In summary, considerable progress on modeling weak defects has been made in the last decade. However, the details of the nature of natural defects and their influence on reliability are still poorly understood. The complex mathematical theories applied to fibre reliability describe very simple, ideal defects and are in advance of our understanding of nature of the natural defects themselves. Further, the paucity of published field data quantifying failure rates, service stresses and environments, does not permit adequate comparison of the modeling with field experience.

C   ZERO STRESS AGING

The subcritical crack growth model that results in EQN (1) predicts no change in strength if no stress is applied. However, the strength of silica fibre does indeed change in time even in the absence of an applied stress. Weak defects, described in section B, are reduced in severity by zero stress aging [7,5] with few exceptions [8]. However, high strength fibre (the high strength mode in FIGURE 1) can exhibit severe degradation upon zero stress aging.

High-strength silica fibre is "pristine" and essentially flaw-free [11]. In moist environments, this fibre does exhibit subcritical crack growth though in this case the "cracks" at least start at atomic dimensions. However, except for applications in which only short lengths of fibre are used, this behavior does not

represent a reliability concern because the occasional weak defects will be strength controlling. For those applications that do only use short lengths (few meters), the subcritical crack growth model (EQN (1)) can be used but with values for the fatigue parameters, *B* and *n*, that are appropriate for the high strength material.

The zero stress strength degradation is more of a concern because the strength can degrade to levels where the fibre becomes too fragile to handle for making connections or repairs (less than about 2 to 3 GPa). While such strengths are substantially higher than the occasional weak defects (with strengths near the proof stress) the strength loss is widespread, not localized, and would require replacement of the fibre rather than a repair.

Zero stress aging is now understood to be caused by roughening of the fibre surface produced by corrosion by moisture [12]. This roughness behaves like pits which locally concentrate the stress. While originally thought to be due to dissolution of silica, a perhaps more accurate description is reactive diffusion of water into silica forming a rough diffusion front behind which a gel layer forms [12]. Zero stress aging has been observed to occur in bare as well as polymer coated fibre [13]; it occurs both in humid environments (e.g. 85°C, 85% humidity [14]) and on the time scale of a few years in room temperature water [15]. The degradation can be slowed or delayed by incorporating colloidal silica powder in the polymer coating which presumably acts sacrificially [16]. Some polymer coatings can delay the onset of the aging degradation and it has been proposed that this effect is caused by 'passivation' of the glass surface. However, fibres with such aging resistant coatings still exhibit subcritical crack growth and so are still reacting with moisture. The exact mechanism by which the coating influences aging is not properly understood.

D   MEASUREMENT TECHNIQUES

The strength of silica fibre must be measured in order to characterize the strength, stress distribution and stress corrosion (fatigue) behavior. Gripping the fibre is an important issue since preferential failure can occur at the grips. Several techniques have been developed. The conceptually simplest technique is uniaxial tension in which the fibre ends are gripped by wrapping several times around capstans. This technique is suitable for testing specimens up to several meters in length. Two-point flexure, in which the fibre is bent into a 'U' shape between two platens, enables testing many fibres simultaneously but has a very short effective test length. It is therefore not useful for looking at long-length strength distributions but is helpful when studying environmental and coating effects, for example. These and other techniques are reviewed in detail elsewhere [17]. A technique worthy of particular mention is a long length continuous tester [18] which involves sequentially stressing 20 meter lengths of fibre. However, the fibre is only loaded up to a given relatively low stress and most of the lengths do not fail; only the occasional weak defect causes failure, thus requiring restarting the equipment. The results of this test provide statistics on the flaws that just pass the proof test; information which is an important input parameter for lifetime models. Also, this test provides information on the distribution of flaws on a preform and so can help in optimization of the preform preparation process.

E   HERMETIC COATINGS

The reliability concerns described above are all dependent on ambient moisture having access to the fibre surface. Application of a hermetic coating will therefore remove any time dependence of strength. Hermetic coatings generally fall into two categories: metals, usually applied by freezing from the melt, and inorganic compounds (such as carbon and nitrides) typically deposited from the vapor phase. Such coatings are more expensive than the polymers and can add significant microbending loss, especially for the freeze-coated metals. For these reasons, hermetic coatings are usually only used in relatively short

lengths for critical applications where the fibre experiences a harsh environment and where optical loss is not a crucial parameter.

F   CONCLUSION

Recent advances have given new insight into the processes that lead to fatigue and aging in silica fibres. Detailed mathematical models for making reliability predictions have been developed. However, the fundamental behavior of the "real", non-ideal defects is still poorly understood. Therefore, the predictions of lifetime models need to be treated with circumspection and may not represent worst-case estimates of reliability.

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