

Optical fiber reliability models

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ABSTRACT

Systems containing optical fiber have design lives on the order of decades so that models for assessing the mechanical reliability of the fiber must rely on extrapolations from accelerated short term testing. Such extrapolations are only valid if all relevant mechanisms are fully understood. The physical processes giving rise to mechanical degradation are reviewed and it is shown that no single model describes all situations. In particular, strong “pristine” fiber can behave quite differently from weaker fiber. Additionally, two degradation regimes are identified, one which is stress assisted (fatigue) and one which can occur even in the absence of applied stress (aging). Recent advances in understanding these phenomena are discussed and promising areas for future work are proposed.

1. INTRODUCTION

Mechanical failure of optical fiber must be avoided to ensure reliability of fiber-based systems. In telecommunications applications the single biggest cause of system failure is failure of the cable.¹ The majority of such failures are due to external factors such as dig-ups, fire, *etc.* Few failures have been reported due to strength loss of the fiber itself.² However, despite the low probability of fiber failure, the associated economic risk is appreciable because of the high cost of fiber repair or replacement. In addition, some of the phenomena described here cause abrupt strength loss after prolonged exposure to moist environments; such effects are not presaged by early failures (such as “infant mortalities”) that would indicate an impending more serious and widespread problem. In other words, strength loss is not well behaved in the sense that it sometimes does not decrease smoothly with time; rather, the failure rate can dramatically increase after a long period of time in a way that is unpredictable from the much lower failure rate prior to that time. Clearly then, it is necessary to fully understand all the different mechanisms that influence mechanical reliability in order to predict such complex behavior.

Silica fiber can be encountered with a broad range of strengths. Fig. 1 shows a Weibull probability plot that is typical of the strength of ~1 km specimens. Two modes are observed: a high strength mode which is very narrow, and a much broader low strength tail. The low strength tail can be controlled by proof testing the fiber which truncates the distribution (dashed line). Therefore, the fiber is essentially mostly very high strength (>5 GPa)

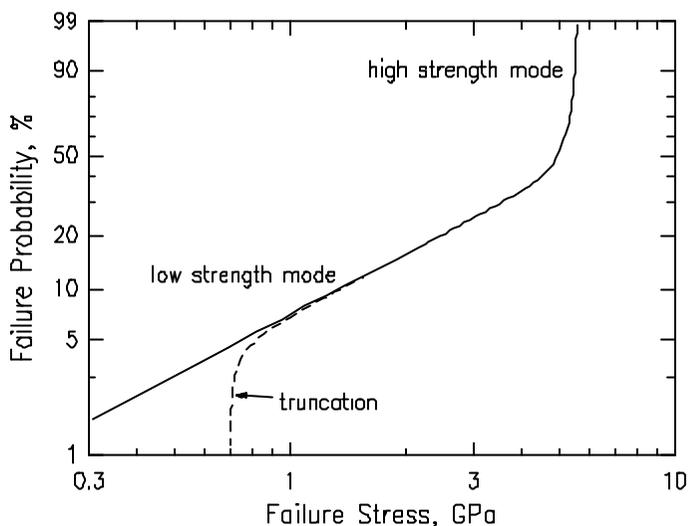


Fig. 1. Typical Weibull plot for ~1 km lengths of fiber.

except for occasional weak defects which have a broad range of possible strengths. These weak defects are associated with extrinsic factors, such as damage to the fiber surface by abrasion, or due to adhesion of foreign particles on the fiber surface. They result from poor manufacturing, handling and installation. In contrast, the high strength fiber between the weak defects has an intrinsic strength close to the theoretical strength of the glass. The strength of short specimens is essentially single-valued and free of defects.³ While the strengths shown in Fig. 1 are achievable on a short time scale, the degradation that occurs over long times when the fiber is exposed to moisture is a concern for reliability. The purpose of this article is to review the models for these degradation mechanisms.

The fiber will not fail mechanically unless it is subjected to a mechanical stress and so it is necessary to know what stresses the fiber will experience in service. Generally, the fiber will experience two types of stress; a relatively low service stress sustained for long periods will cause failure during service. The fiber will also experience much shorter episodes of comparatively high stress during installation, repair or reconfiguration, *etc.* For telecommunications applications this leads to two quite distinct reliability problems. The strength of long lengths of fiber is controlled by the occasional weak defect so that one concern is the failure of weak fiber under low in-service stresses. Current proof test levels are typically ~1 GPa (*e.g.* 0.69 GPa⁴) so that stresses less than a fraction of this (1/4 to 1/3) can be tolerated. Failure at weak defects can be controlled by increasing the proof stress and by limiting the in-service stress; any failures are localized at the defect and are comparatively simple to repair.

In contrast, the high strength sections of the fiber can experience high stresses for short periods. For example, a minimum strength of 2 to 3 GPa is required in order to successfully strip the polymer coating from the fiber for making connections (corresponding to an inert strength of 4 to 6 GPa) which is an order of magnitude higher than the weakest defects expected for proof tested fiber. However, failure at weak defects is unlikely during stripping due to their infrequency and is not generally a problem.

To summarize, for long-length telecommunications applications there are two principle areas of concern. Firstly the failure of relatively weak fiber under sustained loads, and secondly the degradation of high strength fiber, which can occur even without an applied load.

1.1. Fatigue of Fiber Under Stress

The strength loss of silica fiber that occurs when the fiber is exposed to sustained stress in a moist environment is often described by the subcritical crack growth model which assumes the presence of well-defined sharp surface cracks which locally amplify the applied stress at the crack tip. The stress intensity factor, K_I , for a crack of length c subjected to a remotely applied stress, σ_a , is given by:

$$K_I = Y \sigma_a c^{1/2}, \quad (1)$$

where Y is a parameter of order unity which describes the crack shape. K_I is a measure of the intensity of the stress field at the crack tip and when it exceeds a critical value, K_{IC} , the intrinsic strength of the material is exceeded and catastrophic failure ensues.

While Eq. (1) describes the ultimate strength of brittle materials, failure of many ceramic materials (and silica glass fibers in particular) shows time dependence, *i.e.* delayed failure can occur for applied stresses substantially lower than are required to produce immediate catastrophic failure according to Eq. (1). The mechanism for this behavior is now understood to be due to the combined influence of stress at the crack tip and reactive species in the environment - particularly water.⁵ The strain in the bonds at the crack tip in effect reduces the activation energy for the chemical reaction between water and the silica so that silicon-oxygen bonds are slowly broken, progressively advancing the crack.⁶ A power law relationship between the crack growth rate and the applied stress intensity at the crack tip is normally assumed:

$$\dot{c} = A K_I^n. \quad (2)$$

Therefore the applied stress causes the crack to extend, which itself increases K_I (Eq. 1), leading to an increase in the growth rate (Eq. 2). Eventually, K_I reaches K_{IC} and failure ensues. Eqs. (1) and (2) may be combined for any given loading scheme to determine the time to failure. For example, in most reliability models, the applied stress is assumed to be static (σ_a constant) so that the time to failure, t_f , is given by:⁷

$$t_f = \frac{2}{AY^2(n-2)\sigma_a^n} \left(\frac{\sigma_i}{K_{IC}} \right)^{n-2} = B\sigma_a^{-n}, \quad (3)$$

where σ_i is the initial strength of the material in the absence of fatigue and can be related to the initial crack length, c_i , by Eq. (1):

$$K_{IC} = Y\sigma_i c_i^{1/2}. \quad (4)$$

Note that Eq. (3) is derived using the approximation that the initial crack size, c_i , is much smaller than the final crack length, c_f when unstable crack growth occurs:

$$K_{IC} = Y\sigma_a c_f^{1/2}. \quad (5)$$

This is a good approximation except when testing the material very rapidly or in a relatively inert environment. Eq. (3) forms the basis of most reliability models since it relates the expected life of the material to the applied stress and starting strength; or conversely it specifies the maximum permitted service stress for a given service life. Eq. (3) is clearly sensitive to the value of the stress corrosion parameter, n , which is typically 20 or more for silica fiber. Accelerated laboratory testing is used to estimate the values of B and n for the particular fiber and environment of interest. Since such tests are necessarily on a short time scale and on comparatively short lengths (hence relatively strong fiber), the reliability estimates are made by extrapolating Eq. (3) to longer failure times and lower initial strengths. In practice, the weakest defects are removed by proof testing the fiber to some stress level, σ_p . Recently, Griffioen⁸ reviewed several models in the literature based on the power law and showed that they reduced to one basic model but differed principally in their failure or reliability criteria. For a 30 year lifetime the models give allowed stresses typically in the range of one quarter to one half of the proof stress.

The subcritical crack growth model, as outlined above, is comprised of two distinct submodels. Firstly, the micromechanics model describes how a defect locally amplifies the applied stress and so reduces the strength; the assumption that the defect is a sharp crack with an invariant crack tip geometry leads to Eq. (1). The second model concerns the kinetics of how the defect grows and specifically how this is affected by the applied stress. The assumption of a power law dependence on stress intensity leads to Eq. (2). While the model detailed here has been widely used for describing the reliability of ceramics in general, as well as the optical fibers, its applicability to silica fibers is questionable since neither the micromechanics model nor the kinetics model are based on firm physical ground. The two models will now be critically examined.

2. KINETICS MODELS

The power law model for the strength degradation kinetics, Eq. (2), is widely used for its mathematical simplicity; firstly because it is readily

integrable for a wide variety of loading schemes (in particular for dynamic fatigue where the load applied to the fiber increases linearly with time; $\dot{\sigma}_a$ is constant); secondly, the Weibull distribution, which is widely used to describe the variability in strength, is also based on a power law form so that incorporation of statistical effects into the lifetime model is possible with the results expressible in analytical closed form. However, while the power law has been found to fit crack velocity data for macroscopic cracks well,⁹ it is not based upon any physical model. In fact, certain aspects of the power law model are unphysical; the temperature dependence of the degradation kinetics is usually assumed to be contained in the pre-exponent, A , which is assumed to exhibit Arrhenius behavior. However, the activation energy calculated from temperature data has been found to depend on the applied stress.¹⁰ It has been pointed out¹¹ that this represents an inconsistency in the fatigue model which assumes that A is a constant not dependent on stress.

Various alternative kinetics models have been proposed in the literature. Most assume that degradation (or slow crack growth) results from a chemical reaction whose kinetics follow Arrhenius behavior, but that the activation energy is reduced by the application of stress. Two such models will be considered here:

$$\dot{c} = A_1 \exp(n_1 K_I), \quad (6)$$

$$\dot{c} = A_2 \exp(n_2 K_I^2). \quad (7)$$

The first form, Eq. (6), is derived assuming that the stress at the crack tip modifies the activation energy as a linear term.¹² The stress therefore modifies the activation energy via an activation volume. The second exponential form, Eq. (7), is derived from an atomistic model for crack propagation due to Lawn¹³ in which the strain energy release rate, G_I , associated with crack propagation results in a chemical potential gradient which modifies the activation energy. In this case the activation energy incorporates a quadratic term in stress intensity which therefore represents a direct energy modification term via the strain energy density. Lawn¹³ considered the bond rupture to be reversible, *i.e.* bonds could reform as well as break, though at a lower rate because of the applied stress. The form shown in Eq. (7) ignores the reverse reaction rate which is expected to be very slow. Secondly, according to the Lawn model, at very low applied stress the forward and reverse rates are comparable, thus leading to a crack propagation threshold which would imply a fatigue limit. Since no fatigue limit has as yet been unequivocally established for high strength fiber, it is reasonable to assume experiments are operating well away from such thresholds and the reverse reaction (bond formation) can be ignored.

In principle, the stress can influence the activation energy as both activation volume and chemical potential terms and it is not possible to determine *a priori* which is more important. However, what is clear is that in general the fatigue equations can not be solved analytically for the

exponential forms, though solutions for the particular case of static fatigue have been found.¹⁴ For this reason the exponential forms have generally been neglected in favor of the power law form, Eq. (1). The importance of the choice of kinetics function will now be discussed.

Given that $n \sim 20$ for fused silica, it is clear from Eqs. (1) and (2) that the kinetics model is far more sensitive to the stress intensity, K_I , than the micromechanics model. This means that the fatigue equations found by combining the two models tend to inherit the functional form of the micromechanics model. For example, in static fatigue, power law crack growth, Eq. (2), results in power law fatigue, Eq. (3), while the two exponential forms (Eqs. (6) and (7)) result in static fatigue equations that also have approximately the same exponential form. Therefore, when the fatigue equations are used to extrapolate from the results of accelerated experiments, the predictions will be sensitive to the form of the kinetics model, but not to the form of the micromechanics model.

It can be shown that the power law always gives the most optimistic lifetime predictions while the second exponential form (Eq. 7) gives the most pessimistic lifetime predictions.¹⁵ For example, Fig. 2 shows the results of fitting the three kinetics models to static fatigue data for fiber in ambient air taken on a time scale of 3 s to 5 days.¹⁶ While the three models fit the data well, they rapidly diverge upon extrapolation past the data so that the predicted maximum allowed service stresses for a 25 year lifetime span a

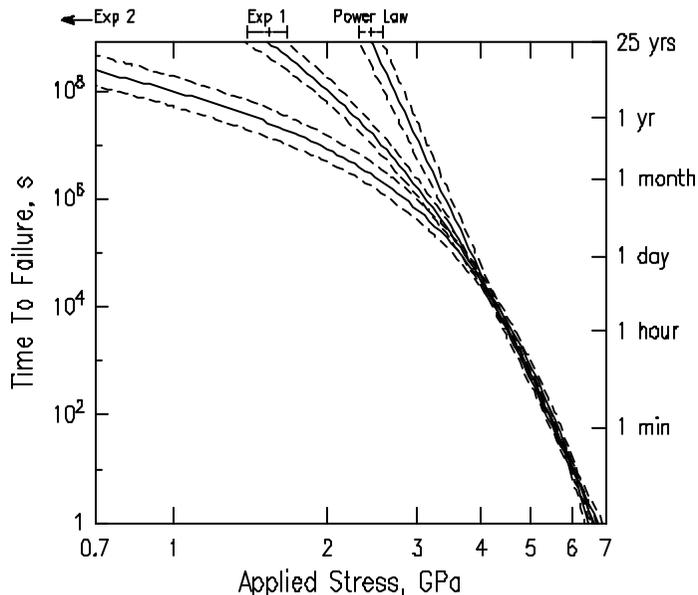


Fig. 2. Three kinetics models fitted to static fatigue data for coated fiber in air and extrapolated to a 25 year life.

decade in stress. An important aspect of this work^{15,11,16} is that careful calculations of the confidence intervals of the predictions have been made – the dashed lines in Fig. 2 represent 95% confidence intervals. For these data it is clear that uncertainty in the lifetime predictions is dominated by uncertainty in the appropriate kinetics model to use, while uncertainty due to scatter in the data is minor. Therefore, in such circumstances it is essential to know the correct form of the kinetics model. Most published data are insufficiently extensive to determine the correct model. Experiments specifically designed to empirically determine which model gives the best fit to data unfortunately did not give a unique answer.¹⁶ Both static and dynamic experiments for both bare and coated fiber in room temperature pH 7 buffer solution were best described by the power law, while the same experiments on the same coated fiber in ambient air were best described by the simple exponential, Eq. (6). These results imply that the situation is more complex than can be described by the simple kinetics models discussed here. In the absence of specific knowledge of degradation mechanisms and kinetics, a suitably conservative approach to design should be employed. Clearly, the power law is not conservative. The first exponential, Eq. (6), is comparatively conservative and is therefore recommended for most applications. The second exponential form, Eq. (7), is extremely conservative and is recommended for particularly critical applications, but such kinetics have not been observed for silica fiber and may result in design requirements that are difficult or impossible to satisfy. However, careful observations of slow growth of macroscopic cracks in fused silica favored the second exponential form.¹⁷

The form of the kinetics model is only important when lifetime predictions are made by extrapolating from experimental data, but is not when interpolating. The differences between the different models can be reduced in Fig. 2 if the data were extended further out in time. The extent of extrapolation is then reduced, as is the sensitivity to the model used. However, this is effectively measuring lifetime rather than predicting it and it is the purpose of fatigue models to avoid this.

Often lifetime predictions are made by extrapolating short term fatigue data for high strength fiber to long term fatigue of weak fiber. It has been found that when simultaneously extrapolating on both time and initial strength the predictions using the subcritical crack growth model become insensitive to the kinetics model used because of the way the model scales with these two parameters.¹⁵ In effect, the crack velocity is similar for strong specimens tested rapidly and for weak specimens tested slowly and this observation has been used to justify using power law kinetics in lifetime models.⁸ However, as will be discussed in the next section, there is no reason to suppose that strong and weak fiber will behave in the same way so that the extrapolation on initial strength may be invalid; the convergence of the different predictions at long times and low initial strength is a result of assumptions that are not valid.

As will be seen, one approach to avoid having to predict weak fiber behavior from experiments on strong fiber is to directly measure the fatigue properties of weak fiber. Under these circumstances lifetime predictions rely on extrapolation of failure time and so will be sensitive to the kinetics model. It is unlikely that the appropriate kinetics model can be determined for weak fiber since the scatter in results is typically an order of magnitude higher than for pristine fiber. Also, because it is less convenient to work with weak fiber, experiments usually only span a small range of failure times. For these reasons, it is important that lifetime predictions based on weak fiber behavior should be conservative and therefore should not be based on power law kinetics.

Power law kinetics can be used under some circumstances with care. For example, when proof testing fiber, the resulting strength can be weaker than the proof stress due to fatigue occurring during the unloading cycle. This effect can be accounted for by making predictions based on the behavior of weak fiber where strength is in the range of the proof stress (*e.g.* Hanson¹⁸). Since the proof test and fiber strength measurements are made on similar time scales the predictions are effectively interpolations, not extrapolations. It is then valid to use power law kinetics, and is especially convenient because the problem is then mathematically tractable.¹⁸ However, in general, it is important that power law kinetics are only used after insensitivity of the results to the form of the kinetics model has been established, rather than assumed.

3. MICROMECHANICS MODELS

By examination of previous work on silica glass both with and without damage, one may postulate four distinct regimes which, without any other information, would be expected *a priori* to have four distinct applicable micromechanics models (Table I). At the low strength extreme, bulk silica with macroscopic cracks is well described by Eq. (1) since the cracks are (at least while propagating) atomically sharp and only subject to externally applied stress. The stress corrosion parameter for weak silica is approximately 40, whether measured directly by crack velocity measurements¹⁹ or by fatigue measurements.^{20,21} At the opposite end of the strength range is short length "pristine" silica fiber. Under inert conditions (*e.g.* in liquid nitrogen) such fiber has a single valued strength close to the theoretical strength of the material.³ Any defects are of atomic dimension and, while atomically sharp, are also atomically wide and should be considered blunt and so are not described by Eq. (1). Additionally, Eq. (1) is a continuum model and the discreteness of the material is expected to have a major influence on the fatigue.²² The generally accepted fatigue parameter, n , is ~ 20 for high strength fiber.

In between these two strength extremes are strengths that are of particular interest since they are of the order of the proof stress. Such strengths

Table I. Types of defect and strength ranges for silica.

Defect Type	n	Strength	Comments
Pristine	20	>7 GPa	Surface phenomena.
Subthreshold	10-20	0.3 – 7 GPa	Crack initiation dominated by residual stresses.
Postthreshold	30	1 – 300 MPa	Crack propagation dominated by residual stresses.
Macroscopic Crack	40	<1 MPa	Sharp, residual stress free cracks.

result from extrinsic effects such as abrasion damage that can occur during all stages of manufacture and deployment. Other sources of defects are particles that adhere to the fiber surface during the drawing process, such as zirconia particles from the draw furnace. Such defects are characterized by the presence of a residual stress field. In the case of abrasion damage, the residual stresses occur around regions of plastic deformation (while fused silica is normally considered brittle, plastic deformation is readily induced by the intense compressive stresses found at the tip of a sharp indenter), while adhering surface particles induce residual thermal stresses in the fiber due to thermal expansion mismatch. Very severe defects of either type exhibit well defined cracks but small defects do not. Modeling such defects using Vickers indentation has shown that the defects with and without well defined associated cracks behave quite differently, there being a discontinuity in both strength and fatigue behavior at the threshold for crack formation.²³ Therefore, low strength fiber is expected to exhibit two regimes which are either subthreshold (*i.e.* without well defined cracks) or postthreshold (*i.e.* with well defined cracks), as shown in Table I. The behavior of both sub- and postthreshold defects is not expected to be described by the subcritical crack growth model due to the presence of the residual stress. However, theoretical models accounting for the residual stresses do describe the behavior of indentations reasonably well.^{24–26} The behavior of postthreshold flaws is modeled by propagation of a crack subjected to combined residual and externally applied stresses, while subthreshold defects are modeled by considering the initiation of a crack from a precrack, again under the combined influence of external and residual stresses.

To summarize, of the four types of defects expected to be encountered in silica, the only one expected to be correctly described by Eq. (1) is the macroscopic crack which is the only type of defect of no relevance to optical fiber reliability. Continuity of behavior is therefore not expected throughout the strength range of interest because of the differences in the strength controlling defects. However, the fatigue equation, Eq. (3), is found to fit fatigue data for t_f and σ_a quite well under many circumstances and this has

been cited for its validity. However, in reliability models, Eq. (3) is used to extrapolate to lower values of σ_i as well as larger values of t_f and it is this extrapolation that depends on the micromechanics model. Extrapolation on σ_i has not been tested empirically in detail and is usually invalid since it may involve extrapolating from pristine fiber behavior to the behavior of sub- or postthreshold-like defects.

3.1. Weak vs. Strong Fiber

While the behaviors of weak (sub- and postthreshold defects) and strong (pristine) fiber are not theoretically expected to be the same, it is sometimes claimed that they empirically show similar behavior, *i.e.* the stress corrosion parameter, n , is around 20 for both. However, when reviewing n values for weak fiber, Kurkjian *et al.*²⁷ found that while n was not particularly variable for pristine fiber, values ranging from ~12 to ~40 have been observed for various types of weak fiber. More recent results also show considerable variability in n values for indented fiber.²⁸

Examination of Table I suggests that, apart perhaps from the subthreshold region, there is a general trend of n increasing with decreasing strength. Michalske and Bunker²⁹ point out that if the crack growth kinetics were really exponential, Eq. (6), the apparent n value, calculated assuming power law kinetics, would follow this trend. They extrapolated macroscopic crack growth data to predict fiber behavior and found reasonable agreement. This led them to conclude that the subcritical crack growth is consistent with high strength fiber behavior if exponential kinetics are assumed. However, a more careful analysis by Matthewson¹⁶ which included uncertainty in K_{IC} , the inert strength σ_i , and the crack shape parameter Y , showed that while exponential crack growth and fiber fatigue data were not inconsistent, the large confidence intervals did not preclude the applicability of any of the kinetics models examined here; there is too much uncertainty to draw definite conclusions. While there may be consistency between pristine fiber and macroscopic cracks, the intermediate sub- and postthreshold defects do not fit in the general trend, as exemplified by abrupt changes in behavior at the threshold.

Other differences between weak and pristine fiber have been observed when aging under zero stress in harsh environments. Pristine fiber strength is degraded in harsh environments; while some polymer coatings may inhibit this behavior, it is generally observed for acrylate coatings and, significantly, for bare fiber as well.^{30,31} In contrast, weak fiber generally (though not always, as we shall see) increases in strength upon aging. The subcritical crack growth model predicts only strength degradation and only then in the presence of an applied stress and so no changes would be expected in the absence of stress. The model is entirely unsatisfactory for describing the observed changes during zero stress aging.

To summarize, we theoretically expect and empirically observe substantial differences in behavior between pristine fiber and fiber with strength comparable to current proof stress levels. No single model adequately describes all this behavior, and any claiming to do so should be treated with skepticism. Therefore, the behavior of weak and strong fiber should (and here will) be considered separately and the behavior of one should not be inferred from the other.

4. FATIGUE AND AGING BEHAVIOR OF WEAK FIBER

Reliability predictions for weak fiber can be made without extrapolating from pristine fiber behavior if weak fiber is studied directly. "Naturally" occurring defects can be studied by examining very long lengths³² but this is inconvenient since it is achieved by testing many short lengths consecutively; long duration experiments are not practical, and testing in environments other than ambient is effectively impossible. The problem is essentially that the weak defects are widely spaced and their position is not known in advance. Therefore the approach generally taken is to introduce artificial defects. Two approaches can be used, firstly to introduce a sufficient number of flaws so that a specimen of any reasonable length will be certain to contain a weak flaw. Alternatively, a controlled discreet defect can be introduced at a known position so that it can be individually studied. The first approach has been widely used and long lengths of fiber have been degraded variously by rubbing the bare fiber during the draw process with abrasive,³³ or another fiber,³⁴ or by blowing steam over the freshly drawn fiber.³⁵ Other techniques include abrading stripped fiber with hard particles³⁴ or hard particles can be incorporated in the polymer coating.³⁶ The effect of adhering surface particles has been studied by introducing particles into the draw furnace³⁷ or by contaminating the preform.³⁸

These techniques for making weak fiber are very useful and are comparatively convenient since long lengths of fiber can be made with relatively uniform properties. However, such techniques have drawbacks. Firstly, it can be difficult to reproducibly damage the fiber, but more importantly each technique produces only one characteristic strength (or strength distribution) and can not explore the complete strength range of interest. This is an important limitation because of the complex behavior of the glass in the region of typical proof stress levels; the narrow strength range explored means that conclusions can not be generalized. Such techniques induce defects of a range of sizes and scatter is quite large so that subtle effects may not be discerned.

An alternative approach is to use indentation by a Vickers diamond pyramid to introduce a flaw at a known position.²³ The residual strength of the flaw can be controlled over a wide range by controlling the indentation load. The results are therefore general in terms of strength but are only applicable to a particular type of defect. The technique is also comparatively

tedious to use. However, for a full understanding of weak fiber behavior, indentation is an important adjunct to the other techniques because it can carefully explore behavior over a broad strength range with good resolution (the Weibull modulus can be as high as 20 or more for indented fiber).

The results of experiments on fibers with a dense population of artificially induced flaws show considerable variability. However, with few exceptions, the stress corrosion parameter, n , typically ranges from 20 to 40^{27,34} so that weak fiber generally degrades more slowly than pristine fiber. Zero stress aging experiments have shown that some strength is recovered upon aging in harsh environments;^{33,34} in one case the strength of abraded fiber nearly doubled after aging for 10 days in 80°C water.³⁴ Additionally, some increase in n has been observed upon aging.^{27,34} Therefore, under harsh conditions that promote fatigue, weak fiber seems to generally both strengthen and have increased resistance to fatigue. This view seems to have led to some complacency, even though the behavior of the defects responsible for the low strengths is not well characterized.³⁹ Also, most data showing strength recovery in harsh environments are for zero-stress aging and the effect of an applied stress under such conditions may inhibit strength recovery. Additionally, recent results on indented fiber show that under some conditions abrupt strength *loss* can occur.

4.1. Indentation Experiments on Silica Fiber

Indentation by a Vickers diamond pyramid is a useful way of introducing controlled damage into a body in order to probe the mechanical properties of the material.²³ Such indentations are also thought to be a good model for contact and abrasion damage by hard angular particles. Indentations of relatively high loads (~10 N or more) have been widely studied and can produce a variety of fractures in the material; the exact behavior depends on the material, (hardness, toughness and elastic modulus), environment, indenter profile and peak indentation load. This subject has been comprehensively reviewed by Cook and Pharr.⁴⁰ However, weak optical fiber correspond to indentation loads of typically 0.1 to 1 N; a regime that has been poorly studied.

The Vickers indenter, being sharp, produces plastic deformation beneath the contact zone. A permanent impression is left in the surface upon removal of the load and residual stresses remain around the plastic zone (Fig. 3a). The plastic deformation does not occur by generalized yielding in the plastic zone but by localized shear occurring on planes at ~45° to the surface. Incipient cracks form where these shear faults intersect.⁴¹ At low indentation loads (<1 N) little else is visible in the optical microscope. At higher loads, radial cracks form during loading from the corner of the contact zone and are due to circumferential tensile stresses in the surface (Fig. 3b). These cracks greatly reduce the residual strength. Lateral cracks (Fig 3c) form on unloading due to tensile components of the residual stress field that are exposed as

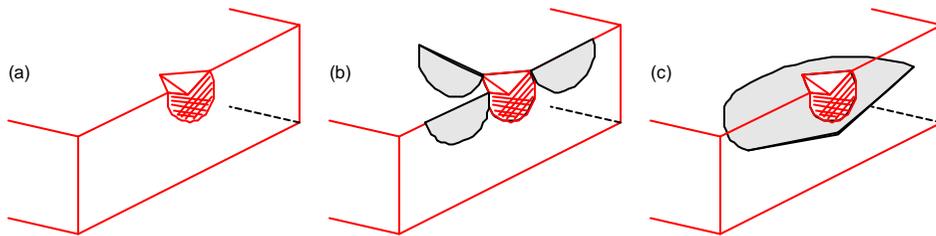


Fig. 3. Schematic section of Vickers indentations showing (a) the plastic zone, (b) radial cracks and (c) the lateral crack.

the compressive indentation load is removed. Lateral cracks do not greatly affect the strength directly but can increase it by their tendency to relieve the residual stresses.⁴²

Early work by Dabbs and Lawn⁴³ showed that the formation of radial cracks results in abrupt changes in both the strength (Fig. 4a) and dynamic fatigue parameter, n , (Fig. 4b) which is ~ 20 for subthreshold indentations (without radial cracks) and ~ 30 for postthreshold indentations (with radial cracks). They showed that the postthreshold value is consistent with a true value of n of 40, but the residual stress field reduces the apparent value to 30. A similar model for subthreshold defects for which the residual stress field surrounds the “crack” rather than is localized at its center, fitted the subthreshold data quite well.⁴⁴ These theoretical models have since been developed in more detail.^{25,26} It is now known that failure of postthreshold indentations is by propagation of the radial cracks under the combined influence of the residual and externally applied stresses while failure at subthreshold defects could be considered as controlled by nucleation of radial cracks, which subsequently propagate to failure. One key observation was that radial cracks in a fatiguing environment could spontaneously “pop-in” from subthreshold defects some time after indentation with attendant abrupt strength loss even in the absence of an applied stress. This clearly raises concerns for reliability.

The indentation work provides a qualitative explanation for the observed behavior of weak fiber. The dominant role of the residual stresses is clear; they have a tendency to reduce the apparent fatigue parameter, n , and this effect is strongest for small subthreshold flaws. This explains the general trend for n to increase for weaker fiber; reflecting the decreasing (but not negligible) effect of residual stress on larger flaws. The zero stress aging behavior of weak fiber can also be interpreted in terms of the behavior of indentations. The residual stresses cause any cracks or incipient cracks to extend upon aging under zero stress in harsh environments. While crack extension causes the stress intensity due to an externally applied stress to increase, the stress intensity due to the residual stress decreases⁴⁴ and this leads to overall strengthening, as observed. This also leads to the important

conclusion that a fiber will *not* fail under the influence of residual stress alone. Crack extension, particularly of small lateral cracks which are often observable, also relieves the residual stresses around the indentation site, again leading to strengthening. Both effects reduce the influence of residual stress during aging, thus explaining the general increase in n which is often observed.^{33,34} It is often claimed that strength recovery could be caused by crack tip blunting; while this is possible, residual stress effects are likely to dominate.⁴⁵

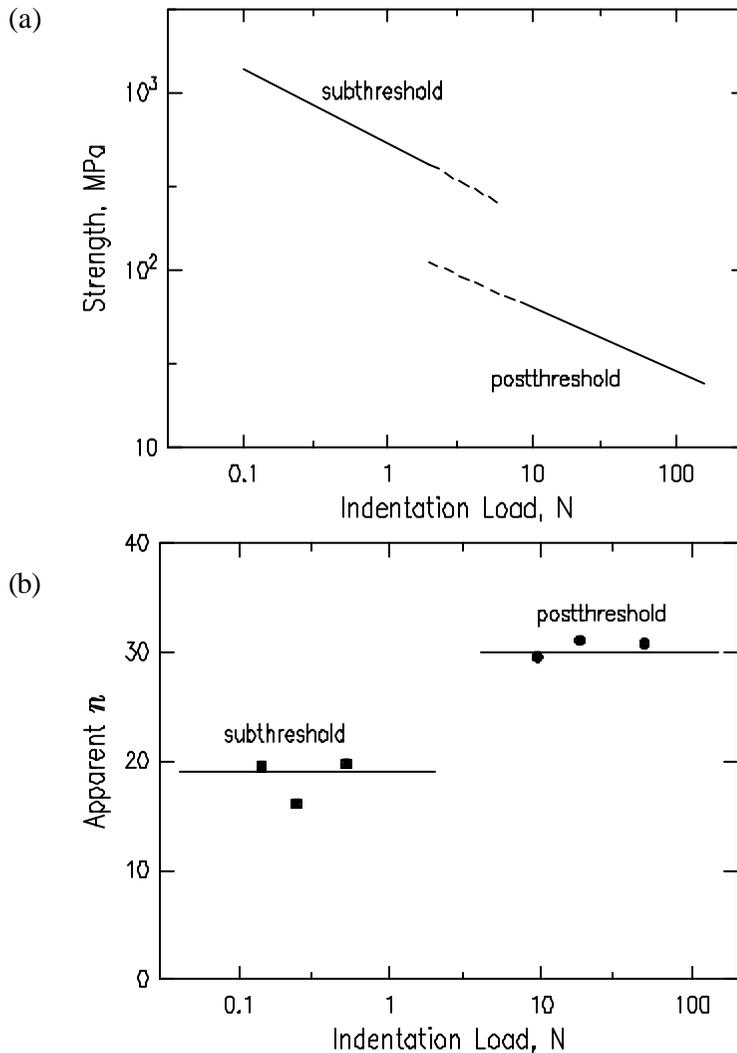


Fig. 4. Plot of (a) strength, measured in dry nitrogen and (b) dynamic fatigue parameter, n , as a function of indentation load for silica fiber (after Dabbs and Lawn⁴³).

The early experimental work on silica^{43,24} was limited in the subthreshold and threshold regions and the severity of the discontinuity in behavior at the threshold was in doubt since, except for one point, all subthreshold data were for optical fibers broken in tension while all postthreshold data were for silica rods broken in bending. Indentation experiments at Rutgers University have been aimed at extending the early work into the subthreshold region, to examine the threshold region in more detail and to determine the importance of crack pop-in. By using fibers of various diameters and appropriate strength measurement techniques (two-point bending³⁵ for stronger fibers and a novel four-point bend technique for weaker fibers^{46,47}) the entire region of interest can be explored.⁴⁸ Fig. 5 shows the inert (liquid nitrogen) strength of indented fiber as a function of indentation load.²⁸ In the subthreshold region strengths of up to 3.7 GPa (5% strain to failure) have been measured. It is noted that the two- and four-point bending results are in close agreement in the region of overlap. The threshold region is extensively explored and bimodal behavior is observed in the load range of 2 to 5 N; some indentations have no radial cracks while others have well defined cracks and are substantially weaker. In fatiguing environments even more complex behavior is expected in the threshold region with bimodal strength distributions – subthreshold indents may fail by two modes; radial cracks pop-in during loading and can either propagate to cause immediate failure or can arrest and then grow stably until later catastrophic failure.^{25,26} Therefore, the uncontrolled weakening techniques such as abrasion, while extremely useful, are not able to map out the full behavior near the threshold since they effectively take a “snap-shot” of the behavior at just one strength. Also shown in Fig. 5 are data of Jakus *et al.*²⁴ for measurements of “inert”

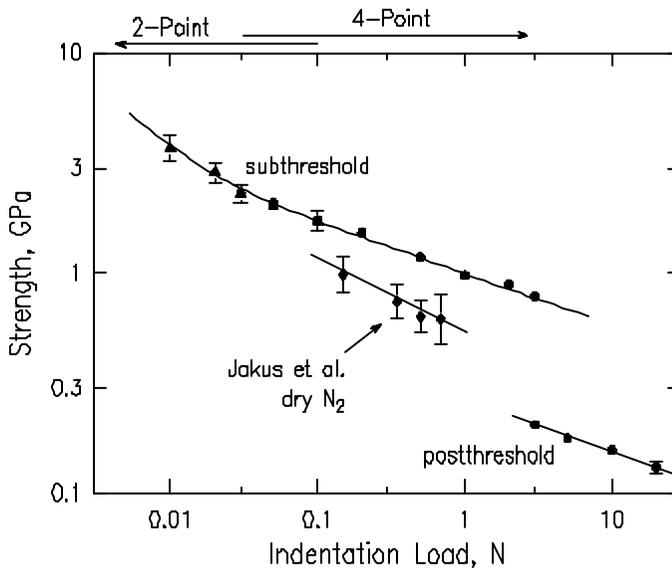


Fig. 5. Inert strength of indented fiber as a function of indentation load.²⁸

strength made in room temperature dry nitrogen. Their results are significantly weaker than in liquid nitrogen and are therefore not in inert conditions (the difference can not be explained by the temperature dependence of elastic modulus which only differs by ~10% between -196°C and 25°C).

Fig. 6 shows the strength of 0.1, 0.5 and 1 0N indentations after aging in 90°C pH 7 buffer solution. After 10 hours, both 0.1 N (subthreshold) and 10 N (postthreshold) indentations show some strengthening, as observed for abraded fiber. However, 0.5 N indentations, which are initially subthreshold, show pronounced bimodal behavior after 10 hours; some specimens gain strength while others show radial crack pop-in and a substantially reduced strength which does not fully recover upon further aging. Inert (liquid nitrogen) strength measurements show similar results. The 0.5 N indents have an initial inert strength of 1.2 GPa but the low strength “popped-in” specimens have a strength of 0.5 GPa after 10 hours aging. Since the proof stress corresponds to the inert strength, the 0.5 N indents would pass a 0.69 GPa test⁴ but if aged under zero stress, “pop-in” would degrade the strength below the proof level. Therefore, proof testing does not guarantee the strength if the fiber is exposed to aggressive environments even under zero stress. This behavior is not accounted for by present reliability models. It is noted that when proof testing, degradation during unloading can lead to defects weaker than the proof stress (*e.g.* Hanson¹⁸) but this effect, unlike pop-in, can be controlled by rapid unloading after applying the proof stress.

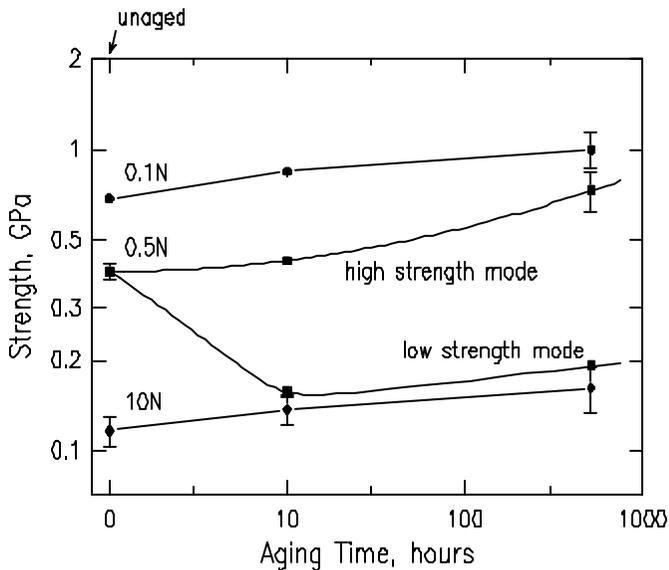


Fig. 6. Residual strength of indented fiber after aging in 90°C pH 7 buffer solution.²⁸

Fig. 7 shows measurements of the dynamic fatigue parameter, n , for 0.5 N indentations in various environments. As observed for abraded fiber, n increases with aging time. However, the value for unaged indentations in pH 7 buffer is 10 ± 1 which is disturbingly low.

Although Glaesemann³⁴ did see slight weakening before substantial strength recovery during aging, there is little evidence for crack pop-in in the literature on abraded fiber. However, this does not mean that pop-in is of no practical importance since it might not have been observed for two reasons. Firstly, pop-in at indents is only observed over a narrow range of strengths; stronger and weaker defects all show monotonically increasing strengths – experiments on abraded fiber might simply not be in the correct strength range. Secondly, abrasion produces a comparatively broad strength distribution and a few specimens showing pop-in might not be distinguishable given the substantial scatter. Significantly, Glaesemann³⁴ observes increased scatter with aging time which could perhaps be due to bimodal behavior, though he cites other explanations. This scatter could readily mask the presence of pop-in. It should be noted that in our experiments, indentations are observed both before and after aging; pop-in is directly observed and the choice of which mode of the bimodal strength distribution to assign a particular specimen is unequivocally established. In contrast, the failing flaw in an abraded fiber is not known in advance and pop-in can only be inferred from the statistics of the strength results.

The relevance of the indentation results may be questioned since they are only a good quantitative model for certain types of defects, and many defects in a practical fiber come from other sources. However, most “real” or

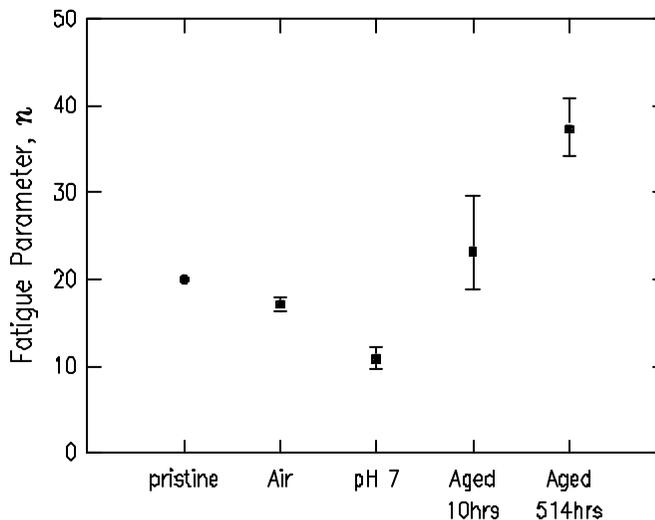


Fig. 7. Dynamic fatigue parameter, n , of fiber indented by a 0.5 N load for various environments.²⁸

practical defects, if severe enough, do have associated cracks and so have a threshold for crack formation. Clearly then, defects just in the subthreshold region have a potential for crack pop-in. The important question is therefore not “are indents a good model for practical defects?” but rather “for any given type of practical defect, where is the threshold for pop-in and how does it compare with the proof stress?”

To summarize, the results for abraded fiber can not be generalized to the whole strength region, while the results for indented fiber only qualitatively indicate how practical defects might behave. However, combining both sets of results explains much of the observed behavior of weak fiber. General improvements in strength and fatigue properties are observed when aging under zero stress, but the results warn that in critical strength regions spontaneous strength loss can occur in harsh environments, even in the absence of applied stress. Reliability models should allow for the possibility of such behavior, either by explicitly including the phenomenon or by being suitably conservative.

5. FATIGUE AND AGING BEHAVIOR OF PRISTINE FIBER

Pristine fiber, the fiber between the weak extrinsic defects, typically has a strain to failure of a several percent and has a very narrow strength distribution. This implies that such material is essentially flaw free;³ any “defects” are of molecular dimension. Therefore the micromechanics model of Eq. (3), where the defects are assumed to be sharp cracks in a continuum, is expected to be a poor description of the “defects” in pristine fiber, which are neither sharp nor large compared with the molecular structure of the glass. However, the fatigue behavior of pristine fiber is empirically found to fit Eq. (3) quite well in at least the dependence of time to failure on applied stress, though substantial deviations are often observed in harsh environments (the aging and fatigue “knees” which will be discussed below). Under these circumstances, the fatigue can be considered well behaved in that it exhibits “linear” fatigue (approximately linear behavior on log-log fatigue plots) and behaves somewhat predictably with, for example, temperature, pH, and water availability.^{10,49,50} Therefore Eq. (3) can be useful, and the crack size, c , can be thought of as an effective flaw size. However, a detailed examination of the behavior has shown some discrepancies. For example, the strength has been found to be sensitive to the presence of certain ionic species in the environment in a way not exhibited by macroscopic cracks. Matthewson *et al.*⁵¹ found that the strength depends on the presence of group I alkali metal ions and exhibited a minimum strength for potassium. This correlates with silica dissolution data which show a maximum for potassium,⁵² while no cation dependence is observed for macroscopic crack growth.⁵³ At high pH the surface of silica is negatively charged but, since fatigue is faster at high pH, the fiber is attacked principally by negative hydroxide ions. Therefore surface effects, and in particular the nature of the electric double layer, can strongly influence fatigue. Rondinella *et al.*⁵⁴ suggest that the alkali cations

effectively act as catalysts transporting the hydroxyl ions to the silica surface; their catalytic power depends on the size and binding energy of their hydration shells. Such behavior would only be observed at a free surface of the glass and not in the highly constrained confines of a crack. Inniss *et al.*⁵⁵ found that at constant pH, the fiber strength depends on the concentration of various salts; NaCl in particular. They found that the strength correlated with the surface charge on the silica. This again suggests that the fatigue of high strength fiber is a sensitive function of surface chemistry and surface effects.

Eqs. (1) and (2) can be integrated for dynamic loading conditions in which the fiber strength is determined as a function of constant stressing rate. Therefore, a sensitive test of the subcritical crack growth model is to compare static and dynamic fatigue measurements. Matthewson¹¹ showed that comparison of static and dynamic results obtained on similar time scales is a test of the micromechanics model rather than the kinetics model. By careful experimentation using identical fiber, environments, and test equipment, he found a discrepancy between static and dynamic fatigue experiments.¹⁶ For example, Fig. 8 shows the dynamic fatigue results obtained directly and by prediction from static fatigue experiments. The static fatigue results predict systematically higher strengths which are statistically significant since the dashed lines are 95% confidence intervals on the prediction and do not enclose the dynamic fatigue data (the predictions are made for the exponential model, Eq. (6), but other models lead to the same conclusion). The reasons

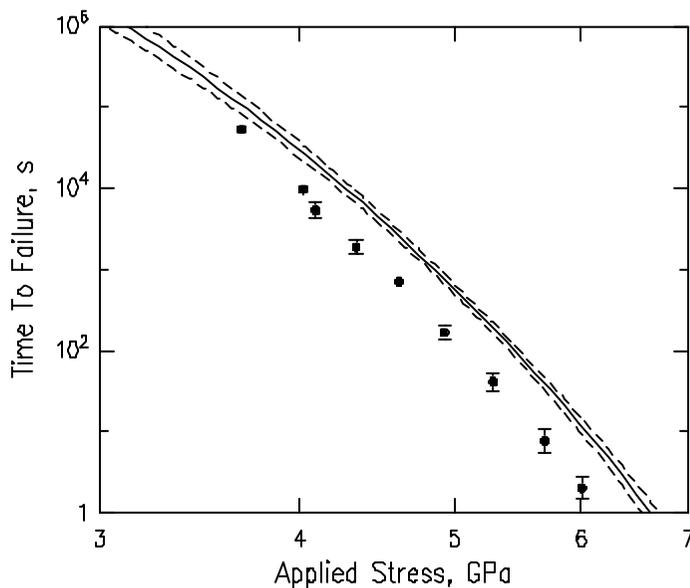


Fig. 8. Dynamic fatigue measured in air for coated fiber showing measured data and predictions made from static fatigue data.

for this discrepancy are not clear, but one possibility is the discreteness of the crack growth – the crack does not advance continuously, but rather, discontinuously as each bond ruptures; the rate of growth is controlled by the bond rupture probability. Hanson⁵⁶ also found small but systematic differences between static and dynamic results using a stochastic model for fatigue. The importance of the discrete nature of crack growth was highlighted in earlier work; Scanlan²² showed that the time to failure can be very sensitive to the time it takes just the first bond to break.

The above perturbations from the subcritical crack growth model are however, relatively minor and may be ignored for many applications. What is far more serious are the substantial perturbations from the simple theory, namely, the fatigue and aging knees often observed in harsh environments. These knees can result in substantially lower performance than predicted by the subcritical crack growth model.

5.1. The Fatigue and Aging Knees

The static fatigue knee is an abrupt decrease in the fatigue parameter, n , at long times to failure which results in a fatigue life which is very much shorter than indicated from short-term data. While originally observed in data for static fatigue in humid air,⁵⁷ the presence of the fatigue knee has only recently been observed again in vapor environments.⁵⁸ Its presence has been well established in harsher, liquid environments. The position of the knee is strongly influenced by the nature of the polymer coating and appears to be suppressed for certain coating formulations such as polyimides, probably due to their strong adhesion to the fiber (*e.g.* see the article by Biswas⁵⁹ in this volume). However, the fatigue knee has also been observed for bare fiber^{30,31} indicating that it is a property of the fiber rather than simply a coating effect. The strength of pristine fiber is usually observed to decrease during aging under zero stress, often abruptly. The aging knee occurs at a similar time to the fatigue knee for both multicomponent⁴⁹ and silica glass.³¹ The aging and fatigue knees are now thought to be due to the same phenomenon, namely the formation of surface roughness or pits. These pits then act as a new source of stress concentrating defects. Their presence has been directly confirmed by both scanning tunneling microscopy⁶⁰ and atomic force microscopy (AFM).⁶¹ While a variety of coated and bare fibers show quite different zero stress aging behavior, it has been shown that the residual strength and surface roughness (measured by AFM) have a unique relationship.⁶¹ This strongly suggests that the fatigue and aging knees are caused by initiation of new surface flaws by surface dissolution rather than by propagation of preexisting defects. The pits are not sharp and their stress amplification depends also on their tip curvature. Recently, Inniss *et al.*⁶² verified the theoretical relationship for the stress intensity factor at a blunt surface pit by measuring both the shape and resulting inert strength of discrete pits produced by etching silica fiber in HF vapor. While qualitatively simple to understand, a quantitative description of the fatigue behavior

of such pits is complex since they must be described by two parameters, width and length, which both can evolve with time.

France *et al.*⁴⁹ modeled the fatigue knee by assuming that fatigue and aging both occur simultaneously. By fitting an empirical function to zero-stress aging data they found an effective crack growth rate in aging of the form:

$$\dot{c} = \frac{2c_0 \alpha \beta}{(1 + \alpha t)^{1-2\beta}} \quad (8)$$

which could then be added to the stress induced growth (Eq. 2) to predict combined aging and fatigue. They found quite good agreement with their predictions for multicomponent glasses, and more recently Cuellar *et al.* found reasonable agreement for various silica and doped silica fibers.⁶³ However, earlier work on fused silica fiber did not give such good agreement.³¹ There are several objections to this model. Firstly, it is not truly predictive of the knee since it uses direct observation of the aging knee to predict the position of the fatigue knee. Secondly, the aging behavior, as exemplified by Eq. (8), is very abrupt with apparently little occurring during the early stages of aging. Thirdly, the model is based on assumptions which are invalid; in particular it is assumed that one population of flaws grows by both stress and some unspecified aging mechanism. The current understanding is that there are two separate flaw populations which behave differently. The variability in the aging and fatigue knee behavior means that it is not possible, as yet, to construct a reasonable quantitative model for the knee behavior. However, with the recent advances in understanding it is possible to construct a physically reasonable qualitative model.

Two flaw populations are considered. The first are intrinsic defects which are comparatively sharp and can be approximately modeled by the subcritical crack growth model. In static fatigue these flaws lead to an effective fatigue parameter, $n \simeq 20$ (Fig. 9b) but are largely unaffected by zero-stress aging (Fig. 9a). The second flaw population consists of surface

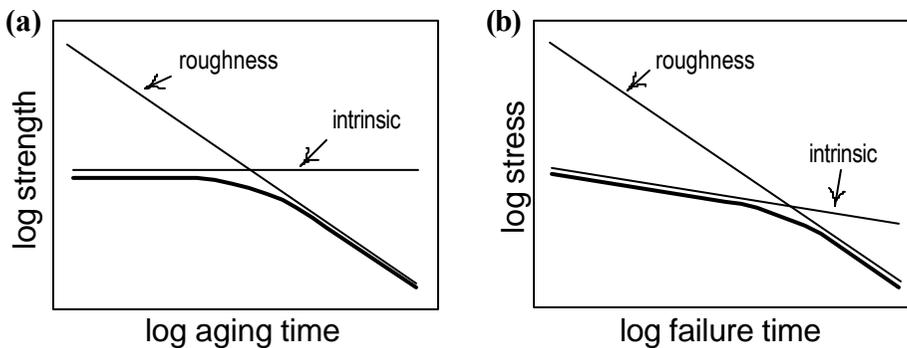


Fig. 9. Schematic of the (a) zero stress aging and (b) fatigue behavior.

pits which form due to dissolution of the surface. The severity of these pits increases with time under zero stress (Fig. 9a). Application of stress is not expected to strongly influence the formation of roughness since, unlike the intrinsic defects, the roughness does not significantly amplify the stress in the early stages of roughening (though this should be confirmed). Therefore, the strength of roughness defects is similar in both fatigue and aging. The two defect populations are assumed to evolve separately so that failure occurs due to the more severe type, *i.e.* at short times the intrinsic defects cause failure while at longer times the roughness defects dominate. The bold lines in Figs. 9a and 9b represent the overall behavior. Note that a static fatigue curve represents the locus of times at which the inert fiber strength equals the applied stress; for a valid comparison of the effect of stress on strength the fatigue plot should be compared to the dependence of *inert* strength on aging time. Several qualitative conclusions can be drawn from this model.

1. The fatigue knee occurs later in time than the aging knee. Because the intrinsic defects do not grow during zero-stress aging, the roughness defects degrade to similar severity in a shorter time. This trend has been observed for a variety of commercial and research fibers⁶³ and is also predicted by France's model.⁴⁹
2. The abruptness of the knee is caused by a switch in the nature of the strength controlling defect, and does not represent any abruptness in the physical processes responsible for the strength.
3. The position of the knee will be sensitive to the roughening kinetics. It is important to note that the roughening is not due to dissolution itself but is due to *differential* dissolution rates from point to point on the fiber surface.³¹ These kinetics are quite variable and one might postulate two extremes of behavior. Firstly, if the fiber surface is uniformly available to the environment for etching then differential etching rates are due to random fluctuations in the glass structure - such randomness is into the depth of the glass as well as across the surface. The rate of roughening is analogous to the accumulation of random noise and would grow with the square root of time, \sqrt{t} . As evidence for this, we found that silica fiber in various alkalis generate ~ 10 nm surface roughness on a time scale of a day, but that the fiber diameter decreased by ~ 10 μm in that same time.⁶⁴ The differential etching rate in this case is orders of magnitude slower than the average rate. At the other extreme, one can postulate a fiber surface that is effectively insoluble in localized regions, but soluble in others. This might occur, for example, when the coating has patchy adhesion. Under these circumstances the differential etching rate is comparable with the average etching rate and so increases linearly with time, t . Such localized etching has been directly observed.⁶⁵

The variability in the roughening kinetics is reflected in the observed variability in the position of the knee and its sensitivity to the coating and its

adhesion.^{63,66} However, it does make it unlikely that a single simple quantitative model can be developed that describes more than a narrow range of fiber types.

An interesting point that results from these considerations is that a t dependence will always dominate a \sqrt{t} dependence at sufficiently long time. This means that a durable fiber, with very low average etching rates, can still exhibit knee behavior if any differential etching occurs and that the knee will then be quite abrupt. Exactly this behavior has been observed for a titania doped fiber which initially shows improved behavior compared to a typical silica fiber, but eventually exhibits an abrupt knee with worse performance beyond.⁶³

The roughening kinetics models can also explain the observation that the fatigue behavior of bare fiber can, at very long times, have longer failure times than the same fiber but coated.³¹ While the bare fiber starts weaker because of closer interaction with the environment, the coated fiber eventually is weaker due to its greater differential etching rate.³¹ A similar crossover in behavior has been observed for the roughness of both coated and bare fiber under zero stress aging.⁶¹

The roughening model outlined here is physically reasonable and successfully qualitatively explains many experimental observations. However, it also may form the basis for a truly predictive model for the presence of the fatigue knee. Unlike France's model,⁴⁹ this model does predict that there are some significant changes occurring *before* the knee, *i.e.* surface roughening that initially does not degrade the overall strength. The presence or absence of this early roughening would be a precursor for the development of fatigue and aging knees. However, the published data for measurements of roughness have concentrated on the knee region and beyond; measurements of surface roughening before the knee is a promising area of research.

While quantitative prediction of the position of the fatigue knee may prove to be difficult, if not impossible, the understanding of the mechanisms leading to the knee have enabled us to produce coating formulations that substantially delay the onset of the knee. This work promises to allow production of fiber whose knee is sufficiently delayed in time that it is not a concern for reliability. The idea, which involves incorporating nanosized (~20 nm diameter) silica particles in the polymer coating of the fibers, is an inexpensive modification of existing coating technologies. The silica particles are relatively soluble because of their surface curvature and dissolve preferentially in environmental moisture. The moisture, being partially saturated with silica, then has a lower reactivity at the fiber surface and surface roughening is substantially depressed.^{67,68} While having little effect before the fatigue knee, only 3 wt% of particles can delay the onset of the knee by a factor of ~100 and times to failure beyond the knee can be extended by factors of up to ~300.⁶⁹ The particles also give substantial protection in

humid environments, as well as in liquids.⁵⁸ Incorporating the particles in the outer of a dual coated system ensures that they can not degrade the strength or optical loss by interacting with the fiber surface, while still retaining most of the protective power.^{69,70} While the additive does make the coating liquid prepolymer thixotropic and more viscous, this can be controlled by stirring prior to coating.⁶⁹ Even more beneficial results can be expected with optimization of the particle size and concentration. The technique also promises to be useful for other glass systems, such as the heavy metal fluorides, which have substantially lower durability than silica.⁷¹

6. CONCLUSIONS

This article critically examines the fundamental physical models for the degradation of optical fiber strength that occurs in the presence of moisture. Current quantitative reliability models are almost exclusively based on the power law subcritical crack growth model which is shown to be flawed in almost all aspects; power law kinetics are unphysical and unduly optimistic and neither strong nor weak material contains simple cracks. High strength, “pristine” material does not contain sharp well defined cracks and often the behavior is dominated by the formation of strength degrading surface roughness by etching. In weak material, any sharp cracks that may be present are strongly influenced by the presence of residual stress. Of particular concern is the recent observation that some kinds of weak defect can spontaneously lose strength to below the proof stress.

However, it is recognized that for practical purposes it is often necessary to make some kind of estimate of expected lifetimes despite our lack of quantitative understanding of the relevant mechanisms. Under these circumstances, use of the subcritical crack growth model is an unavoidable necessity because of the lack of alternatives. However, it should be treated as a semi-empirical scaling model rather than a fully predictive model. In particular, careful consideration should be given to the confidence intervals of the predictions; variability in all aspects of the model should be considered, not just variability due to scatter in input data. Of particular importance is the assumed form of the degradation kinetics model; it is recommended that at the very least, an exponential form should be considered since the ubiquitous power law form gives unduly optimistic results. Published results of reliability modeling rarely consider confidence intervals for predictions and so it is hard to interpret their significance.

6.1. Future Directions

Clearly there are many areas available for fruitful research. Perhaps one of the most important is to more fully characterize and understand the behavior of weak fiber. For this it is necessary to study both “real” and model defect populations as well as to study individual controlled defects produced by indentation or other techniques. In particular, the conditions

that lead to crack pop-in should be determined for the various types of severe defect encountered in practice.

Surface roughening has been shown to be the cause of the abrupt knees observed in both static fatigue and zero stress aging of high strength fiber. However, this research so far is mostly of a qualitative nature and more quantitative characterization is required. In particular, the nature of roughening before the knee is of especial interest since it may form the foundation of a predictive model for the presence of the knee. It has been shown that incorporating fine silica particles in the polymer buffer coating slows the formation of surface roughness and promises to be a practical method for substantially delaying the onset of the fatigue and aging knees.

Lifetime predictions are often sensitive to the mathematical form assumed for the degradation kinetics (crack growth rate). Initial results in this area suggest that there is no unique form appropriate for a broad range of fiber types and environments. However, further exploration should determine what range of models might be encountered and, in particular, whether degradation is ever more severe than predicted by a simple exponential form.

7. ACKNOWLEDGEMENTS

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