

Humidity Dependence of the Fatigue of High-Strength Fused Silica Optical Fibers

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Strength and dynamic fatigue behavior of silica fibers has been measured as a function of ambient humidity. Bare and polymer-coated fibers were compared to determine the influence of the coating. The results verify earlier work that suggests the degradation reaction is approximately second order with respect to humidity. However, we verify this result using rigorous data analysis techniques and, unlike the earlier work, the result is shown to be independent of the form of the kinetic model for crack growth. Trends in the calculated fatigue parameters illustrate that a simple exponential crack growth law best describes the humidity data. No significant differences were found between coated and bare fibers, provided the coated fibers were properly equilibrated. A data analysis methodology is given for obtaining valid reaction orders independently of the crack growth law form.

I. Introduction

THE reliability of optical fibers has been a topic of research and interest for many years. One particular problem is the prediction of lifetimes from standard laboratory measurements. To date, most fibers are proof tested at a typical stress of 0.7 GPa¹ to assure a minimum strength.² Lifetime predictions are then made based on the proof stress, but in this procedure some questionable assumptions are made. Firstly, the ambient environment of the proof test is generally assumed to be the same as the service environment to avoid having to determine the dependence of strength on the water activity. This is a safe assumption provided the worst expected service environment is less aggressive (i.e., drier and cooler) than the proof environment, but this is usually not the case. This difficulty is further aggravated if proof testing is performed in-line during manufacture, which means the fiber has a strength characteristic of the environment closer to that of the draw furnace, which is much drier than ambient.² This issue can be resolved if the humidity dependence of strength is well understood, which is one purpose of the work described here. Finally, current industry standards assume a power law form for the stress dependence of fatigue. Predicted lifetimes are highly sensitive to the form—the power law has no physical significance and gives an overly optimistic lifetime compared to other forms based on chemical kinetics theories.^{3,4} In this work, a comparison of crack velocity models will be made to determine which model best describes the humidity effect.

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The effect of humidity on slow crack growth in silicate glasses has been evaluated by direct measurement of the crack velocity as a function of stress intensity, temperature, and humidity. Some of this work determines an effective reaction order with respect to humidity where values typically range from 0.5 to 1.^{5–7} Muraoka *et al.* found a higher value of approximately 2.5 for indentation cracks in silica.⁸ However, the slow crack growth data are not usually accurate enough to determine the form of the kinetics model, and the relevance of the data for such large cracks to the behavior of “pristine” fiber is not clear.

Procter *et al.*⁹ measured the strength of hand-drawn bare silica fiber in various humidities. However, because the scatter in their results was so great, a reaction order could not be determined from their data. Duncan *et al.*¹⁰ and Sakaguchi¹¹ studied the dynamic fatigue of silicone-coated fibers and their results show a second-order dependence at moderate humidity ($\geq 5\%$) though the low-humidity data ($< 0.01\%$) of Duncan *et al.*¹⁰ appear to behave differently (\sim first-order dependence). However, they interpreted their results in terms of a power law and it is not clear whether the reaction order of 2 depends on the power law model and/or is perturbed by the presence of the silicone coating. A reaction order of about 2 for E and S glass fibers was found by Gupta.¹²

It is clear from the literature that the humidity dependence of the fatigue of silica fiber is not well understood. Slow crack growth measurements do not give similar results to fiber strength measurements. Apart from the work by Procter *et al.*,⁹ all of the strength versus humidity data in the literature are for coated fiber and the role of the coating is not clear. Also, the strength data are obtained by dynamic fatigue, which does not give the reaction order directly, and therefore some assumptions about the stress dependence of the kinetics must be made. To address these issues we have directly compared the humidity dependence of strength for both polymer-coated and bare fibers. The results are interpreted using several kinetics models and it is shown that the reaction order can be determined independently of the particular kinetics model assumed.

II. Crack Growth Models for Fatigue

The subcritical crack growth model for fatigue assumes that the strength is controlled by sharp, stress-free cracks. Even though in this work, “pristine,” high-strength silica fiber is used which does not contain well-defined cracks,¹³ it is assumed that crack growth and not crack initiation controls fatigue. The power law, designated model 1 here, may be expressed³

Model 1

$$\frac{dc}{dt} = A_1 \left(\frac{K_I}{K_{IC}} \right)^{n_1} \quad (1)$$

where the subscript for A and n refers to the model number. K_I is normalized by K_{IC} in order to give A_1 the dimensions of velocity.

If we assume that n_1 is a material constant² (an assumption we will test later), then all of the environmental dependence must be in A_1 . A simple chemical kinetics model for fatigue, where the reaction rate between water and silica is Arrhenius, would mean A_1 is defined as

$$A_1 = \nu f(a_{\text{H}_2\text{O}}) \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

In this expression the reaction rate constant is assumed to have apparent activation energy, Q , and some functional dependence on the water activity, $f(a_{\text{H}_2\text{O}})$; ν is a frequency factor. The activation energy is assumed to be stress independent in this model since the effect of stress is completely described by Eq. (1). However, Kao¹⁴ found that A can be described by an Arrhenius dependence on temperature, but that the activation energy depends on the applied stress and hence K_I . This observation is not consistent with Eq. (1), in which the term in K_I is meant to contain all of the stress dependence.¹⁵ This is one drawback of this model. $a_{\text{H}_2\text{O}}$ is the thermodynamic activity of the water, which is equal to the water vapor partial pressure, $p_{\text{H}_2\text{O}}$, for moderate pressures. At a given temperature, the saturated vapor pressure, $p_{\text{H}_2\text{O}}^{\text{sat}}$, is constant and hence $p_{\text{H}_2\text{O}}$ is proportional to the relative humidity (RH), hence

$$\text{RH} = \frac{a_{\text{H}_2\text{O}}}{a_{\text{H}_2\text{O}}^{\text{sat}}} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^{\text{sat}}} \quad (3)$$

The site of the water/silica reaction is not in direct contact with the air; it is covered by either the coating or an adsorbed layer of moisture. However, if it is assumed that the water at the crack tip is in equilibrium with the vapor, then the activities at the crack tip and in the vapor must be the same. We expect this to be a good approximation since the fibers are strong and any cracks are of molecular dimension,¹³ which means that very little water is consumed by the growth of such small cracks. Therefore, crack growth will not be expected to significantly reduce the local concentration of water. It is also reasonable to assume that the mass transfer is not rate limiting since moisture diffuses through the coating rapidly.^{16,17} This assumption will be justified by our results, which show little difference between coated and bare fiber. Therefore, as is shown in Eq. (3), the activity at the crack tip is proportional to the relative humidity in the ambient environment. Equation (2) then becomes

$$A_1 = \nu f_1(\text{RH}) \exp\left(-\frac{Q}{RT}\right) \quad (4)$$

and shows the expected relationship between A_1 and the temperature and humidity of the test environment.

A more physically reasonable chemical kinetics model proposed by Wiederhorn¹⁸ assumes that the stress at the crack tip modifies the activation energy of the chemical reaction via an activation volume. This treats the stress at the crack tip as if it were a negative pressure. Effectively, the activation energy reduces linearly with the stress intensity:

$$Q = Q_0 - b \frac{K_I}{K_{\text{IC}}} \quad (5)$$

where Q_0 is the zero stress activation energy, and b is a constant. This leads to an exponential form of the kinetics model designated model 2 here:

Model 2

$$\frac{dc}{dt} = A_2 \exp\left[n_2 \left(\frac{K_I}{K_{\text{IC}}}\right)\right] \quad (6)$$

where A_2 is a fit parameter that has environmental dependence, and n_2 is a fit parameter independent of the environment. Incorporating humidity in the same way as for model 1 gives

$$A_2 = \nu f_2(\text{RH}) \exp\left(-\frac{Q_0}{RT}\right) \quad (7a)$$

$$n_2 = \frac{b}{RT} \quad (7b)$$

A third model, designated model 3, is based on an analysis due to Lawn,¹⁹ which effectively assumes that the strain energy density at the crack tip modifies the activation energy as a contribution to the chemical potential. His analysis predicts a threshold for slow crack growth, but provided K_I is not close to this threshold, a quadratic dependence of the activation energy on stress intensity is found:³

$$Q = Q_0 - b' \left(\frac{K_I}{K_{\text{IC}}}\right)^2 \quad (8)$$

where b' is a constant. This leads to

$$A_3 = \nu f_3(\text{RH}) \exp\left(-\frac{Q_0}{RT}\right) \quad (9a)$$

$$n_3 = \frac{b'}{RT} \quad (9b)$$

where A_3 is a fit parameter with an environmental dependence and n_3 is a fit parameter independent of the environment.

Model 3

$$\frac{dc}{dt} = A_3 \exp\left[n_3 \left(\frac{K_I}{K_{\text{IC}}}\right)^2\right] \quad (10)$$

These three models have two fit parameters; the exponents, n_i , describe the stress dependence while the preexponents, A_i , describe the overall reaction rate and the environmental dependence. They differ only in the mathematical form for the dependence on K_I .

It is important to consider the different kinetics models for two reasons. The first is that interpretation of experimental data often depends on the form of the kinetics model. For example, in dynamic fatigue, where constant speed loading, ν , in two-point bending is used integrating and assuming that the final crack length is effectively infinite gives²⁰

$$\sigma_f^{n_i-1} = \frac{(n_i - 1) K_{\text{IC}}^2}{(n_i - 2) A_i E Y^2 (1.198) r} \sigma_i^{n_i-2} \nu \quad (11)$$

where ν is the velocity of the faceplates, E and r are Young's modulus and the radius of the fiber, respectively, and σ_f is the failure strength, Y is the crack shape parameter, and σ_i is the inert strength. The humidity dependence of σ_f does not directly give the humidity dependence of A_1 unless n_1 is known and therefore the result depends on the assumption of model 1 being appropriate. If, for example, one calculates an apparent reaction order from the humidity dependence of A_1 , that value might depend on the assumed kinetics model, namely the power law. If one of the exponential forms is assumed the results might well be different. Therefore, it is necessary to compare the results of data analysis using all of the reasonable kinetics models to know whether these results have general significance or merely are predicated on the assumed mathematical form of the kinetics model.

The second reason for considering the different models is that extrapolations to low applied stress and long times to failure for reliability estimates are sensitive to the assumed form of the kinetics model.^{3,4,21} Determination of the kinetics model by measurement of both static and dynamic fatigue over a broad range of failure times in the same environment tends to favor the power law, i.e., model 1.²¹ An alternative way of assessing models is to examine the environmental dependencies. The three models considered here all assume that the stress dependence is described by the n_i ($i = 1, 2, 3$), while the environmental dependence is contained in the A_i , which depends on the humidity explicitly through the functions $f_i(\text{RH})$. In this paper we examine the kinetics models by measuring the strength and dynamic fatigue at various humidities to determine which model is most consistent with the

data, i.e., shows the least dependence of n_i on humidity. Further, we will use the results to determine the reaction order, m , defined by

$$f_i(\text{RH}) = (\text{RH})^m \quad (12)$$

While the humidity dependence of the strength of fiber has been studied elsewhere,^{10,11,22} none of the results are interpreted in terms of kinetics models. The data are generally sparse and only consider polymer-coated fiber. Since the presence of the coating may perturb the kinetics, we will present results not only for coated but also for bare fiber.

III. Experimental Procedure

Optical fibers with three different polymer coatings were used in this study. One specimen was a standard telecommunications fiber (125 μm diameter glass) covered with a UV-curable polyurethane-acrylate with an overall diameter of 250 μm . The other two coatings were a silicone (261.5 μm overall diameter on 140 μm diameter glass) and a polyimide (245 μm overall diameter on 220 μm diameter glass); the polyimide coating is used where high temperatures are encountered (up to $\sim 200^\circ\text{C}$). The acrylate coating was stripped off the fiber to obtain the bare fiber specimens. The coating was removed by immersion in $\sim 200^\circ\text{C}$ sulfuric acid for 30 s followed by rinsing in water, and then acetone. Stripping in this way does not degrade the strength of the fiber provided sufficient care is taken both while stripping and during subsequent handling and testing.²³

The fiber strength was measured at five different faceplate velocities (1, 10, 100, 1000, 5000 $\mu\text{m/s}$) using a two-point bending apparatus.²⁴ The strength was measured in different humidities by allowing the coated fiber to equilibrate overnight in the appropriate environment. In earlier work we have shown that the strength stabilizes within a few hours after the fiber is placed in the test environment.^{16,17} Twenty samples were broken at each faceplate speed. At the lower speeds, up to 10 specimens could be broken simultaneously by supporting the fibers between multigrooved faceplates.²⁵

No equilibration is needed for bare fibers since the glass surface is immediately in contact with the humid environments. Bare fibers must be tested one at a time using faceplates without grooves to avoid abrasion damage.²⁴ Since the bare fiber is delicate and more time-consuming to test, only 10 samples were broken at each speed.

All fibers were broken in a temperature and humidity controlled chamber. The temperature was held at $25.0 \pm 0.1^\circ\text{C}$ and the humidity in the range of 20% to 95% was controlled to within $\pm 1\%$.

The strength data were fitted to each of the kinetic models, and the fatigue parameters, A_i and n_i , were determined using a computer program. The main reason the power law (Eq. (1)) is used so widely is that it is comparatively simple to extract analytic expressions for fatigue behavior under simple loading conditions. In contrast, the exponential forms (Eqs. (6) and (10)) are not analytically integrable for dynamic fatigue (constant rate of loading). Fitting to experimental data was therefore achieved by numerical integration of Eqs. (1), (6), or (10) from $K_{\text{I}} = 0$ to K_{IC} , together with a least-squares algorithm. A key feature of the fitting program that distinguishes it from earlier work³ is that the shape of the minimum in the residue is used to estimate the confidence limits for the fit parameters together with their correlation.^{21,26} Throughout this work, reasonable values for key parameters were assumed: $K_{\text{IC}} = 0.75 \text{ MPa}\cdot\text{m}^{1/2}$, $Y = 1.16$,²⁷ and $\sigma_i = 12 \text{ GPa}$.⁹ The values of the n_i are sensibly independent of these parameters; the values of the A_i are not independent, but while their magnitudes do depend on the values chosen, the trends observed with humidity do not change. Therefore, all of the conclusions drawn from this work are independent of these parameter values. All error bars presented here represent a 95% confidence interval.

In this numerical analysis we have assumed that the fatigue strength for a given loading rate and humidity is entirely controlled

by fatigue crack growth as given by either model 1, 2, or 3. The loading rates used in this work are much higher than those thought to be necessary to observe the influence of threshold behavior on the fatigue strength²⁸ and are much lower than those necessary for region II crack growth behavior to be significant.²⁹

IV. Results and Discussion

The dynamic fatigue data for each fiber are shown in Fig. 1. The Weibull moduli for the strengths of these fibers were ~ 50 corresponding to a dispersion in the strength of $\sim 2.5\%$. Figure 2 summarizes the strength of bare and coated fibers as a function of relative humidity. These data were found by interpolating a linear regression fit to the results of all five faceplate speeds to a speed of 37.5 $\mu\text{m/s}$.³⁰ This speed is chosen since it corresponds to that used by Duncan *et al.*¹⁰ The relationship between the strength and humidity is nonlinear, both on this linear graph and on a semilog plot. Figure 2(a) shows data for the bare and acrylate-coated fiber and compares them to the earlier results of Duncan *et al.*¹⁰ All three sets show the same trend with humidity. For clarity, data for the polyimide- and silicone-coated fiber are shown separately in Fig. 2(b). The results for the bare and acrylate- and polyimide-coated fibers agree well with the results of Duncan *et al.*¹⁰ Interestingly, there is no difference in behavior between the bare and coated fiber, except for the silicone coating. Even though the strength of the silicone-coated fiber is consistently higher than the rest of the fibers, the strength still follows the same trend, i.e., decreasing with increasing humidity. The reason for high-strength behavior of the silicone-coated fiber is not known. This coating could not be stripped in hot acid so it was not possible to directly compare the bare and coated strengths for this particular fiber.

The fatigue parameters, n_1 and A_1 , found by fitting model 1 to the humidity data shown in Fig. 1, are graphed in Figs. 3 and 4, respectively. n_1 shows a systematic decrease with humidity for the bare and coated fibers, while the values of $\log A_1$ (solid circles) are roughly constant. If the power law is considered as anything other than purely empirical, the common assumption that n_1 is effectively a material constant while A_1 contains the humidity dependence is clearly wrong. The trends observed in Figs. 3 and 4 are modest compared with the size of the error bars. However, this is deceptive since the trends in the raw data (Fig. 1) are clear; namely, the slope systematically changes with relative humidity. The error bars are large because the values of A_i and n_i are strongly correlated. Since the models all assume that the n_i are constant, we found values for A_1 assuming a fixed value for n_1 which is calculated from a weighted average of the values in Fig. 3. This forces all of the environmental dependence into A_1 . This is a weak constraint since it uses an underlying assumption of the models, i.e., that the n_i are independent of the humidity. The result of this constraint is shown in Fig. 4 (open circles). The error bars on $\log A_1$ are substantially smaller and better represent the uncertainty. If the kinetics model successfully describes the effect of both humidity and loading rate, the constrained and unconstrained values should be similar. However, Fig. 4 shows substantial discrepancy between the constrained and unconstrained values of $\log A_1$. Again, model 1 therefore does not give a consistent description if it is assumed n_1 is constant.

The fatigue parameters for models 2 and 3 are shown in Figs. 5 through 8. Model 2 shows the least dependence of n_i on humidity; the constrained and unconstrained values of $\log A_2$ show essentially identical behavior. This is consistent with the underlying assumptions of this model. Model 3 shows some discrepancy between constrained and unconstrained $\log A_3$ values, though not as severe as for model 1.

(1) Reaction Order

The reaction order, m in Eq. (12), was calculated by linear regression from the data in Figs. 4, 6, and 8; the results, shown in Table I, are given for both the constrained and unconstrained values of $\log A_i$. Most of the constrained and unconstrained values are significantly different though there is more similarity in the

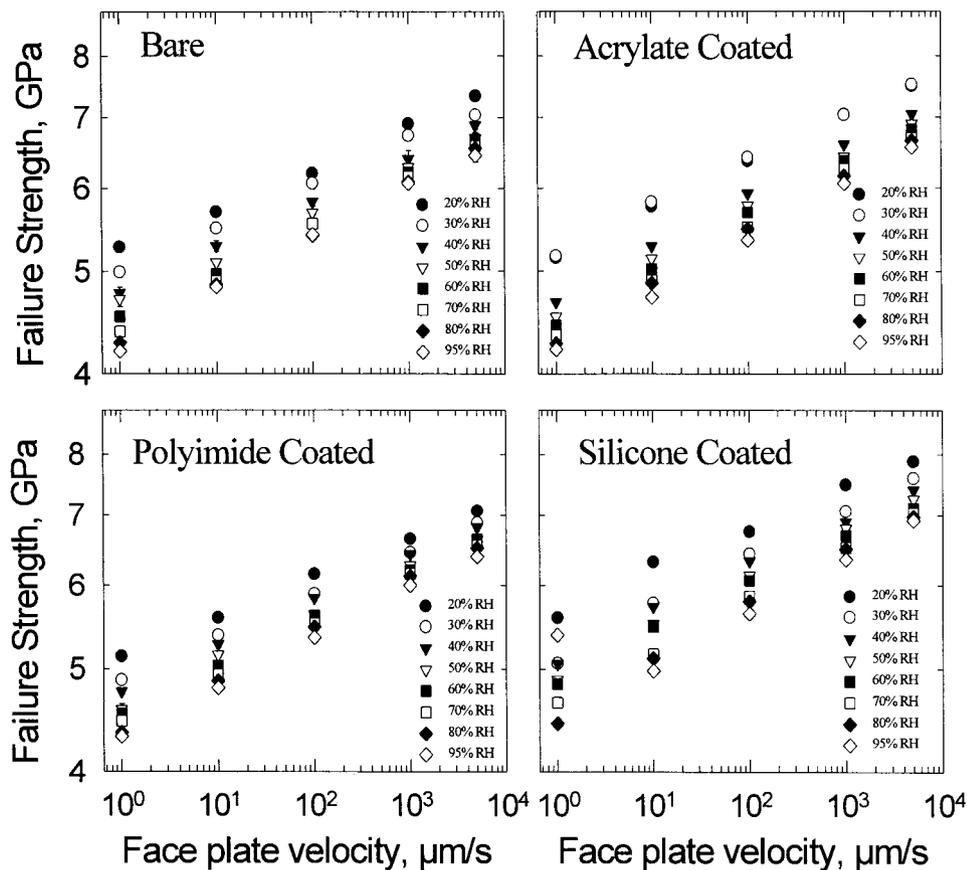


Fig. 1. Strength as a function of faceplate velocity for the four fibers studied at eight different humidities.

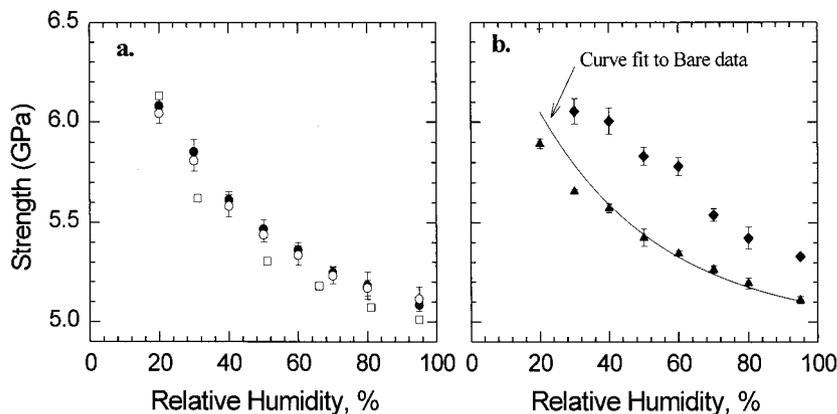


Fig. 2. Strength as a function of relative humidity calculated for a faceplate velocity of 37.5 μm/s: (a) Data for (○) bare fibers, (●) acrylate-coated fibers, and (□) strength data calculated from Duncan *et al.*¹⁰ for silicone-coated fiber. (b) Data for (▲) polyamide and (◆) silicone-coated fibers compared to the bare data.

values for model 2. However, all models and all specimens give similar values of m between 2.0 and 2.5 when the A_i are constrained, but for the most part give substantially different values for the unconstrained A_i . This clearly shows that calculations of a reaction order from strength data must be performed with care. The results may be dependent upon which kinetics model is assumed. We show here, at least in the humidity range studied, that the reaction order is independent of the assumed kinetics model *only* if a constant value of n_i is assumed, *even* if it is observed to vary with the environment.

From Table I, the reaction order for the constrained data is around 2. This value is in agreement with the high-humidity data ($\geq 5\%$) of Duncan *et al.*,¹⁰ who analyzed their data assuming a power law, and also compares reasonably favorably with the value

of 2.5 obtained from direct measurements of crack growth rates from indentation cracks.⁸ The simplest interpretation of a second-order reaction is that two water molecules take part in the rate-determining step, which seems unlikely. Alternatively, the strength of silica decreases with pH,^{31–34} indicating that the glass is reacting with OH⁻. Assuming that some dissociation of an adsorbed water layer occurs, we may consider the following equilibrium:



with an equilibrium constant

$$K_1 = \frac{[\text{H}^+][\text{OH}^-]}{[\text{H}_2\text{O}]} \quad (14)$$

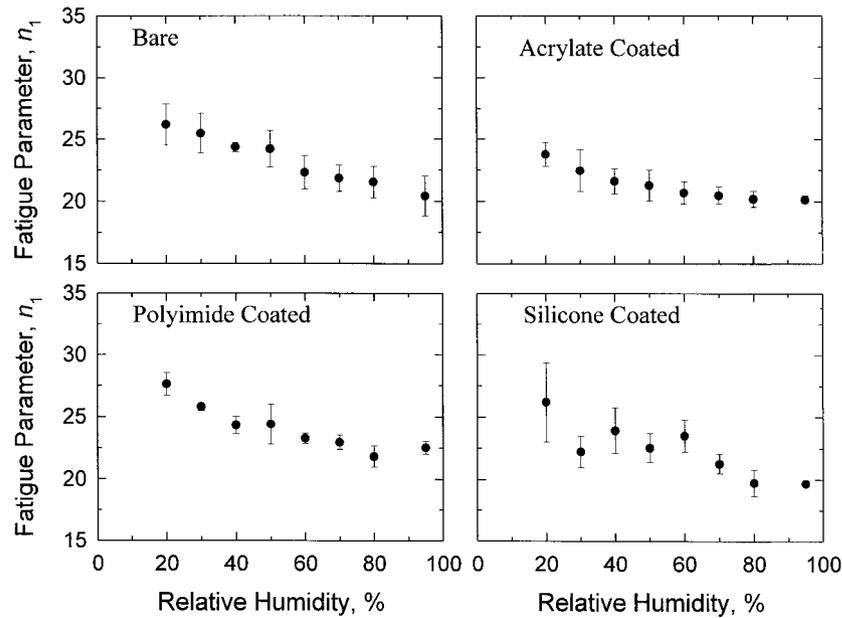


Fig. 3. Fatigue parameter, n_1 , vs relative humidity for bare and coated fibers.

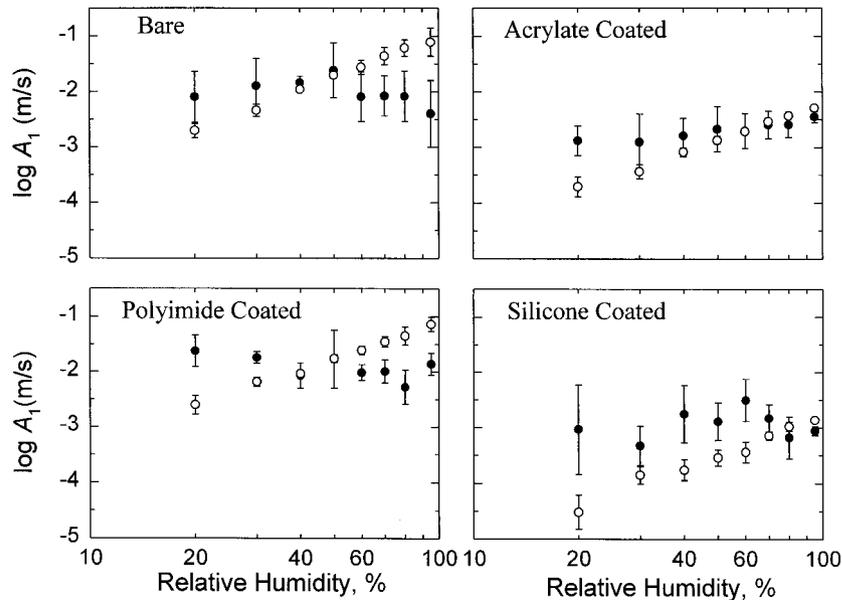


Fig. 4. $\log A_1$ vs relative humidity using (●) unconstrained and (○) constrained values for n_1 for bare and coated fibers.

The hydronium ion forms from the proton:



$$K_2 = \frac{[\text{H}_3\text{O}^+]}{[\text{H}^+][\text{H}_2\text{O}]} \quad (16)$$

Eliminating $[\text{H}^+]$ from Eqs. (14) and (16) gives

$$[\text{OH}^-] = \frac{K_1 K_2 [\text{H}_2\text{O}]^2}{[\text{H}_3\text{O}^+]} \quad (17)$$

if it is assumed that the reaction rate is first order in hydroxide and independent of $[\text{H}_2\text{O}]$ then

$$A_i \propto [\text{OH}^-] \propto \frac{K_1 K_2 [\text{H}_2\text{O}]^2}{[\text{H}_3\text{O}^+]} \quad (18)$$

i.e., it would appear second order in water for a constant pH. The actual reaction mechanism, while not known, is likely to be more complex. Also, fatigue strength measurements in aqueous environments indicate a weaker dependence on $[\text{OH}^-]$.³⁵

(2) Quality of Fit

Thus far, each model has been discussed in terms of how well it incorporates the dependence on the test environment, i.e., humidity. It is also important to examine how well each model fits the dynamic fatigue data, irrespective of the environmental conditions. Our results were found to be consistent with earlier, more extensive experiments,²¹ which showed a poor fit for model 3 but a better fit for model 1 than model 2.

(3) Comparison with Slow Crack Growth Data

The fits to the dynamic fatigue data have been used to predict the slow crack growth velocity as a function of applied stress

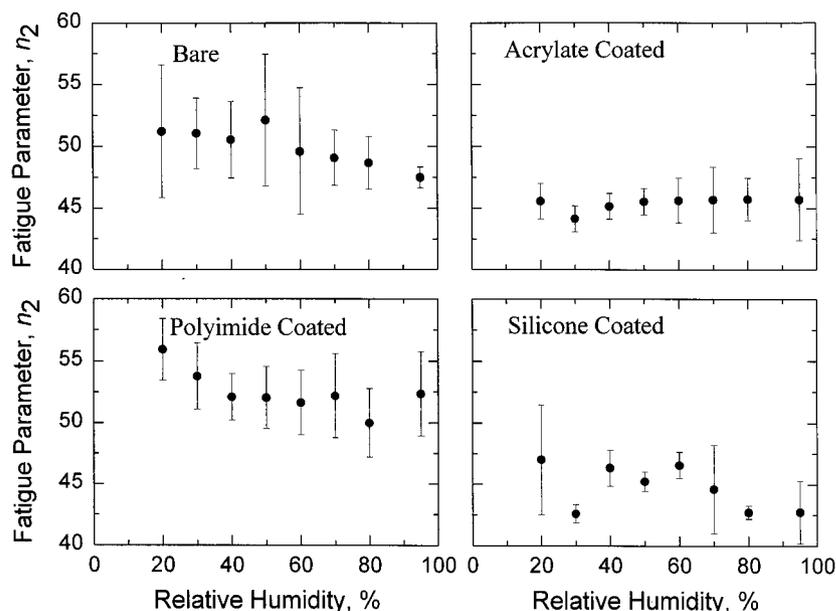


Fig. 5. Fatigue parameter, n_2 , vs relative humidity for bare and coated fibers.

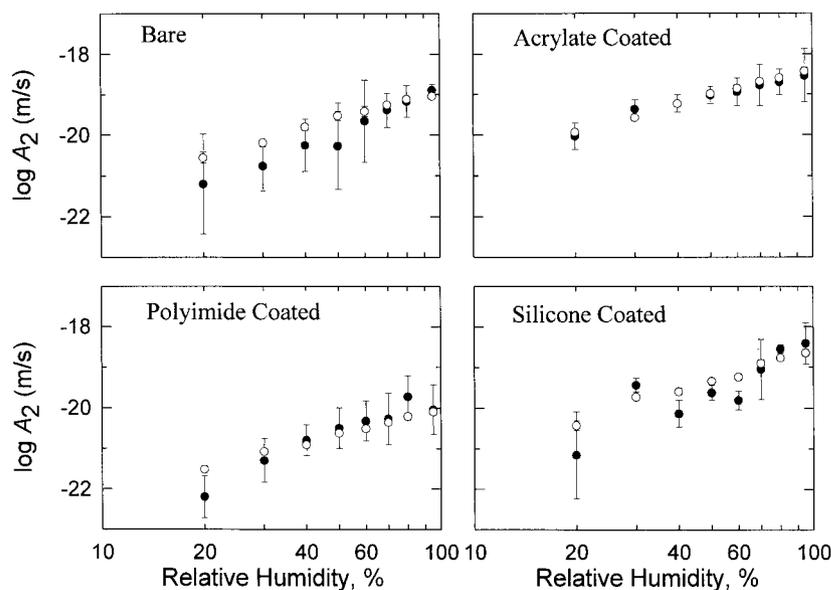


Fig. 6. $\log A_2$ vs relative humidity using (●) unconstrained and (○) constrained values for n_2 for bare and coated fibers.

intensity (V - K behavior). Until this point, the values chosen for three physical parameters ($Y = 1.16$, $\sigma_i = 12$ GPa, $K_{IC} = 0.75$ MPa·m^{1/2}) have not been important since they only affect the magnitude of the values of the A_i but do not influence their trend with humidity; varying the values of these parameters within reasonable limits does not change any conclusions drawn thus far. However, when predicting the V - K behavior from dynamic (or static) fatigue data, these parameters all need to be known with precision. None of these parameters are accurately known—especially Y and σ_i for pristine fiber since the nature of the defects is not well understood. Figure 9 shows V - K predictions from the dynamic fatigue of the acrylate-coated fiber at 25°C, 60% humidity for both (Fig. 9(a)) the default values above and (Fig. 9(b)) for $Y = 2.06$ and $\sigma_i = 11$ GPa. These modest changes in the parameters that are well within reasonable bounds produce more than an order of magnitude change in crack velocity at a given stress intensity.

Literature data for slow crack growth in silica are not extensive. Figure 9 shows data from three sources (heavy lines). Sackaguchi

*et al.*⁷ present data in a limited velocity range for bulk silica for various humidities; the trend for 20°C, 60% humidity is shown. Also shown are results from Michalske *et al.*³⁶ in room-temperature water. Muraoka and Abé³⁷ measured the velocity of small indentation cracks in silica fiber, for both as-indent and annealed cracks in 25°C, 60% humidity. The results for the annealed cracks, which should have no residual stresses from the indent, are shown in Fig. 9. However, the accuracy of these data is not clear given the annealing might affect the behavior, and the shape parameter for their cracks might be erroneous because the cracks are not short compared to the fiber diameter.

Comparison of the experimental data shows that the crack velocity in the liquid environment is approximately an order of magnitude faster than in humid air. A similar result has been found for pristine silica fiber. Matthewson and Yuce³⁸ found the time to failure in static fatigue was shorter in 85°C water than in 85°C, 85% humidity air by a similar factor.

Comparing the experimental results with the predictions from the fiber behavior yields little in the way of definitive conclusions.

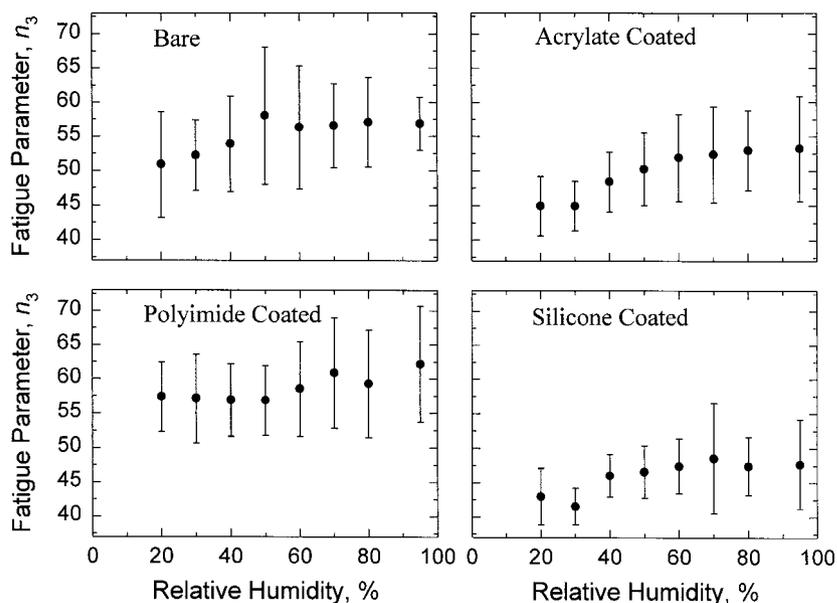


Fig. 7. Fatigue parameter, n_3 , vs relative humidity for bare and coated fibers.

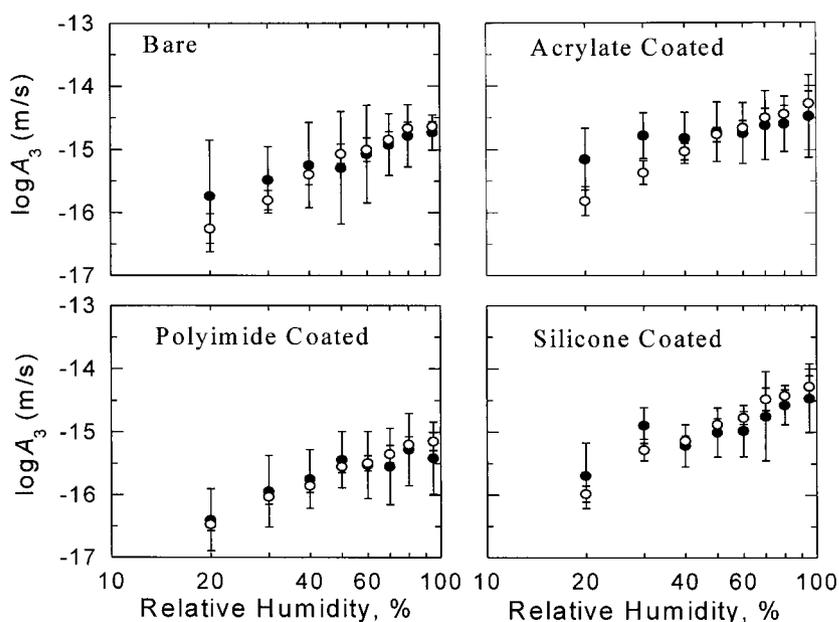


Fig. 8. $\log A_3$ vs relative humidity using (●) unconstrained and (○) constrained values for n_3 for bare and coated fibers.

Any of the models can give good agreement with experiment over a limited range of K_I if suitable but reasonable values for parameters are chosen. The slow crack growth data do show some curvature in the log–log plots in Fig. 9 and therefore tend to favor the exponential forms, model 2 or 3.

V. Conclusions

In general, coated and bare fibers give similar humidity dependence of their strength and fatigue. The polymer coatings studied here have a negligible effect on the kinetics of the fatigue as long as the fibers are properly equilibrated in the test environment before testing. Even though the three coatings studied here have a negligible effect, this may not be the case for other coatings. Therefore, it is always useful to compare coated and bare data to distinguish if there is a coating effect.

The results also show that fatigue data must be analyzed carefully in order to extract valid values for parameters such as the

apparent reaction order for humidity. In particular, the values obtained may depend as much on the kinetics model assumed as anything else. A protocol is outlined for calculating the reaction order independently of the kinetics model, which involves constraining the value of n to be constant. The strength degradation kinetics for the bare and coated fibers are approximately second order with respect to humidity.

While in earlier work the power law was found to give the best fit to fatigue data, it is shown here that the power law gives a poor and inconsistent description of the humidity dependence. The simple exponential model, $\exp(K_I)$, gives a moderately good fit to fatigue data, and the best description of the humidity data. The quadratic exponential, $\exp(K_I^2)$, gives a poor fit to fatigue data. Based on this and earlier results, the simple exponential model gives the best description of the overall behavior. It should be noted that lifetimes predicted by extrapolating from accelerated laboratory data are significantly shorter when using the exponential than the commonly used power law.

Table I. Reaction Orders (m) Calculated for Each Model Using Unconstrained and Constrained Values for the n_i

Model		m^\dagger			
		Bare	Acrylate	Polyimide	Silicone
1	Unconstrained	-0.48 ± 0.77	0.70 ± 0.18	-0.51 ± 0.47	-0.13 ± 0.84
	Constrained	2.49 ± 0.15	2.16 ± 0.12	2.19 ± 0.26	2.25 ± 0.27
2	Unconstrained	3.68 ± 0.27	1.98 ± 0.40	3.41 ± 0.73	2.63 ± 1.83
	Constrained	2.18 ± 0.26	2.31 ± 0.14	2.10 ± 0.16	2.42 ± 0.34
3	Unconstrained	1.51 ± 0.16	0.75 ± 0.30	1.53 ± 0.52	1.18 ± 0.82
	Constrained	2.29 ± 0.34	2.19 ± 0.24	2.02 ± 0.19	2.45 ± 0.27

[†]Uncertainties are 95% confidence intervals.

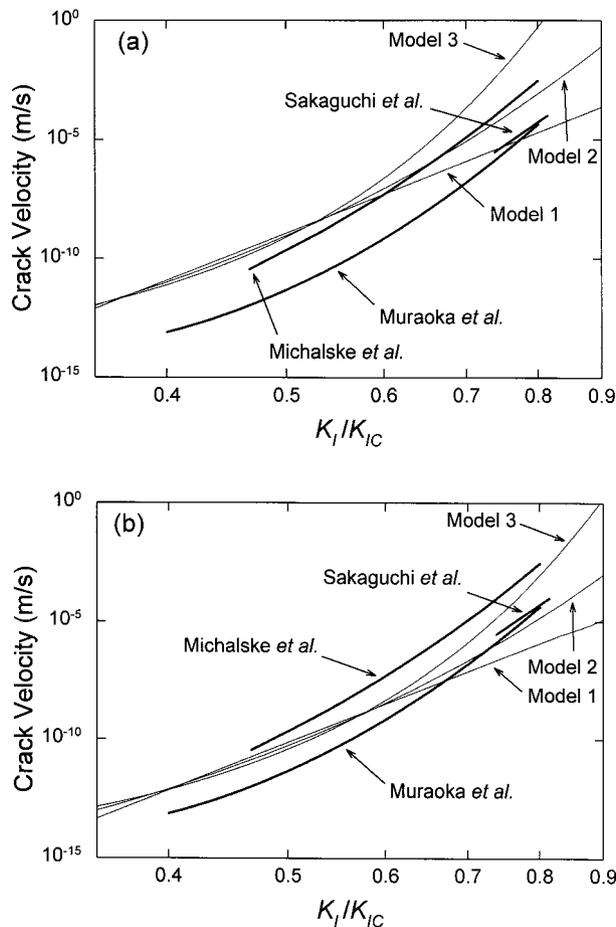


Fig. 9. Slow crack growth velocity predicted for models 1, 2, and 3 from dynamic fatigue data for the acrylate-coated fiber at 60% RH and 25°C. Calculations are made with (a) $Y = 1.16$, $\sigma_i = 12$ GPa and (b) $Y = 2.06$, $\sigma_i = 11$ GPa. Predictions are compared to experimental data from Refs. 7, 37, and 36.

Comparison between published slow crack growth velocity data and predictions from the fiber fatigue tend to favor the exponential forms. However, the comparison is not particularly useful since some of the physical parameters are not accurately known. In essence, the flaws leading to failure in pristine fiber are different from and are many orders of magnitude smaller than the macroscopic cracks used for velocity measurements. It is therefore not clear how applicable the results presented here are to silica with well-defined cracks.

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