MECHANICAL RELIABILITY PREDICTIONS: AN ATTEMPT AT MEASURING THE INITIAL STRENGTH OF DRAW-ABRADED OPTICAL FIBER USING HIGH STRESSING RATES

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ABSTRACT

The strength of draw-abraded optical fiber was found to level off at stressing rates in the range of 200,000 kpsi/s (1400 GPa/s). Non-power law curvature at high speeds can be explained with a two-region power law crack velocity model. Modeling of this data enables one to incorporate complex stress/time events into lifetime predictions.

INTRODUCTION

Mechanical reliability predictions for optical fiber are based on knowledge of the initial strength and strength degradation over time from this initial value due to subcritical crack growth. The initial strength or inert strength is the strength in the absence of fatigue or subcritical crack growth. The modeling of strength degradation from this initial value is often thought of in terms of short and long-term loading events such as proof testing and in-service life, respectively. There is considerable data on the long-term fatigue of optical fiber, but significant work remains on initial strength measurements and strength degradation during short-term loading events like proof testing and fiber processing. The purpose of this paper is to report on a recent attempt at measuring the initial strength of flaws near the proof stress level and their growth during short-term loading events.

BACKGROUND

An excellent summary of initial strength measurement techniques and results up to 1995 was published by Kurkjian et al.[1] These authors concluded that measurements at liquid nitrogen temperatures have inherent difficulties and high speed testing methods need further development. Testing in vacuum is noted as a simple and direct method of measuring the initial strength. Since this publication there have been two notable publications on initial strength measurements, both using the high-speed test method.

Gouronnec and Ev Anno[2] reportedly achieved stressing rates as high as 1000 GPa/s on as-drawn fiber. An example of their data shown in typical dynamic fatigue fashion is shown in Figure 1.

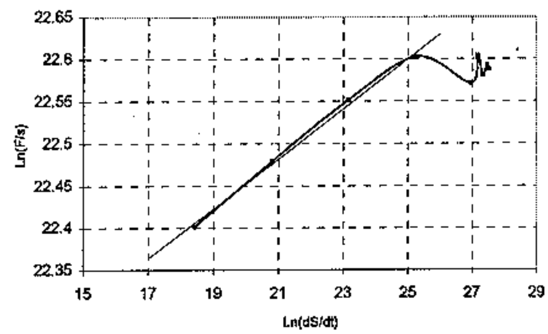

Figure 1. Strength versus stressing rate data on as-drawn fiber from reference 2.

They measured the initial strength of as-drawn fibers to be in the 6 to 7 GPa range which is similar to that measured in tension by Svensson et al.[3] It has already been shown that these strengths are lower than one would expect for as-drawn fiber.[4] In addition, the shape of the dynamic fatigue curves at the highest rates in Figure 1 show the strength to decrease at successively higher rates. It is not clear if this is the behavior of the fiber or the test technique. Whereas the results in Figure 1 are for as-drawn fiber, the interest here is the behavior of flaws near the proof stress level. It is these flaws that are affected by proof testing and in-service stresses.

The other study consisted of high speed tensile testing of draw-abraded fiber.[4] Loading rates on the order of those experienced by fiber during proof testing were achieved. Of particular interest was the non-linear dynamic fatigue behavior at the higher loading rates. This is shown in Figure 2.

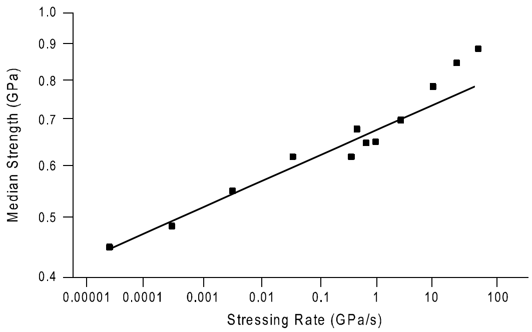

Figure 2. Dynamic fatigue plot showing curvature at high stressing rates from data in reference 4.

Evidence of reaching the initial strength level was not observed; namely, a leveling off of the strength at the highest rates. Here we seek to extend this work to see if new high-speed test methods can shorten test times enough to avoid the effects of fatigue.

EXPERIMENTATION

Draw-abraded fiber was used in this study because it is identical to standard fiber in composition and manufacturing process while providing a high density of flaws near the proof stress level. The fiber used in this study was a standard single-mode silica-clad fiber coated with CPC6 coating.

High speed testing was used in this attempt at measuring the initial strength for three reasons. First, the data obtained in successively faster stressing rates allows one to "fill in" strength values between those obtained at usual test speeds and the highest speeds. This allows observation and modeling of flaw growth behavior at speeds found during proof testing and fiber handling. Second, testing at high speeds allows one to maintain the same test environment for all tests. This reduces the possibility of other phenomenon affecting the measured strength as is the case for testing at low temperatures.[1,6] Some have hypothesized that the environment plays a role in the establishment of the initial strength,[4] however, this remains to be proven.[1] Third, there have been many new developments in the area of high speed testing that hold promise for reaching and detecting the initial strength of optical fiber.

In this study three loading techniques were used to generate strength values over nearly eight decades of stressing rates. For the slower speed tests, 0.005 to 100 kpsi/s (3x10-5 to 0.7GPa/s), a conventional universal testing machine[α] was adapted with eight load cells and corresponding capstans. Thus, instead of the usual single fiber testing method, eight fibers could be tested in tension simultaneously. This greatly decreases the overall experimental time at the slower rates. A belt slide apparatus similar to that described in reference 3 was used to generate stressing rates ranging from 150 to 7000 kpsi/s (1 to 50 GPa/s). For the highest load rates, a pneumatic piston[β] was fitted with a gas reservoir at the inlet to provide a ready volume of air for the piston chamber. Nitrogen pressure levels ranging from 40 to 95 psi (280 to 665 kPa) were used to achieve stressing rates ranging from 53,000 to 2.2×10^5 kpsi/s (365 to 1530 GPa/s).

A gauge length of 0.5 m was used for all tests. A small amount of slack in the fiber gauge length was introduced at the higher loading rates to allow the test device to reach its maximum speed before fiber loading.

Of primary importance to high speed testing is the mass of the fiber attachment system and the method of data acquisition. All tests on the belt slide and air piston were performed with two load cells in place, a conventional lightweight strain gauge load cell[χ] and a piezoelectric load cell.[δ] The piezoelectric load cell was chosen such that drift and resonant frequency problems were minimized for the range of failure times used in this study.

Fiber was attached to both load cells by carefully taping the fiber to a nylon screw that was threaded directly into the load cell.

[α] Instron Corp., Canton, MA.
[β] Airmatic-Allied, Inc.
[χ] Interface, Inc., Scottsdale, AZ.
[δ] Kistler Instrument Corp., Amherst, NY.

The total weight of the screw and tape was approximately 1 gram. Fiber pullout from the tape was not an issue since the maximum loads were sufficiently low with the abraded fiber.

The data acquisition rate for the strain gauge load cell at the highest speeds was 40,000 HZ. At the highest loading rate the failure times were on the order of 10^{-3} seconds; and therefore, the number of data points using this load cell were considerable. The signal from the piezoelectric load cell, on the other hand, was monitored at $5x10^6$ HZ using a digital oscilloscope. This yielded several thousand data points per test at the highest speed. Figure 3 shows a typical loading curve for both load cells operating at the fastest loading rate.

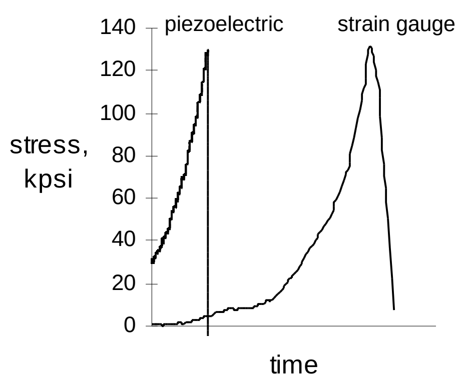

Figure 3. Loading curves for both load cell types at the fastest loading rate.

The curvature shown in Figure 3 is typical for strength test optical fiber; and therefore, the stressing rate was taken from the last 20% of the loading region. The temperature and humidity were maintained at 22°C and 50%, respectively. A minimum of 15 specimens per loading rate were tested. Only failures in the gauge length were accepted. All Weibull slopes, m, were in the 10 to 20 range.

RESULTS AND DISCUSSION

The strength versus stressing rate is plotted in typical dynamic fatigue fashion in Figure 4. In Figure 4 only the middle two or three data points are shown for each stressing rate.

At the lower rates a typical n value in the low 20s is found. As the stressing rates increase the local slope decreases somewhat before increasing significantly at the higher rates. The last two rates have nearly the same strength values.

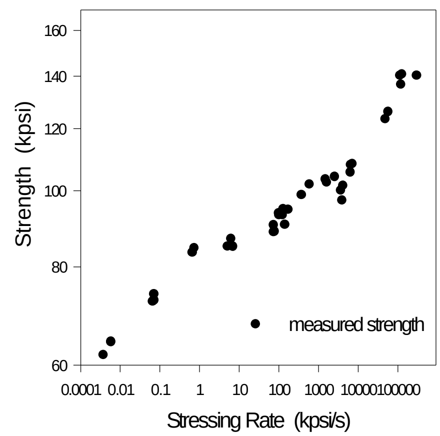

Figure 4. Middle strength values for a wide range of stressing rates in an ambient environment using draw-abraded fiber.

There are two possible explanations for the same strength values at the two fastest loading rates. Either the limit of the load detection system has been reached or strengths very close to initial strength values have been achieved. The failure times at these rates are well within the capability of the piezoelectric load cell and with the low mass attachment it is believed that the measurements are accurate.

Comparing the strengths at the highest rate to those at a typical loading rate of 6 kpsi/s (0.04 GPa/s) reveals approximately 40% strength degradation from the initial strength. This is in the range of what has been found for tests in liquid nitrogen environments. Note that in this comparison one must take into account the dependence of strength at low temperatures.[1,5]

The curvature in the dynamic fatigue plot is expected. A model for such behavior has been proposed where region II type crack growth is incorporated into the basic power law crack growth model. This was first suggested by Fuller et al.[7] for proof test events and recently was used to model optical fiber strength data obtained at high speeds.[8] The basic model is shown in Figure 5 below in terms of crack velocity, V, and stress intensity factor, K_I.

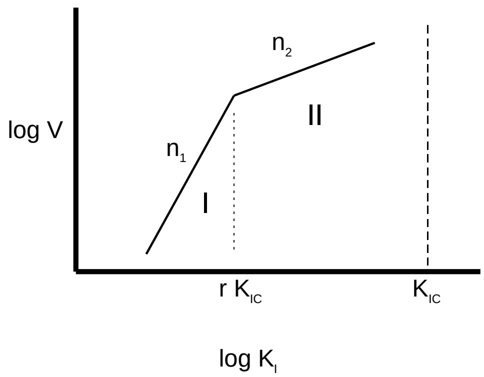

Figure 5. Schematic of the two region power law crack velocity model.

The basic mathematical form of the two region power law model is,

$$\frac{da}{dt} = V_c r^{(n_2-n_1)}\left(\frac{K_I}{K_{IC}}\right)^{n_1} \text{ for } K_I \le rK_{IC} \quad \text{(1a)}$$

$$\frac{da}{dt} = V_c \left(\frac{K_I}{K_{IC}}\right)^{n_2} \text{ for } K_I > rK_{IC} \quad \text{(1b)}$$

A more detailed description this model is given in reference 8. The data in Figure 4 were analyzed using this model and the results are shown in Figure 6.

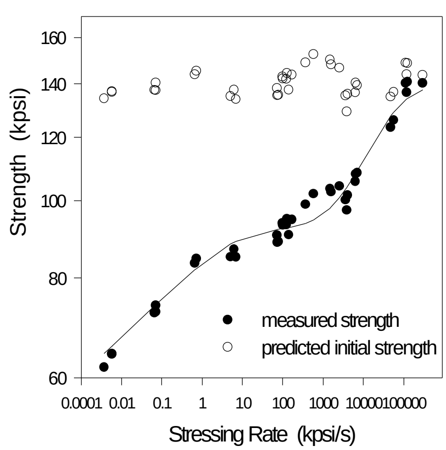

Figure 6. Predicted initial strengths and measured strengths using the two-region power law model from reference 7. the predicted measured strength using this model is shown as a line.

The open circles in Figure 6 represent the predicted initial strength for each measured strength value. The line in this figure is the predicted measured strength using the same model. There is good agreement between the predicted measured strength and the measured values with this model. This suggests that the curvature in the data can be explained using existing crack growth models.

The fact that the measured strength can be modeled over a wide range of stressing rates allows one to model a variety of fiber processing events. For example, proof testers and many coloring machines often operate at speeds well into the non-linear region of the data in Figure 4. The loading rates and dwell times on these machines can be more accurately modeled than in the past. Furthermore, this data allows one to model successive stressing events with greater accuracy.

SUMMARY

Strength testing over eight decades in stressing rates was performed on draw-abraded silica-clad fiber. A maximum stressing rate of 220,000 kpsi/s was achieved by using an air piston. The strength leveled off approximately at a level 60% above typical testing values. The curvature in the dynamic fatigue plot was modeled using a two-region power law model. Such data combined with a proper model can be used to model multiple stress events.

ACKNOWLEDGEMENTS

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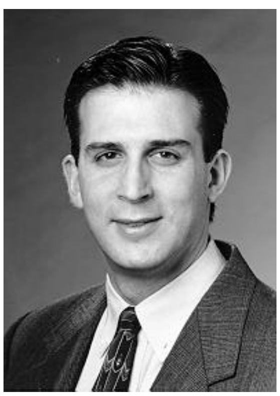

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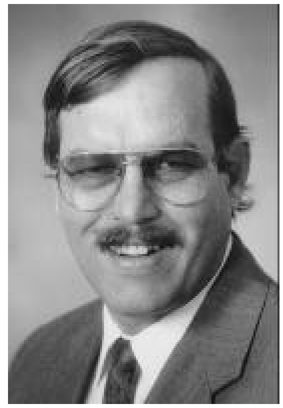

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