Fatigue behavior of silica fibers of different strength

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ABSTRACT

It was obtained that $(t_s S_i^2)$-(σ_s / S_i) and (σ_d / S_i)-(σ' / S_i^3) are universal coordinates for presentation of static fatigue and dynamic fatigue data respectively. Usage of these coordinates helps to correctly compare the results of tests of different kinds of fibers (strong and weak) regardless of the initial defect size. Presentation of the dynamic fatigue data for pristine and indented fibers in universal coordinates shows a very similar behavior of both fiber types in spite of their difference in strength.

Keywords: fiber strength, static fatigue, dynamic fatigue, fiber reliability

1. INTRODUCTION

A single-region power law for crack growth into silica glass is widely used to predict the lifetime of optical fibers in communication networks. This model is based on numerous investigations of fatigue of high-strength fibers (5-6 GPa). However, long-term reliability of optical fibers in communication systems depends on large flaws, which can survive proof testing at a level of ~0.7 GPa. A few earlier works showed that the fatigue behavior of low-strength fibers was similar to the behavior of high-strength fibers (more or less linear log-log graphs with fatigue parameter n~20)[1-4]. Fresh results of dynamic fatigue measurements in a wide region of stressing rates[5-7] demonstrate a complicated multi-region behavior of the fatigue curve for abraded and indented fibers. In a previous work[8], a different behavior of dynamic fatigue curves was predicted, owing to a different size of the initial defects. The aim of this report is to find a method for correctly comparing fatigue data of weak and strong fibers.

In earlier papers[9,10,11], a so-called "universal fatigue curve" was used to correlate the results of static fatigue measurements for different kinds of samples. Coordinates $(t/t_{0.5}) - (\sigma/S_i)$ were used for this purpose, where t is the time-to-failure under stress σ, S_i is the initial inert strength of the sample, $t_{0.5}$ is the time-to-failure at $\sigma = 0.5S_i$. There exist several reasons to continue research in this direction:

- the above "universal" presentation was deduced using simple power or exponential laws of crack growth;
- it is useful only for static fatigue measurements;
- it requires knowledge of an additional parameter $t_{0.5}$.

Therefore, it is desirable to solve the problem of correlating fatigue measurements of different fibers in a more general form.

2. THEORY

Stress concentration in a crack tip is characterized by stress intensity factor K_I, which is defined in terms of applied stress σ and crack length a

$$K_I = Y\sigma\sqrt{a}\ , \tag{1}$$

where Y ~ 1 is a constant determined by the crack geometry.

An effect of subcritical crack growth or fatigue in brittle materials, such as glass or ceramics, is usually described as a dependence of crack growth rate on stress concentration in the crack tip:

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$$\frac{da}{dt} = \Phi\left(\frac{K_I}{K_{IC}}\right), \tag{2}$$

where K_{IC} is the critical stress intensity factor depending on the properties of a specific material. Power or exponential laws are often used in equation (2), but we will deal with an arbitrary positive function defined in the range $0 < K_I < K_{IC}$.

One more term to be introduced is inert (or intrinsic) strength S:

$$S = \frac{K_{IC}}{Y\sqrt{a}}. \tag{3}$$

This is the strength in the absence of slow crack growth or fatigue. The strength in liquid nitrogen is close to the inert strength.

Two types of tests are widely used to observe fatigue effects; namely, static and dynamic. In the first case, constant stress σ_s is applied to the sample, and time-to-failure t_s is measured. In the second test, an increasing load with a constant loading rate $\sigma' = d\sigma/dt$ is applied to the sample, until it breaks at some load σ_d. The dependence of time-to-failure on the applied stress is called static fatigue, the dependence of breaking strength on the loading speed is called dynamic fatigue. The both dependencies can be derived from equation (2), taking into account that the point of $K_I = K_{IC}$ is the point of failure.

For *static fatigue* ($\sigma = const. = \sigma_s$) the following two equations can be taken into account

$$k = \frac{K_I}{K_{IC}} = \frac{\sigma}{S}, \tag{4}$$

and

$$a = \left(\frac{k \cdot K_{IC}}{Y \cdot \sigma}\right)^2. \tag{5}$$

As the result, equation (2) can be transformed into

$$d\left(\frac{k \cdot K_{IC}}{Y \cdot \sigma_s}\right)^2 = \Phi(k) \cdot dt. \tag{6}$$

At the beginning of the test the initial crack size is a_i, the corresponding initial inert strength is S_i, and the following relation is created:

$$k_i = \frac{\sigma_s}{S_i}. \tag{7}$$

Thus,

$$dt = \left(\frac{K_{IC}}{Y \cdot k_i \cdot S_i}\right)^2 \frac{dk^2}{\Phi(k)}. \tag{8}$$

The solution of equation (8) is

$$t_s \cdot S_i^2 = \left(\frac{K_{IC}}{Y \cdot k_i}\right) \cdot \int_{k_i}^{1} \frac{2k \cdot dk}{\Phi(k)} = \Psi(k_i) = \Psi\left(\frac{\sigma_s}{S_i}\right). \tag{9}$$

In the case of a single-region power law, the well-known solution of equation (8) for $S_i^{n-2} >> \sigma_s^{n-2}$ is

$$S_i^2 \cdot t_s = B \cdot \left(\frac{\sigma_s}{S_i} \right)^{-n}, \qquad (10)$$

where n and B are the fatigue parameters.

For *dynamic fatigue* ($\sigma = t \cdot \sigma'$), equation (2) can be transformed into

$$d\left(\frac{k \cdot K_{IC}}{Y \cdot \sigma} \right)^2 = \Phi(k) \cdot \frac{d\sigma}{\sigma'}. \qquad (11)$$

By introducing a term $v = (\sigma / S_i)$, we obtain

$$\left(\frac{K_{IC}}{Y \cdot S_i} \right)^2 \cdot d\left(\frac{k}{v} \right)^2 = \Phi(k) \cdot \frac{S_i}{\sigma'} \cdot dv \qquad (12)$$

or

$$\frac{\sigma'}{S_i^3} \cdot d\left(\frac{k^2}{v^2} \right) = \left(\frac{Y}{K_{IC}} \right)^2 \Phi(k) \cdot dv, \qquad (13)$$

where k lies in the range from 0 to 1, and v from 0 to (σ_d / S_i). The analytical or numerical solution of equation (13) will give the following dependence:

$$\frac{\sigma_d}{S_i} = \chi\left(\frac{\sigma'}{S_i^3} \right). \qquad (14)$$

For a single-region power law, the solution for $S_i^{n-2} >> \sigma_d^{n-2}$ is

$$\frac{\sigma_d}{S_i} = \left(B \cdot (n+1) \cdot \frac{\sigma'}{S_i^3} \right)^{\frac{1}{n+1}}. \qquad (15)$$

Thus, if cracks of different size have the same dependence of the crack growth rate on the stress intensity factor (eq. (2)), all the results of static fatigue tests lie on one curve in $(t_s S_i^2)$-(σ_s / S_i) coordinates. Accordingly, all the dynamic fatigue results lie on one curve in (σ_d / S_i)-(σ' / S_i^3) coordinates. In other words, universal static and dynamic fatigue curves can be drawn in the coordinates discussed above.

3. EXPERIMENT AND DISCUSSION

We used the above considerations of the universal static and dynamic fatigue curves to compare the results of tensile testing of optical fibers of different strengths in a wide range of loading speeds. Earlier we reported[7] testing indented fibers. Because the strength distribution of samples damaged by a cube corner indenter was very narrow, those results enabled us to observe unambiguously a non-linear character of dynamic fatigue, which consisted of at least three regions (Figure 1). Strength in liquid nitrogen was also measured for those samples.

For comparison, the same tests were performed in the present work on strong (pristine) fibers. To avoid the problem with fixing the sample at high loads, a specially drawn 40 μm fiber was used. Figure 2 shows only single-region curve obtained for a strong fiber. To understand the difference between dynamic fatigue of indented and strong fibers, experimental results have to be plotted in universal coordinates. Unfortunately, we failed to measure the inert strength of the strong fiber. So, we used the value of 12 GPa proposed earlier in literature[12] to characterize the inert strength of a pristine fiber.

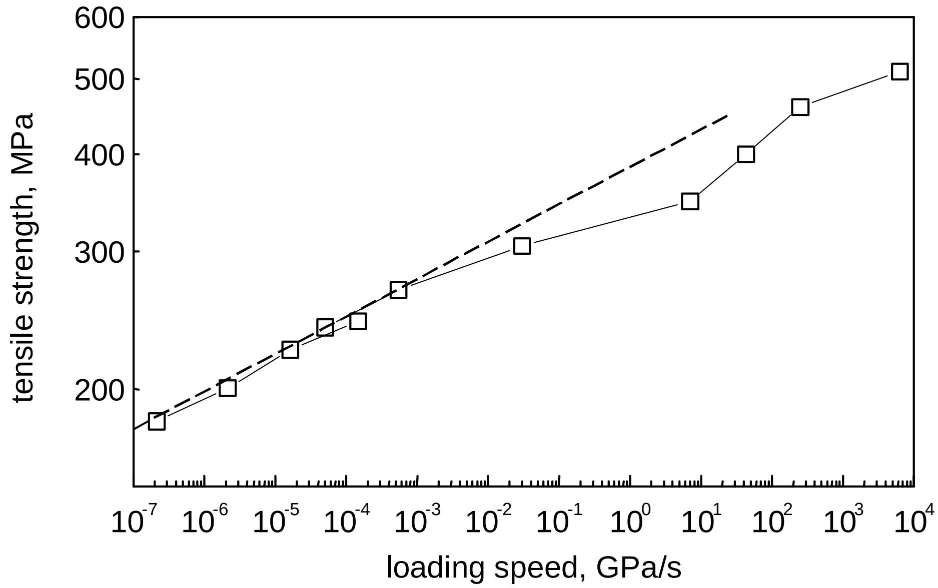

Figure 1. Results of tensile testing of indented fibers[7]. Dashed line corresponds to n = 21.

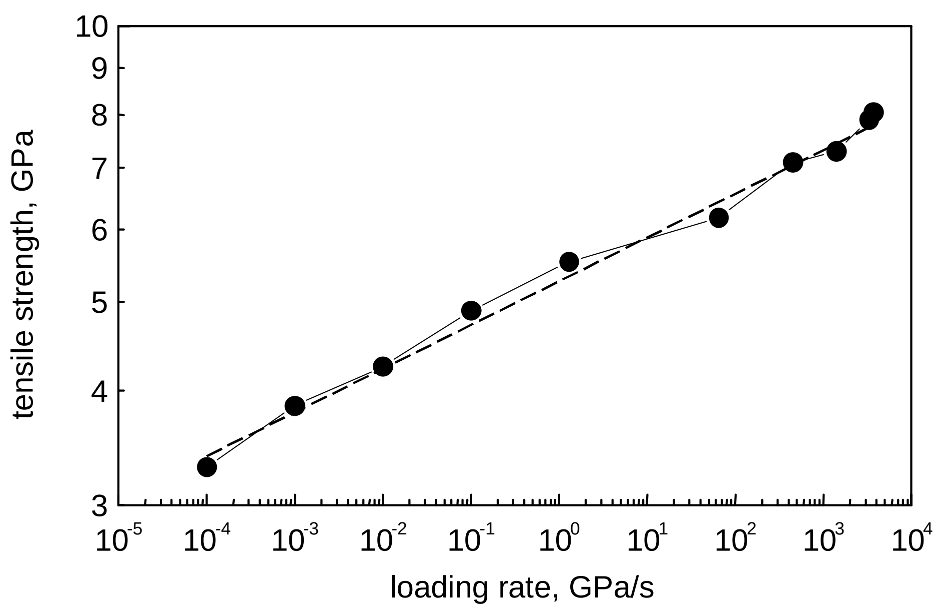

Figure 2. Results of tensile testing of high-strength fibers. Dashed line corresponds to n = 21.

Figure 3 shows that in universal coordinates, the results for both strong and weak fibers practically lie on the same curve. This graph demonstrates that owing to factor S_i^3, the experimental data for a strong fiber corresponds to a much slower testing speed in the case of weak fibers. This is the reason for the absence of non-linearity at the higher speeds of the dynamic fatigue curve for strong fiber. Some discrepancy is observed only for the highest loading speed. This is a problem for further investigations. The region of high loading speeds is extremely important for estimation of the fiber strength after proof test and further reliability calculations. On the other hand, most measurements of fatigue parameters by the fiber suppliers and users were performed on strong fibers. Therefore, the conclusion that fatigue behaviors of strong and weak fibers are very close, at least in region 1 (responsible for long-term fatigue behavior), could also be very important for the fiber lifetime estimation. Systematic experiments should be performed on fibers with different types and sizes of defects to gain deeper understanding of the fatigue behavior at high and low loading speeds. In particular, inert strength of pristine fiber should be measured directly, influence of possible difference in geometry factors *Y* for different types of defects and different behavior of fatigue curves for pristine and weak fibers at the highest loading speeds should be studied carefully.

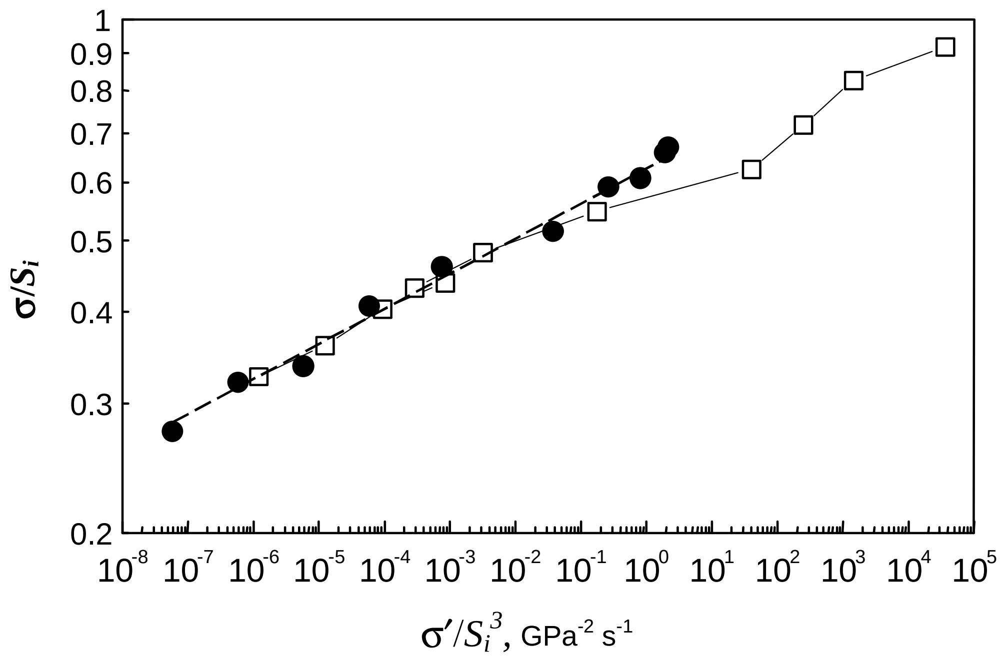

Figure 3. Joint plot of tensile strength of indented (open squares) and high-strength (black circles) fibers. Dashed line corresponds to n = 21.

4. CONCLUSION

It was obtained that $(t_s S_i^2)$-(σ_s / S_i) and (σ_d / S_i)-(σ' / S_i^3) are universal coordinates for presentation of static fatigue and dynamic fatigue data respectively. Usage of these coordinates helps to correctly compare the results of tests of different fibers (strong and weak) regardless of the initial defect size. Presentation of the dynamic fatigue data for pristine and indented fibers in universal coordinates shows a very similar behavior of the both fiber types in spite of their great difference, when the results are plotted on ordinary coordinates.

5. AKNOWLEDGMENTS

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