Application Note: Fiber Strength and Reliability

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Revised 02/06/2015

Glass Strength

A material is said to be brittle if it breaks before undergoing significant plastic deformation, which is permanent and non-recoverable. A brittle material is characterized by the dependence of its mechanical strength on the severity of its surface flaws, which cause localized stress intensification. The plastic deformation reduces the intensified stress, resulting in a material property that depends more on its intrinsic properties than on its surface quality. As a typical brittle material, silica glass has a breaking strength that is dictated by the severity of its surface flaw, not by the intrinsic strength of Si-O bonds. As one would expect, the breaking strength of glass varies widely, since the surface flaws or micro-cracks can be inherent to the glass or a result of external damage. The Griffith theory of brittle fracture can describe the strength of silica glass. In this theory, the stress intensity factor or fracture toughness, K_I, is introduced to describe the local stress intensification by surface flaws or micro-cracks:

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

where σ_a = applied stress;
Y = a geometry factor, ~ 1.16;
C = crack length.

The stress intensity factor, K_I, is a function of the applied stress and flaw size. It increases as the cracks grow larger in size. When K_I exceeds the critical stress intensity factor for the material, K_{IC}, which is a constant and a material property, a crack will propagate rapidly and fracture will occur catastrophically.

K_{IC} = 0.789 MPa $(\text{meter})^{1/2}$ for fused silica

Strength, σ_f, is therefore defined to be the stress at which fracture occurs.

$$\sigma_f = \frac{K_{IC}}{Y\sqrt{C}}$$

This expression of glass strength states quantitatively that the strength of the glass is inversely proportional to the square root of crack length. Using this equation, silica glass containing a largest crack of ~0.8 µm will probably break at an applied stress of 100 kpsi (0.69 GPa).

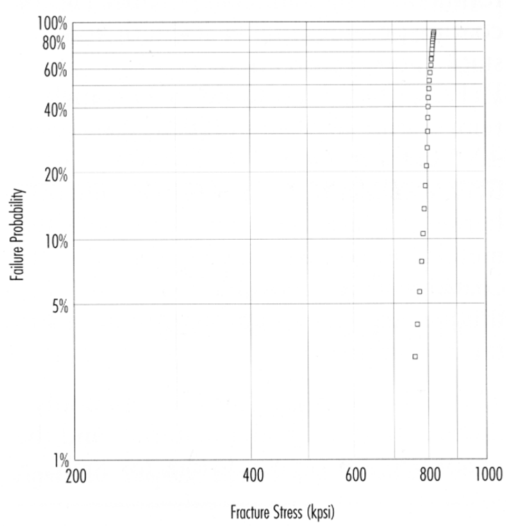
Fiber Strength

A fiber can be viewed as a glass cylinder having an infinite length with a distribution of surface flaws. Therefore the most severe crack will dictate the strength of the fiber, just as a weakest link does to a chain. The strength of fiber is commonly characterized by Weibull Statistics: the Weakest Link Theory.

The most common way to experimentally determine fiber strength and strength distribution is tensile load testing. In this testing, a fiber length is pulled at a given strain rate until the fiber breaks; the stress level at which the fiber breaks is then recorded. After about 20 breaks are recorded, the distribution of strength is normally represented on a chart using *Weibull* statistics. According to a two-parameter Weibull distribution, the distribution of the fiber strength can be easily displayed by plotting lnln(1/(1-F)) vs. $\ln\sigma_f$ as shown in the figure below:

$$\ln\ln\left(\frac{1}{1-F}\right) = m\ln\sigma_f - m\ln\sigma_0$$

where F = the cumulative failure probability
σ_f = breaking stress
m = Weibull slope
σ_0 = Weibull scale



In addition to showing the median fiber strength, the sorted data on a Weibull distribution yields a Weibull modulus or slope. The Weibull modulus m is a measure of scatter in the strength and is inversely related to standard deviation. A fiber with a very broad distribution of strength, indicative of an out-of-control process, may have a Weibull slope in the range of 2.5~20. Alternately, a very tight distribution of breaking strengths will typically have a Weibull slope of 50 or greater. When referring to the strength of a given fiber, very often the median fiber strength and the Weibull modulus will be specified.

<u>Prooftest</u>

To ensure a minimum strength for a fiber with a strength distributed over its length, a fiber is usually dynamically loaded to a predefined stress level over consecutive short lengths to remove weak sections in a process known as prooftesting. This removes flaws larger than a certain size and yields fiber lengths of known minimum strength.

The most common method employs a weighted pulley to stress the fiber to a defined prooftest level (usually 100 kpsi or 0.69 GPa). Variable speed capstans may also be used to apply the same stress level. For certain specialty fibers, a radial prooftester may be used to bend the fiber and impart the required prooftest stress.

Fatigue

The strength of silica optical fiber has not only a distribution, but also a time-dependence. The fiber strength degrades over time due to crack growth that is enhanced by moisture. The degradation of fiber strength over time is known as *fatigue*. The fatigue can be characterized using the fatigue resistance factor, *n* (also known as the "stress-corrosion factor" or the "*n*" value), as defined by the equation below:

$$\left(\frac{\sigma_1}{\sigma_2}\right)=\left(\frac{\dot{\sigma}_1}{\dot{\sigma}_2}\right)^{\frac{1}{n+1}}$$

where σ_1 = breaking stress 1
σ_2 = breaking stress 2
$\dot{\sigma}_1$ = strain rate 1
$\dot{\sigma}_2$ = strain rate 2
n = n parameter or fatigue factor

The fatigue resistance factor, *n*, is determined with tensile load testing by straining the fiber at different rates; the natural logarithm of breaking stress of the fiber is then plotted versus the natural logarithm of strain rate. The slope of the resultant straight line is 1/(n + 1). The *n* value is an important measure of the material's resistance to subcritical-crack growth. That is, the higher the value for *n*, the less sensitive the strength is to change in strain rate.

For this reason, the application stress for most fibers should not exceed 20% of the prooftest level, or around 20 kpsi for fibers normally prooftested to a level of 100 kpsi or greater. In essence, we are making an allowance for strength degradation over time to ensure the fiber will be able handle the lower application stress. At very high strain rates (where the fiber is pulled quickly), the cracks on the glass surface do not have enough time to propagate, resulting in a higher breaking stress. Conversely, at low strain rates, the cracks have more time to grow, and a lower breaking stress results. Drawn on a ln(stress)-ln(strain rate) plot, the slope of the line will determine the *n* value of the fiber.

Lifetime Prediction

Lifetime prediction is not a trivial task as it requires a lot of information about the environment of the specific application, fiber design, and fiber characteristics unique to its manufacturing process. This is especially true for the optical fibers used for harsh environments which are less well under stood than the environment for telecommunication applications.

The following equation is widely used to estimate fiber lifetime for telecommunication applications. Once n value is calculated, desired application stress and the acceptable failure rate are determined, t_f can be calculated.

$$t_f = t_p \left(\frac{\sigma_p}{\sigma_a} \right)^n \left\{ \left[1 - \frac{\ln(1-F)}{N_p L} \right]^{\frac{n+1}{m_d}} - 1 \right\}$$

where

t_f, time to failure (lifetime)

t_p, prooftest time

σ_p, prooftest stress

σ_a, applied stress

F, failure probability

N_p, prooftest break rate

L, fiber length under tension ($L = 0.4 L_B \left(\frac{n m_d}{n+1} \right)^{-1/2}$ for bending)

m_d, Weibull m from dynamic fatigue

Bending

For a fiber in bending, the application stress, σ_{bending} can be calculated using the expression below:

$$\sigma_{bending} = E \left(\frac{r}{R} \right)$$

where E = Young's modulus of silica glass, ~ 72 GPa or ~10440 kpsi
r = fiber radius (glass portion only)
R = bend radius

For example, a fiber with 125 micron diameter and a designed application stress level of 20 kpsi, the bend radius should be no less than 3.3 cm.

Carbon Coating

For certain fibers, a much higher application stress is required. This is particularly true in the specialty applications where sensor fibers may be suspended in oil wells or crammed into tight bends on a fighter jet. As the equations above indicate, one way to extend a fiber's lifetime is to increase the prooftest stress and remove all fiber that falls below the specified prooftest level. However, this is not always practical, especially if long lengths are required. Another option is to increase the n value of a fiber; this can be achieved with *hermetic* coatings.

Hermetic coatings (e.g., carbon) are applied over the glass fiber and, by definition, prevent water from coming in contact with the glass surface. Because crack growth is accelerated by the presence of water, a hermetic fiber will show very little degradation in strength over its lifetime – as such, hermetic fibers usually have n values greater than 100. As the equations above indicate, this has a dramatic effect on both the lifetime and the application stress that can be used on a fiber.

Summary

The varied breaking strength of silica fiber can be attributed to the distribution in flaw severity along the fiber length. Micro-cracks can be inherent to the glass itself or a result of the manufacturing process and handling of the fiber. Fiber strength also degrades with time due to fatigue as a result of crack growth accelerated by interaction with moisture. To reduce the flaw formation and crack growth, freshly made fibers are immediately coated with polymer coating. For fiber users, care should be exercised to minimize the handling, stripping, wiping of bare fibers and exposing them to flames. Fiber strength can be described using Weibull statistics. Proof-testing will eliminate weak sections of the fibers to ensure a minimum strength. The lifetime of fiber in a service environment can be estimated using the fatigue model. To increase fiber lifetime, fibers with higher n values are recommended.