Strength and fatigue measurements using the fibers with laser-induced glass defects

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Received 15 June 1995; accepted 11 August 1997

Abstract

As a result of optical damage the chain of cavities originate along the core of the single-mode fiber. These defects are not influenced by the atmospheric water. We suggest the optically damaged fibers to be a convenient object for the investigation of static fatigue of silica glass at room temperature and a very low level of moisture. Results on the strength and fatigue for fibers with laser-induced glass defects are presented. The atmosphere inside the defects is evaluated to contain water with concentrations approximately equal to that in the fiber material.

1. Introduction

Polymer-coated optical fibers have been widely used in optical communication systems. The mechanical strength and long-term reliability of these fibers are limited by water enhanced stress corrosion of glass. The dependence of time-to-failure $t_5$ on applied stress $\sigma_5$ for the fibers is described by

$$t_5 = B\sigma_5^{-n-2}/\alpha_5^n,$$

where $S$ is the fiber inert strength (i.e. in an inert environment, for instance in liquid nitrogen) and $n$ and $B$ are static fatigue parameters, that depend on the environment. The most important for fiber reliability parameter, $n$, is approximately 20 (under the typical relative humidity of 30–100%). In order to provide the long-term (25–40 yr) lifetime, the polymer-coated fibers should be proof-tested under a load that is 3–4 times the service stress that affects fibers in the cable during the exploitation period. Moreover, recent investigations showed a catastrophic strength decrease of acrylate-coated fibers in water [1,2] which makes the evaluations of the fiber lifetime, based on the static fatigue model, too optimistic.

To avoid the interaction between the moisture and the fiber surface and improve the fiber reliability, various hermetic coatings (such as metal, carbon, etc.) were developed [3–5]. The perfectly hermetically-coated fiber should be fatigue-free, but as shown in Ref. [6], some weak crack growth under stress in dry environment could take place due to thermofluctuations ($n \sim 130–150$). Nevertheless the reliability of a hermetically-coated fiber should be much better than that of a polymer-coated one.
In the case of a real hermetically-coated fiber it is important to be sure that all possible types of defects demonstrate weak fatigue effects. Our previous study presents the results on hermetically-coated fibers with surface defects (scratches and melted-in particles) [7, 8]. It has been demonstrated that these fibers in some cases can display the static fatigue with parameter \( n \approx 20-40 \). This behavior is due to the presence of a small amount of water adsorbed on the fiber surface under the metal coating [7] and the cracking of the carbon coating around the defects [8]. As a result of investigation, additional requirements to the coating application processes were formulated.

Other possible types of defects, such as internal particles and bubbles, have not been practically studied thus far. Because of the isolation of these defects from the atmosphere, it is unnecessary to apply the hermetic coating to the fibers that are damaged internally. However, the problem of obtaining a large group of defective samples with a narrow strength distribution remains. For example, for a 10%-spread in strength values, an approximately seven-fold spread in measured time-to-failure occurs if \( n = 20 \). For the same spread in strength a 45-fold increase in measured time-to-failure occurs if \( n = 40 \) and if \( n = 100 \) the time-to-failure spread increases \( \sim 14000 \) times. Under these circumstances, any method used to obtain samples with internal defects of approximately equal size as well as the investigation of the fatigue properties of these samples become the matter of importance and interest. In this paper we demonstrate that the optical damage of the single-mode optical fibers is a perfect method for producing samples with defects required to perform the fatigue measurements. All the defects (cavities) that are formed in the fiber core have approximately the same size as the core diameter.

2. Experimental

A series of experiments were reported on catastrophic optical fiber breakdown by laser radiation in the 0.45–1 \( \mu \text{m} \) spectral region with the power density in the core about 3–10 MW/cm\(^2\) [9–11]. Depending on the fiber’s characteristics, as a result of such damage the regular bullet- or channel-shaped cavities which have dimensions of the order of a few wavelengths, originate in the core of the waveguide. These cavities are filled with a solid or gaseous substance. The observation of the change in the refractive index in areas surrounding the fiber core that occurs in this process is reported by Ref. [11]. The mechanism of damage is apparently stipulated by a number of non-stationary processes of radiation absorption in the glass and plasma, glass heating and heat conductivity. The possibility of obtaining the same result by the simple heating of the fiber was discussed in Ref. [12]. The authors of Ref. [12] explain their results by the thermal energy release during the exothermic reaction between the core glass germanium oxygen-deficient defects and oxygen, that quickly diffuses into the fiber at temperatures up to 700–1000\( ^\circ \text{C} \). Thus several versions of explanation of the damage mechanism exist [9–12]. However, the melting and evaporation of glass of the fiber core is a known experimental result.

In our experiments a single-mode germanosilicate core optical fiber was used (8 mol\% GeO\(_2\), \( \lambda_{\text{cut-off}} \approx 1.1 \mu \text{m} \)). The propagation of the damage wave was caused by launching approximately 600 mW of average power of radiation of a cw Ar-laser (\( \lambda = 0.488 \) or 0.514 \( \mu \text{m} \)) within the fiber and a premeditated contamination of the fiber’s rear end [11]. Typical damage tracks are shown in Fig. 1.

The measurements of the strength and dynamic fatigue were performed on the universal testing machine Instron 6022. When taking the measurements at liquid nitrogen temperature the polymer coating of the fiber was etched, in the region between the clamps of the testing machine. The reason for this is because the Young modulus of the polymer coating

![Damage tracks along the core of a single-mode optical fiber originate as a result of the damage wave propagation.](image-url)
increases abruptly at the temperature of liquid nitrogen, which can in turn misrepresent the experimental results.

Although the two-point-bending method [13] was proven to be very useful for the measurements at these low temperatures, we were not able to take advantage of it for the following reason. The core of the fiber, that is precisely the part of the fiber that gets damaged as a result of the optical breakdown, remains unstressed under bending. Therefore the bending strength of optically damaged fibers do not differ from that of undamaged ones.

3. Results and discussion

Fig. 2 demonstrates the results of the fiber strength measurements for optically damaged fibers at room temperature and in liquid nitrogen. It can be seen from the fractographic analysis of the broken parts of the fiber (Fig. 3), that it is precisely the cavities in the fiber core that lead to fiber failure. Experiments performed in Ref. [14] demonstrate that such cavities in silica glass are described by an overstress coefficient equal to 2–3 and therefore their influence on the tensile strength of the high-strength polymer-coated fibers at room temperature must be significant. For this reason an approximately tenfold decrease of the inert strength observed with the damaged fibers in comparison to the ‘fresh’ ones may be explained by high roughness (or even cracking) of the inner surface of these cavities. At the same time the scatter of values of the tensile strength is rather small (Weibull parameter, $m \sim 20$). This permits the...
use of optically damaged fibers for the dynamic fatigue investigation, when fiber samples are tensile tested at different loading speeds and the difference in the tensile strength is measured. This method is equivalent to the direct static fatigue measurements, when the constant load is applied to the sample to measure the time-to-fatigue. Both methods allow the fatigue parameters $n$ and $B$ to be obtained [15].

It should be noted that significant difference exists between the strength of the damaged fibers in liquid nitrogen and that at room temperature. A considerable shift of the Weibull plots at different testing speeds is also noteworthy. The static fatigue parameters $n = 44$, and $B = 2 \cdot 10^{-7}$ GPa$^2 \cdot s$ can be calculated from our experiments and the expression for dynamic fatigue

$$\sigma_d^{n+1} = B S^{n-1} (n + 1) \frac{\partial \sigma}{\partial t},$$

where $\sigma_d$ is the tensile strength at room temperature, $\frac{\partial \sigma}{\partial t}$ is the loading speed and $S$ is the inert strength.

Fig. 4 demonstrates this result, showing that $n$ for optically damaged fibers has an intermediate value between $n = 20$, for silica fibers in moist atmosphere and $n = 150$ for fibers in inert atmosphere at room temperature (thermo-fluctuation mechanism of failure). This result may be explained by some presence of water within the cavities inside the fiber core. Approximately the same values of $n$ were obtained when we investigated the metal coated fibers, which had some water adsorbed at the silica surface before the fiber was coated [7].

The level of humidity within the cavities’ atmosphere can be estimated by the experimental relationship between the silica fiber strength and the humidity of the surrounding medium [16]:

$$\sigma (\text{RH}) = \sigma (100\%) \sigma \left( \frac{\text{RH}}{100\%} \right)^{-\alpha},$$

where RH is relative humidity and $\alpha \approx 0.1$. From our experiments $\sigma (\text{RH}) / \sigma (100\%) \approx 1.45$. We estimate the humidity of the fiber core cavities’ atmosphere as $\sim 2.5\%$ using Eq. (3). Such a rate of moisture might seem rather high for the fiber that contains $\sim 1$ ppm of water. However, assuming that

Fig. 4. The dependence of the tensile strength on the testing speed for laser-damaged single-mode fibers (dynamic fatigue): (a) in liquid nitrogen, (c) at room temperature. For comparison the dependence for (b) the thermofluctuation model and (d) for the fibers with surface defects are presented. RH: relative humidity, $n$: fatigue parameter.
all the water from the volume of glass that is equal to that of a cavity remains inside of the cavity after the propagation of the damage wave, the same level of moisture (of about 2%) is calculated, which agrees with our estimation.

4. Conclusion

The laser-induced fiber damage leads to the decrease of fiber strength while the bullet- or channel-shaped cavities that are formed as a result of a damage wave propagation are not exposed to the outer atmosphere. The inner atmosphere of the cavities contains water with concentrations approximately equal to that in the fiber material. This is the reason for a relatively low value of obtained fatigue parameter, $n = 44$, in comparison with the ultimate $n \sim 130–150$ under water-free conditions. It can be seen that the inner cavity-like defects of the hermetically coated fibers can significantly reduce fiber reliability. Therefore additional requirements on preforms for hermetically-coated fibers should be formulated.

Our experiments demonstrated that optically damaged fibers are convenient objects for the investigation of the static fatigue in silica glass at room temperature and very low rates of moisture (0.1–1% RH). This type of defect cannot be easily produced by other methods.

References