STRENGTH AND DYNAMIC FATIGUE CHARACTERISTICS OF AGED FIBER

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Abstract

An experiment was performed to examine the strength and dynamic fatigue performance of polymer coated optical fiber after various aging conditions including: 30-day hot-humid zero stress aging, shelf life aging, and cyclic hot-humid aging. When compared to as-received fiber, the strength and stress corrosion resistance (n_d) increased with both 30-day hot-humid aging and shelf life aging. The strength and fatigue values of the 2-year-old shelf life fiber showed a strong resemblance to the values from the 30-day hot-humid aging experiment. Testing was also performed at 50% R.H. and 100% R.H. to determine how the test environment affects the mechanical properties of the fiber. Strength values at 100% R.H. were lower compared with values tested at the standard 50% R.H. This is consistent with changes in the B parameter. For the as-received fiber, there was no significant change in n_d between 50% and 100% R.H., however the aged n_d appeared to be slightly higher at the 100% R.H. condition compared to the 50% R.H. environment. It was also determined that cycling humidity and temperature during aging had no impact on strength or fatigue of the fibers tested.

Introduction

Zero stress aging of optical fiber has been and continues to be of interest in understanding the mechanical behavior during the fiber's lifetime. The aged fiber performance is commonly measured by performing dynamic strength and fatigue measurements after exposure to a hot-humid environment for a period of time. This condition is designed to simulate a lifetime of harsh aging in the field. The ability of a fiber to withstand the environments in which it is exposed and maintain its pristine strength is of importance to insure continued functionality and handleability in the field. Several studies have examined the effect of aging on fiber strength. Aged glass surfaces have been examined using Atomic Force Microscopy (AFM).[1] It was determined that strength degradation was directly related to pits which developed on the glass surface. The roughness was attributed to dissolution of silica during the aging process. This resulted in high stress concentrations in the pitted regions, thus resulting in lower strength values. It is important to note that although strength reduction can occur due to zero stress aging, the strength levels are not reduced to levels where long-term reliability is an issue. Recently, it has been suggested that cyclic aging of fibers between wet and dry conditions may also lead to strength reduction.[2]

It has been determined that water penetrates through typical polymer coatings rapidly, in as little as ten minutes.[3] If moisture readily reaches the glass surface and leads to pitting, it would be expected that strength degradation would consistently occur with standard accelerated aging tests. However, studies have shown that strength degradation does not always occur after aging, and strength and dynamic fatigue values can even increase after aging.[4] The secondary coating chemistry, which can act as a moisture barrier, has been shown to play a role in the susceptibility of a fiber to strength reduction.[5] Clearly, a dependence between aging and coating type is present.

It is the purpose of this paper to investigate the strength and fatigue behavior of pristine fiber as it is exposed to various environments and conditions. Zero stress aging at 85°C/85% R.H. for 30 days was performed to understand how the strength and fatigue performs after hot-humid exposure. The test was performed at both 50% R.H. and 100% R.H. environments to determine the influence of the test environment on dynamic stress corrosion parameters (n_d and B). Also performed was a time after draw study to determine how the fiber's mechanical properties vary with shelf life. Finally, the cyclic aging study was performed to see how the fiber performs when altered between a hot-humid and a room temperature-dry environment.

Experimental Procedure

All fibers tested were standard dual-polymer coated silica optical fibers. Samples were aged 30-days using a standard temperature-humidity chamber. Fiber was aged on 6-inch diameter glass spools. The tension on these spools is minimal and 'zero stress' aging is assumed. Cyclic aged samples were alternated between an 85°C/85% R.H. environment and a 23°C/dry environment each day for 60 days. Both the aged and the cyclic aged samples saw a total of 30-days in 85°C/85% R.H. for comparison purposes. The dry environment was set to 0% R.H., however in actuality the humidity varied between 10 and 15%. Time after draw samples were tested at various shelf life intervals up to 3 years. The samples were stored on standard shipping reels in a constant 23°C/50% R.H. environment.

Dynamic fatigue testing was performed on the samples using four strain rates: 0.025%/min., 0.25%/min., 2.5%/min, and 25%/min. Samples were tested using the following two methods: a horizontal ganged rotating-capstan tester, and a vertical stationary-capstan tester. Each apparatus contains sixteen separate load capstans and corresponding load cells to minimize the time required to perform the tests. The testing was performed in a controlled 23°C±2°/50%±5% R.H. environment. The 100% R.H. environment was achieved using a water bath and cover over the horizontal test bench. Actual stressing rates were recorded, and along with the breaking stress, were used to calculate fatigue parameters of each fiber tested. Statistical Weibull strength information was obtained by examination of one or more of the strain rates tested.

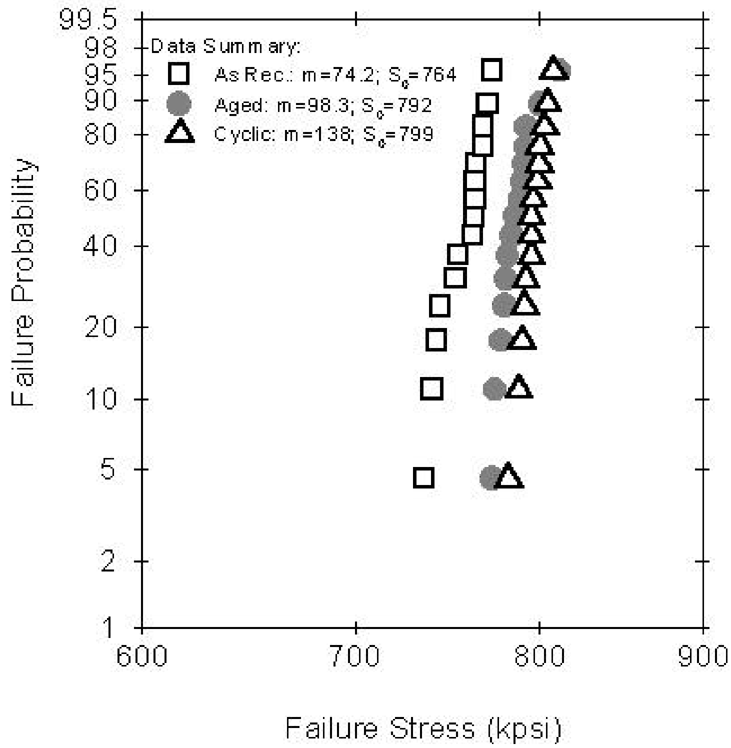

Figure 1. Weibull plot showing strength distributions for as-received, 30-day aged, and cyclic aged fibers.

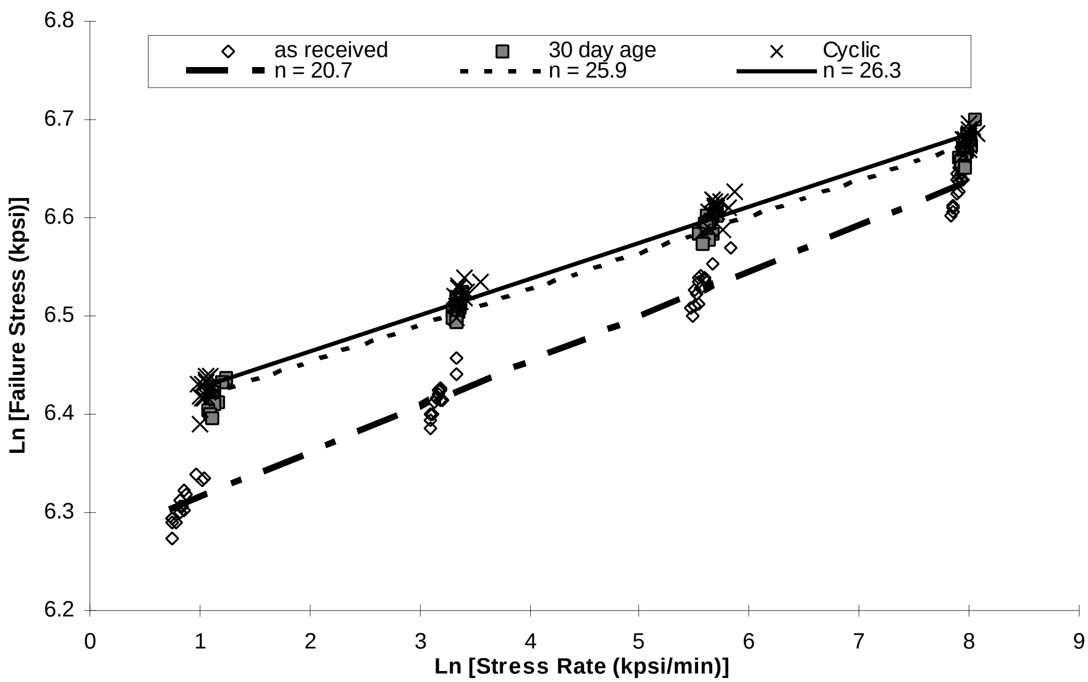

Figure 2. Dynamic fatigue plots for as-received, 30-day aged, and cyclic aged fibers.

Results

Weibull statistics were performed on the cyclic aging fibers before and after exposure to aging. Figure 1 shows as-received, 30-day aged, and cyclic aged strength distributions. Weibull slopes and failure stresses for each condition remain high with no signs of strength degradation. The cyclic aged data mirrors the 30-day aged data, showing a slight increase in strength compared to the as-received fiber. Two separate fibers tested showed the same trend with cyclic aging. Of the fibers tested, it is evident that cycling heat and humidity during an aging test has no impact on the strength, and that the effects of aging are cumulative based on the time spent in the hot-humid condition.

Little change in the dynamic fatigue performance was noted between aged and cyclic aged fibers. Figure 2 shows dynamic fatigue plots for as-received, aged, and cyclic aged fibers. The dynamic fatigue values (n_d) for three fibers are shown as a function of environment in Figure 3. The n_d value is inversely related to the slope of a line fit though the ln[failure stress] versus ln[stress rate] data:

$$n_d = (1/\text{slope}) - 1 \qquad (1)$$

In the fibers tested, the stress corrosion resistance increased after aging in hot-humid conditions. The n_d values observed after aging were roughly 3 to 4 points higher than the n_d values measured in the as-received conditions. The increase in strength observed with aging coincides with the decrease in fatigue (increase in n_d). Figure 2 shows that failure stresses increase more rapidly at slower stressing rates than at faster rates, which results in a higher calculated n_d value. In all the fibers tested no significant strength degradation was present.

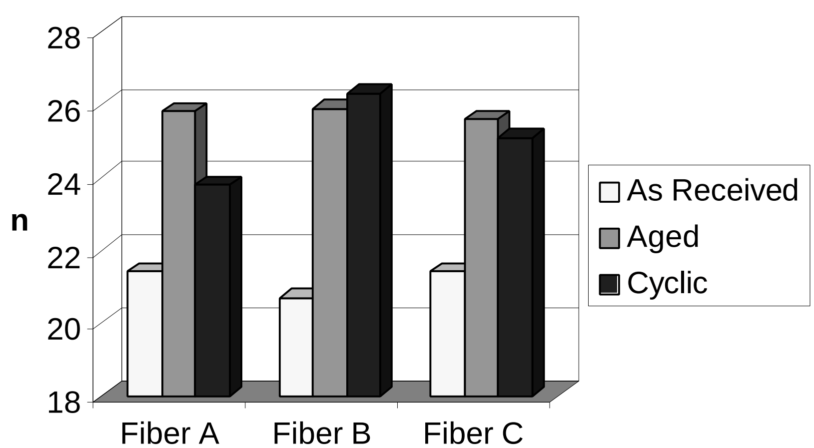

Figure 3. Dynamic fatigue parameter (n_d) as a function of aging environment for three fibers.

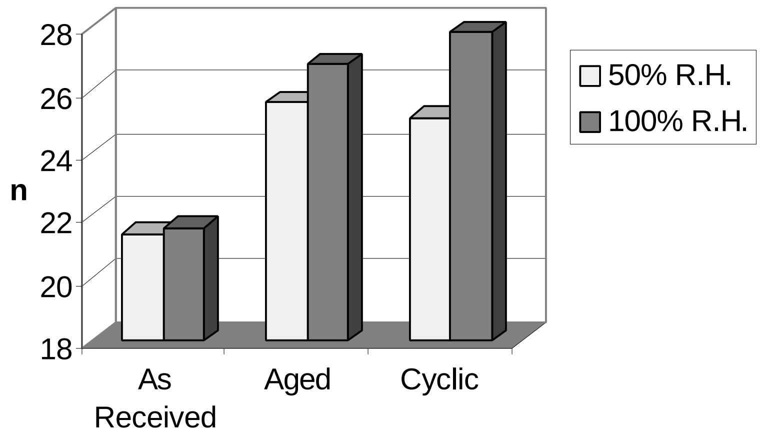

Figure 4. Dynamic fatigue parameter (n_d) as a function of relative humidity.

Dynamic fatigue testing was performed on one fiber at both the standard 50% R.H. and at 100% R.H. Figure 4 shows the relationship of n_d with relative humidity. No correlation between n_d and relative humidity was observed for the as-received fibers. The aged and cyclic aged samples showed a slightly higher n_d value for 100% R.H. compared to 50% R.H., however this could be within the variability of the measurement. Further studies need to be performed to determine if in fact the aged n_d is influenced by relative humidity. Figure 5 shows the dynamic fatigue plots for the fiber tested at 50% and 100% R.H. When compared to testing at 50% R.H., the 100% R.H. failure stresses decreased in both the aged and unaged samples. This decrease in failure stress resulted from the presence of additional water in the atmosphere to facilitate crack growth.

Dynamic fatigue testing was also performed on three fibers at various time intervals after the draw dates for a period of two to three years. Figures 6 and 7 show how the n_d and the median failure stress at the 25%/min. strain rate varied with time after draw. Figure 8 shows the fatigue plot for one fiber at four different times ranging from 14 to 493 days after draw. Both the fatigue and the median failure stress increase with time. These values increase fairly linearly until approximately 500 days after draw, where they begin to level off. With this fiber/coating system, n_d values will increase by 1 point approximately every 120 days during the first year. Again, the failure stresses increase more rapidly with time at the slower stressing rates than at the faster rates, elevating n_d.

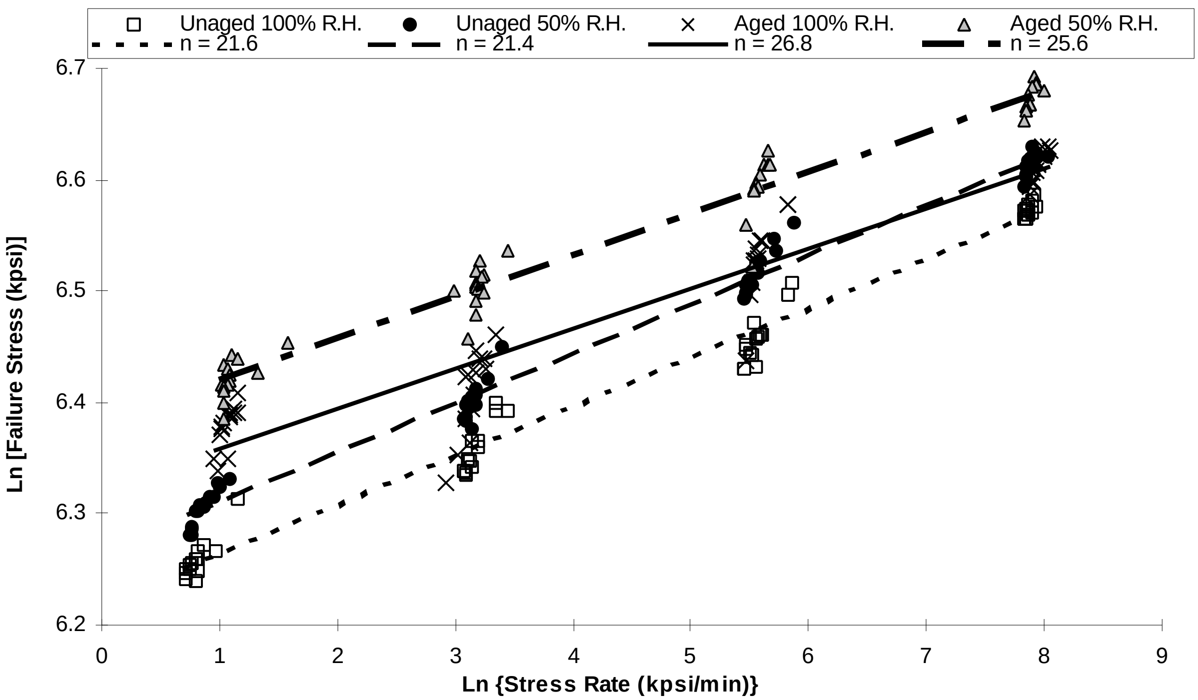

Figure 5. Dynamic fatigue plot for fibers tested at different relative humidity values.

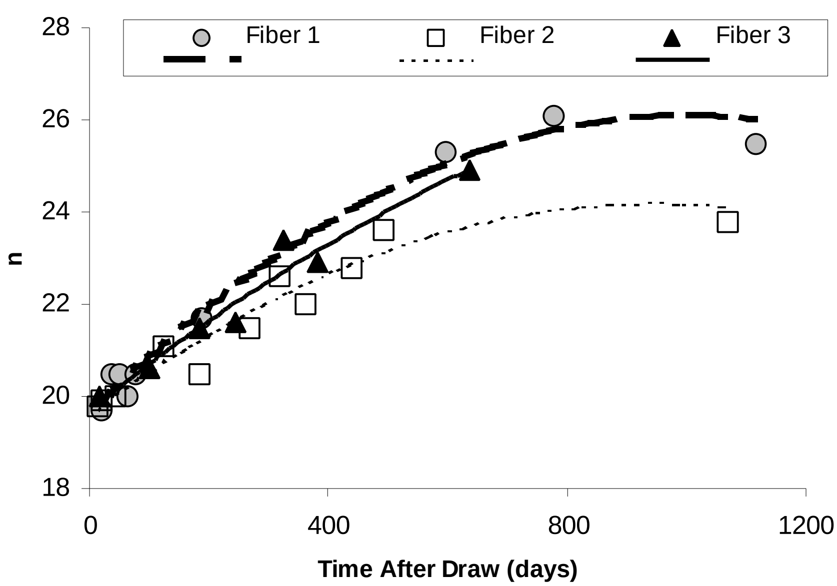

Figure 6. Dynamic fatigue parameter (n_d) versus time after draw.

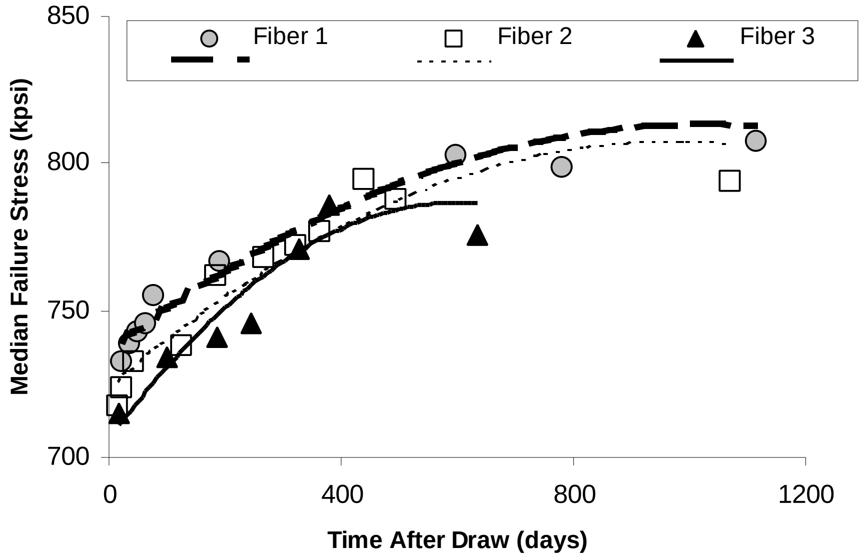

Figure 7. Median failure stress versus time after draw.

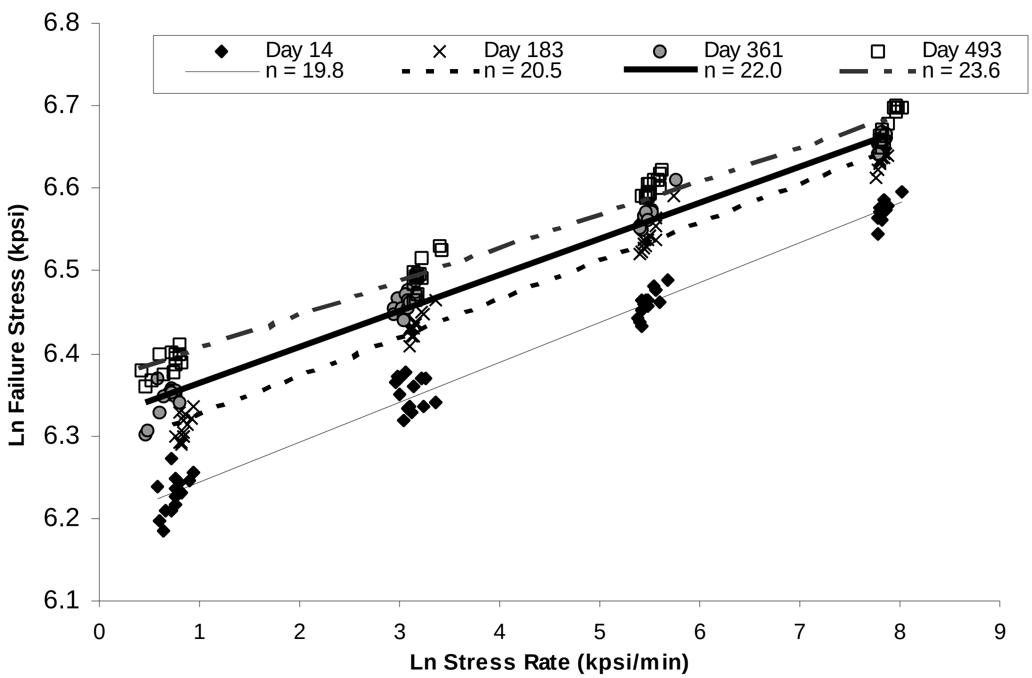

Figure 8. Dynamic fatigue plot showing how fatigue varies with time after draw.

Discussion

The strength decrease at higher humidity observed in Figure 5 corresponds to an increase in the B parameter. The B value for 100% R.H. is estimated to be a factor of 3.5 smaller than the B value for 50% R.H. Equation 2 shows the power law relationship between time to failure and the fatigue parameters (n_d and B):

$$t_f = BS_i^{n-2}\sigma^{-n} \qquad (2)$$

where t_f represents the time to failure, S_i is the initial strength, and σ is the applied stress. According to the findings in this study, it is evident that the environment in which the fiber is exposed can indeed affect the reliability predictions.

An increase in n_d after aging, and a corresponding increase in failure stress, was consistently observed for the type of fiber examined in this study. This increase was observed on environmental aging as well as shelf life aging. It was determined that n_d values after two years of shelf life aging were similar to n_d values after 30-day exposure to 85°C/85%R.H. It is known from past experimentation and analysis that not all fiber systems show the same mechanical attributes after aging. Some show strength degradation, some show constant dynamic fatigue with aging, while some show this increase in n_d. The basic question remains, does the glass or coating contribute to the aging properties of the fiber?

One possible cause for the increase in dynamic fatigue resistance is that the coating chemistry changes over time. As the fiber ages, it is possible that the coating becomes more resistant to OH ions penetrating through to the glass surface during the fatigue test. Once the coating has reached equilibrium, the fatigue value stabilizes. Another hypothesis, involving the glass chemistry, states that pristine glass surfaces could contain sites where a hydroxyl could be attached, but is not. If these sites are filled in by the process of humid aging, stress corrosion might be reduced because the aged surface is more effectively covered by Si-OH that would tend to resist attack by additional water molecules. Since the fracture behavior of small flaws is governed by the rupture of the first bond, changes in the glass surface chemistry from aging could influence the n_d value.

Although an increase in the aged failure stress at a specific strain rate is observed, one should not conclude that the fiber is becoming drastically stronger or that the 'flaws' are becoming smaller. The change in n_d with aging increases strength values by less than 5% on the pristine fibers tested. High speed testing would show that the actual strength, without the presence of fatigue, would be the same for unaged and aged fibers. However, the fact that no aged strength degradation was present is of great importance to insure the mechanical behavior of the fiber. It should also be cautioned that the elevated fatigue resistance with aging has only been observed on pristine fibers. Testing on abraded fiber, with flaws near the proof stress level, would be necessary to determine the impact of the increased n_d on the true reliability of the fiber. Until the reliability behavior of large flaws is fully modeled, an n_d value of 20 should still be used in lifetime calculations.

Conclusions

Thirty-day hot-humid aging experiments performed on polymer coated optical fiber showed an overall increase in both median failure stress and the dynamic fatigue parameter (n_d) after aging. The increase in the median failure stress is due to the increase in fatigue resistance. Tests performed at 100% R.H. resulted in lower failure stresses than tests run at 50% R.H., consistent with a decrease in the B parameter at 100% R.H. The impact of R.H. on as-received n_d was minimal. However, 30-day aged n_d values were slightly higher when tested at 100% R.H. compared to 50% R.H. The study also showed that cycling humidity and temperature during the aging process has no impact on strength or dynamic fatigue. Time after draw studies showed n_d increased with shelf life in ambient storage conditions, and median strength increased as a consequence of the increase in n_d. The strength and fatigue values of 2-year-old fiber showed a strong resemblance to the values from the 30-day hot-humid aging experiment. Since the exact cause of the increase in fatigue resistance is not known, further investigation of aged fatigue on bare glass and large flaws is warranted. Until this additional work is completed, one should be cautious about using elevated n_d values for reliability calculations.

Acknowledgments

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