Strength and reliability of silica optical fibers for automotive communication networks

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ABSTRACT

Demand for new safety, sensor, control, information and entertainment technologies in automobiles is stretching the data rate limits of communication networks using conventional wiring and plastic-based fibers. Thus far, the switch to high-bandwidth glass optical fibers has been hindered by concerns about the fiber's reliability. In this study, we present zero-stress aging data for glass optical fibers with different protective coatings exposed to environmental conditions relevant to the automotive industry.

Keywords: optical fiber, automotive, aging, strength, reliability, environmental effects, coatings

1. INTRODUCTION

As plastic optical fiber (POF) gains widespread use in automotive data bus systems, it faces restrictions that may limit its long-term implementation. For example, current plastic fibers in use for data links are formulated from polymethyl methacrylate (PMMA) which limits the upper operation temperature of the fiber to 85°C; this essentially confines POF to applications within the passenger area of the automobile.[1] In addition to a constrained temperature range, POF also has a high attenuation level (≈150 dB/km) that restricts both the fiber length and minimum bending radius (typically, >25mm).[2]

Proposed solutions to the limitations of plastic optical fiber include various glass optical fibers, particularly polymer-clad silica fibers generically referred to as "PCS" fibers. This fluoroacrylate-coated glass fiber design can meet the attenuation and bandwidth requirements for the next generation of automotive support devices. More importantly, these specially coated glass fibers can withstand temperatures above 85°C, allowing for use in a wide array of automotive environments and applications. However, concerns about the long-term reliability of silica-based fibers have slowed acceptance of PCS fiber as a replacement for POF in the automobile. Because the protective coatings applied to a silica optical fiber are a critical determinant of the strength and reliability characteristics of a fiber, this paper presents aging data for glass fibers with various coatings soaked in aqueous and chemical environments to demonstrate how silica-based fibers withstand conditions found in automotive applications.

2. STRENGTH AND RELIABILITY MODELING

2.1 Strength and fatigue model

The strength of a glass fiber is determined by the "weakest link" theory where the minimum strength is determined by the maximum flaw on the glass surface:

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

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where: K_I = stress intensity factor
σ_a = applied stress
Y = crack geometry factor
C = maximum flaw size (crack depth)

As the stress intensity factor (K_I) exceeds a critical stress intensity factor (K_{IC}), failure occurs. The critical stress intensity factor (also known as fracture toughness) for silica K_{IC} is estimated at 0.75 MPa-m$^{1/2}$; using equation (1), we can then demonstrate the relationship between the failure stress (σ_f) and the critical flaw size. In the standard process of prooftesting, a fiber is exposed to a given stress to screen out fiber with low strength due to large flaws. In operation, the fiber is under an applied stress (e.g. tensile or bending) and crack growth proceeds according to the following empirical relationship:

$$dc/dt = AK_I^n \quad (2)$$

where: A = constant
K_I = stress intensity factor
n = stress corrosion susceptibility factor (or fatigue factor)

The fatigue factor is a measure of how strongly crack velocity depends on the applied stress. This factor is typically determined by a standard procedure (FOTP-28) comparing a fiber's breaking stress vs. the applied strain rate. For hermetic fibers where water is segregated from the glass surface, the "n" value is usually greater than 100, indicating a very slow crack velocity at typical stress intensities of fiber use. For non-hermetic fibers, the "n" value is typically around 20. A greater "n" value translates to a slower crack growth under moisture-assisted stress and thus a longer fiber lifetime.

2.2 Fiber lifetime estimation

If the "n" value of a fiber is calculated and the fiber is exposed to a known application stress, the time-to-failure can be estimated from the mechanics of sub-critical crack growth. An early model formulated by S.M. Weiderhorn determined time-to-failure (t_f) as a function of the applied stress and the "n" value:

$$t_f = B\, S_{int}^{\,n-2} \sigma^{-n} \quad (3)$$

where: B = crack growth parameter
S_{int} = intrinsic strength of the fiber
σ = application stress

However, for any given fiber the crack growth parameter B is not known due to variability caused by the fiber's application environment. Lifetime prediction equations[3,4] based on the Weiderhorn model have aimed to make reasonable estimates of a fiber's lifetime under a given application stress and environment. Regardless of the model, it is intuitively understood that lifetime is extended by 1.) a high initial strength, as determined by prooftesting 2.) a low application stress and 3.) a high "n" value. A conservative "rule of thumb" design guideline[5] for silica fibers is that the short-term stress (≈ 1 second) should not exceed one-half of the prooftest level and the final application stress should not exceed 20% of the prooftest stress.

Since glass fatigue, and thus a fiber's lifetime, depends on the presence and mobility of water on the glass fiber surface, fiber aging research can gauge how well a primary coating will protect the fiber. In zero-stress aging, the fiber is immersed in water (or other solvents) and the degradation of strength is charted over time; in this manner, the effectiveness of the fiber coating in preserving fiber strength can be assessed. It should be noted that aging studies focus primarily on the function of the coating in direct contact with the glass fiber surface; in almost all cases, an optical fiber will be covered by additional buffers or jackets (e.g. nylon, Teflon™) to provide a high level of protection.

3. DETAILS OF EXPERIMENTS

3.1 Zero-stress aging effects in water and chemicals

Fiber samples were drawn from a common preform and coated with the following protective coatings: 1.) acrylate, 2.) HCS® Hard Clad Silica, 3.) polyimide and 4.) carbon-polyimide coating (these coatings will be discussed in turn). The fiber samples were then cut into 25cm lengths and immersed in various aqueous and chemical environments; the strength of the fiber samples was tracked with two-point bend testing. The aqueous soak conditions tested included water at room temperature, saltwater at room temperature and water at 80°C. The results of zero-stress aging in aqueous environments have been reported previously[6] but in this paper we also present data on fibers soaked in acetone (dimethyl ketone), isopropyl alcohol and toluene (methylbenzene). These chemicals are relevant to this study because they are not chemically dissimilar from solvents (e.g. gasoline, cleaning agents) often encountered in automotive applications.

As a baseline for comparison, the aging results for acrylate-coated fiber are presented below. The acrylate coating is by far the most common type of protective coating used on optical fiber, particularly fiber used in the telecommunications market. For this study, the glass fiber was coated with a 37μm thick layer of secondary acrylate which was then cured with ultra-violet lamps. The baseline strength of the acrylate fiber was measured with two-point bending at 6.39GPa (927 kpsi) and the dynamic fatigue (“n”) was estimated to be a value of 20.

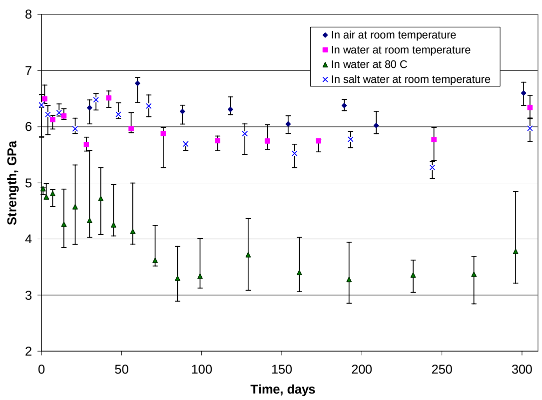

Figure 1: Acrylate fiber aging behavior in water

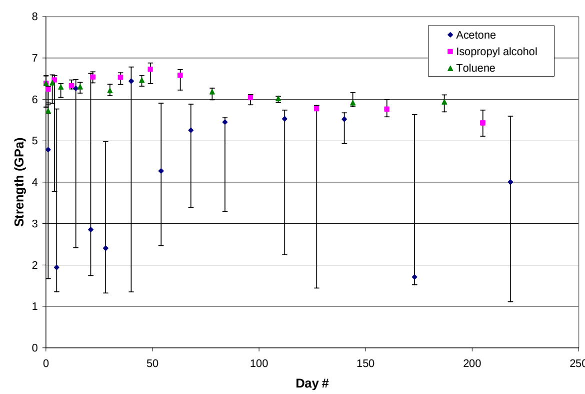

Figure 2: Acrylate fiber aging behavior in chemicals

As the graphs indicate, the acrylate-coated fiber experienced degradation in strength proportional to the temperature of the aqueous environment. For example, the acrylate fiber soaked in 80°C water dropped 80% of its initial strength after only one day of aging. This would indicate that the acrylate fiber, by itself, is not a good barrier to water ingression. Although the acrylate fiber showed little change in strength after isopropyl or toluene soak, the acetone data indicates a very wide distribution of strength but with a consistent minimum strength of ≈1.5 GPa.

The HCS® Hard Clad Silica is a proprietary fluorinated acrylate polymer that is used as a cladding (or optical coating) on the glass fiber; this base fiber is currently being proposed as a replacement for the POF-based physical layer of automotive multimedia networks. The HCS® coating was applied to the silica fiber to a thickness of 11μm and cured with ultraviolet lamps. Using two-point bend testing, the initial strength of the HCS fiber was measured at 6.55 GPa (950 kpsi) and the “n” value was calculated to be a value of 21. The aging behavior of the HCS fiber can be seen in the following graphs:

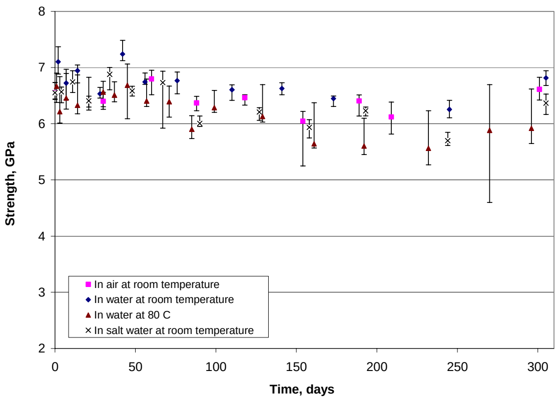

Figure 3: HCS fiber aging behavior in water

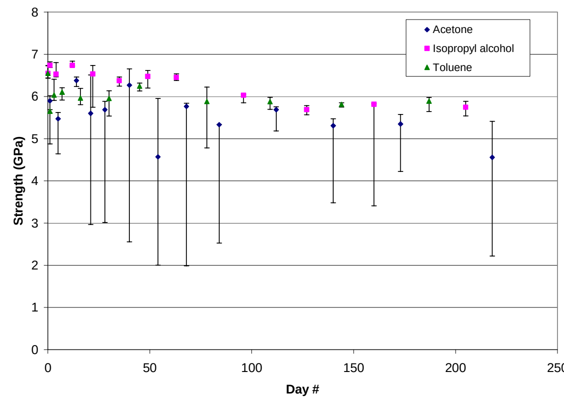

Figure 4: HCS fiber aging behavior in chemicals

Although the HCS® has a primary function as a cladding to guide light, the aging data indicates that it serves well as a barrier to moisture that can lead to a degradation of strength over time. Even in the most aggressive test of 80°C water, the fiber retained 90% of its original strength after 10 months immersion. Much like the acrylate fiber, the HCS® fiber showed little loss of strength in isopropyl alcohol or toluene, but a wide strength distribution after soaking in acetone. However, none of the tested samples indicated a final strength below 2GPa.

One of the many advantages of the HCS/PCS fiber is the ability to withstand temperatures from -65°C up to 125°C which allows for use in areas of the automobile inhospitable for plastic fiber. However, for more aggressive conditions up to 300°C (e.g. engine compartment) a polyimide-coated optical fiber may be employed. Polyimide is a thermally-cured coating that is typically applied in very thin layers; for this test, fiber was prepared with a 7µm thick layer of polyimide. The initial strength was measured at 6.93 GPa with an "n" value of 22.

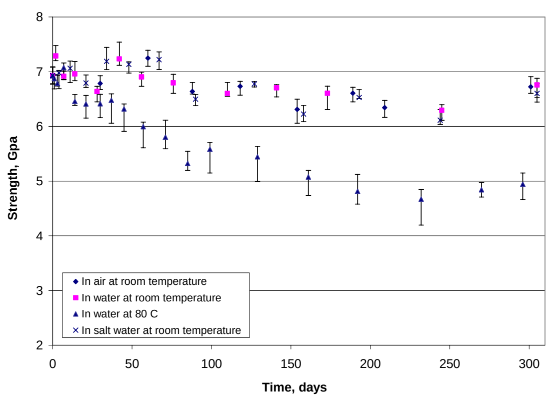

Figure 5: Aging behavior of polyimide fiber in water

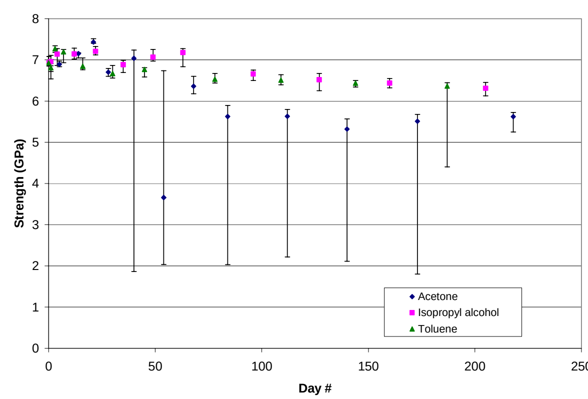

Figure 6: Aging behavior of polyimide fiber in chemicals

Like the acrylate fiber, the polyimide-coated fiber exhibited a significant drop in fiber strength in the 80°C water; however this degradation of strength was more gradual and predictable with a much tighter strength distribution (max-min range <0.5 GPa vs. >1.0 GPa for acrylate). For the other aqueous conditions tested, the polyimide fiber retained over 90% of original strength. For the chemical soak data, once again the acetone data indicates a wide distribution of strength over the duration of the soak test, with a minimum strength consistent at 2GPa.

As noted previously, hermetic coatings can isolate the fiber surface from the environment and reduce or eliminate strength and fatigue effects due to moisture and other reactive chemicals. For this study, a sample of carbon-polyimide fiber was prepared by introducing a hydrocarbon gas to the silica fiber and producing a pyrolytic reaction where a thin (300Å) layer of graphitic carbon is bonded to the glass surface. (Except for the carbon layer, this fiber is similar to the polyimide fiber described above). Because the carbon layer is an effective barrier to water, this fiber has an "n" value calculated at >100. However, because the applied carbon layer lowers the strength of the fiber, the initial strength of this fiber was measured at 4.12 GPa.

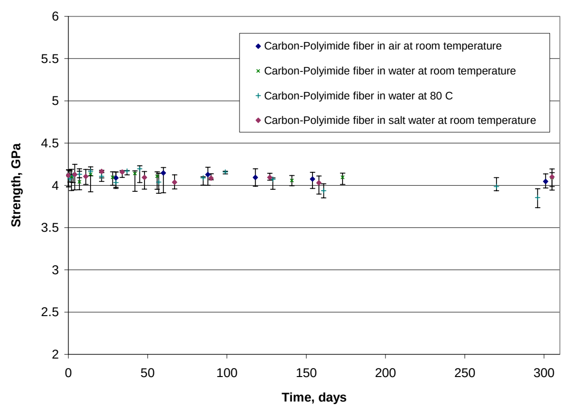

Figure 7: Aging behavior of carbon-polyimide fiber in water

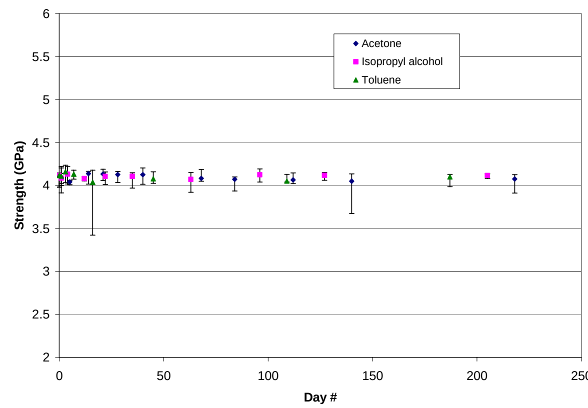

Figure 8: Aging behavior of carbon-polyimide fiber in chemicals

As the data indicates, the carbon layer provides protection from the effects of water or chemical-driven aging as there is no appreciable degradation in strength after several months' immersion.

4. CONCLUSIONS

The long-term reliability of a glass-based optical fiber is examined through the use of zero-stress aging of fiber samples in both aqueous and chemical environments relevant to automotive applications. The results illustrate the impact of fiber coatings on the strength and reliability characteristics of silica optical fibers; furthermore, care should be taken to specify the appropriate protective coatings to meet the operational and environmental requirements of the application. The mechanical and optical characteristics of HCS®/PCS fibers indicate this fiber type is suitable for use across a broad range of temperature and operating environments. The aging results indicate that this fiber will retain strength over an extended period in aggressive watersoak conditions. However, all the non-hermetic fiber designs tested showed susceptibility to the effect of acetone immersion. To insure an extended lifetime in an aggressive chemical environment, a hermetic (e.g. carbon) fiber can serve as an effective barrier to eliminate the effects of fatigue and chemical-driven strength degradation.

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