Properties & Reliability of Improved Large Acceptance Optical Fibers

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ABSTRACT

The high power diode laser systems with their laser diode bars and arrays not only require special fibers to couple directly to the diode emitters, but also require special fibers to couple from the laser to the application sites. These power delivery fibers are much larger than the internal fibers, but must be flexible, and have not only good strength but also good fatigue behavior. This is particularly important for industrial systems using robotic arms or robots to apply the high power laser energy to the treatment site. The optical properties of hard plastic clad silica (HPCS) fibers are well suited for the needs of delivery of high power from diode laser bars and arrays to an application site. New formulations for HPCS fibers have been developed which have demonstrated fibers with good mechanical strength in preliminary tests. A systematic study has been undertaken to determine the strength and fatigue behavior of thee 'new' HPCS fibers and to compare them with results for earlier HPCS fibers. Benefits of stronger median dynamic strengths and tighter flaw distributions have been found. Short to medium length time to failure results, indicate that the static fatigue parameters of the new high numerical aperture (NA) optical fibers are at least as good as those for standard NA HPCS fibers, which is an advance from previous results on the older formulation clad fibers.

1. INTRODUCTION

Laser based applications in micro-packaging, microelectronics, and optoelectronic manufacturing benefit from the use of optical fibers coupled to the laser sources. Both economical and technical benefits are possible. Efficient coupling is key to accepting laser beam energy into the fibers for many cases. In some cases the ability to spread the output may be the key factor. The availability of optical fibers having low optical losses and high numerical apertures provide the opportunity to use smaller dimensioned fibers while still maintaining highly efficient coupling. Smaller fibers are more flexible, more resistant to fatigue, occupy less space and weigh less.

Classically, using laser energy for other than communications, data transfer, or sensing usually involves lasers with moderate to high output power, as in laser welding, marking or ablation. Transmission of such laser energy requires a medium with high temperature stability and ultra low loss, so that potential heat gain from internal absorption and its effects are minimized.

Silica is a good material in terms of both its optical and thermal properties. It can be produced synthetically with ultra-high purity and it has little absorption across a wide range of wavelengths from about 200 nm to over 2000 nm, especially when its production processing includes minimization of OH bonds within the glassy silica structure. The glassy region for silica is thermally stable to well above 1500 C. The bond energy of silica is greater than 20 GW/cm^2. Silica core/clad fibers are thus among the best materials to use in optical fibers for high energy laser transmission.

The transmission and/or thermal properties of silica are generally reduced by any significant doping of the material to change its refractive index. Among the problems that arise is that the thermal expansion coefficient of pure silica is very small, whereas doped silicas usually have higher thermal expansion coefficients. Until very recently this was a major problem limiting the ability to manufacture thermally stable silica/silica(F) core/clad fibers to a Numerical Aperture (NA) of no greater than 0.22. Doping the core did allow for a somewhat higher NA but often changed other properties needed for specific applications. For example, a highly Ge-doped core, clad with a pure silica cladding, can have an NA of about 0.33. These cores are generally sensitive to ultraviolet wavelengths and also have potential thermal mismatch problems limiting effective core size and power handling.

An alternative, which uses the advantages of pure silica core and has high numerical aperture version, is Hard Plastic [polymer] Clad Silica (HPCS) fiber. They are available for use in both UV and VIS/NIR spectral regions, dependant primarily on the OH levels in the silica used as the core. The spectral behavior and mechanical reliability of this fiber type, especially for the newly formulated low index cladding which yields high NA fibers, are presented below along with a review of their advantages and liabilities as compared to all silica optical fibers.

2. EXPERIMENTAL

High-OH fibers typically have $\geq$600 ppm of OH, while low-OH fibers typically have <2-4 ppm of OH. The emphasis in this paper is on the low-OH HPCS fibers.
The NIR and VIS spectral losses of low-OH HPCS fiber with nominal core diameter for both types was 600 μm.

A "cutback" method was employed using a Monolight Optical Spectrum Analyzer (OSA), manufactured by Macam Photometric Ltd of Livington, Scotland. The system includes a scanning monochromator, a 3-channel controller, a power supply, two light sources (deuterium and tungsten), and input and output blocks to handle fiber from 70 μm to 1000 μm in diameter.

The "cutback" method consisted of using two pieces of same-type fiber with a length ratio of about 1:4 or 1:5. Long lengths of over 25 m were measured via a Tektronix ODTR, and shorter lengths were manually calculated (i.e. the number of loops were counted and multiplied by Π times the diameter of the spool.) The "cutback" length (in meters) was calculated by subtracting the shorter length from the longer length of fiber. More complete details on the spectral measurements were reported earlier[1].

The numerical apertures for the different fibers in this study were made using a set up which involved taking diameter measurements of the projections onto a black surface shielded from direct ambient light at five different distances from the fiber end. A white light source was over-launched and overfilled into the input end of the fiber. Meter long samples were used with about a 180 degree angle bend relative to the output end. The bend radius was on the order of a 40-50 cm. The ends were secured to metal blocks to guarantee stability of placement during testing and to improve reproducibility. NAs calculated at the five distances were averaged to yield the reported NA.

The primary mechanical property reported is the dynamic strength as measured by a universal testing machine and plotted on a Weibull plot. Gauge length was 1 meter. The fiber is stretched while horizontal and anchored at the two ends by wrapping several loops around a tapped mandrel of approximately 10 cm diameter. About 1.7 meters of fiber is consumed per trial. Results presented below are generally from one or two fibers where 15-20 samples are taken from a specific fiber run. Tests were made at ambient temperature and relative humidity. Temperatures ranged in the 20-27 C, and relative humidity [RH] primarily was 30% ± 7%, although some samples were tested with RH at 72%. Strength data are plotted according to the generally accepted Weibull approach.

Additionally the static fatigue behavior has been measured also. Tests use half meter gauge lengths with the fiber wrapped snuggly around a metal rod, anchored at the ends with waterproof tape. The wrapped samples are then immersed in room temperature water and the time to failure is recorded. Typically at least five fiber samples are measured for each rod diameter, i.e. bending stress level. Affects of fiber jacket thickness are incorporated into the stress calculations. The data are plotted based on the power law, which is still the most generally accepted approach to presenting static fatigue data.

3. RESULTS

Figure 1 shows the typical spectral loss of standard, low-OH HPCS fiber (HWF) with core/clad geometries of 600µm/640µm and a numerical aperture (NA) of 0.37 (standard NA) from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the ‘standard’ hard plastic cladding.

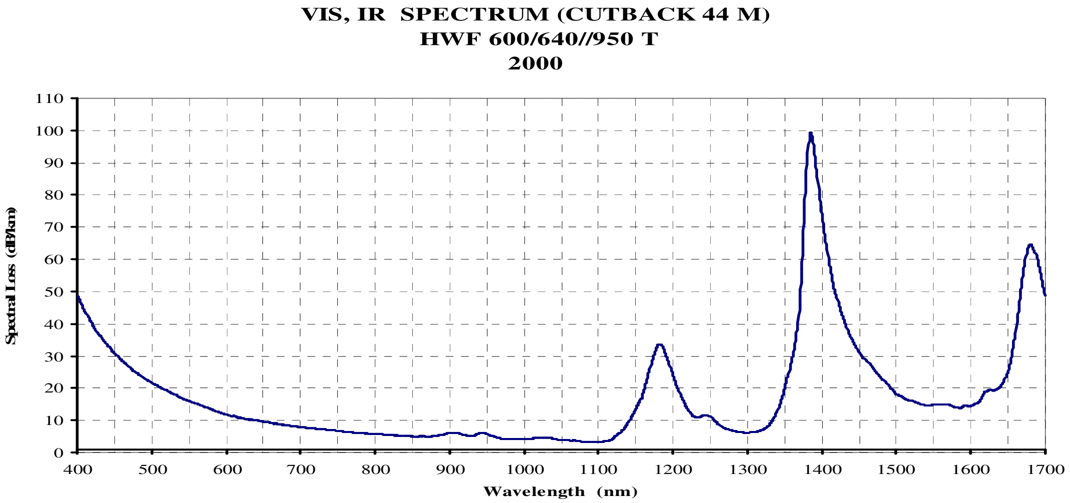

Figure 1: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.37

Figure 2 shows the typical spectral loss of standard, low-OH HPCS (HWF) fiber with core/clad glass geometries of 200µm/230µm and the new high numerical aperture (NA) of 0.48 from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the ‘Hi NA’ hard plastic cladding. Jacketing is same material and relative thickness as for the standard NA HPCS fiber.

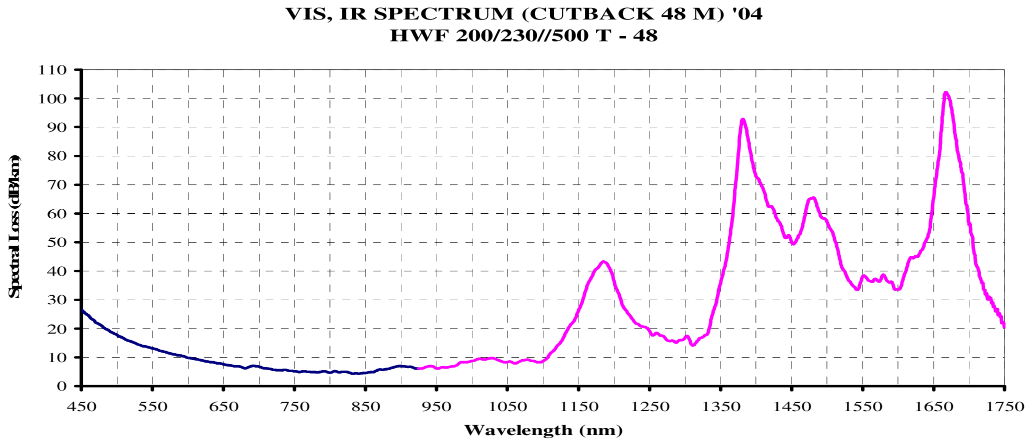

Figure 2: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.48

In Figure 3 we have a comparison of three fibers using different core glass lots and the same hard plastic cladding lot. Demonstrates the rough reproducibility of the spectral testing. Note that the jacketing material here is different and much thinner than for fibers in the prior two figures.

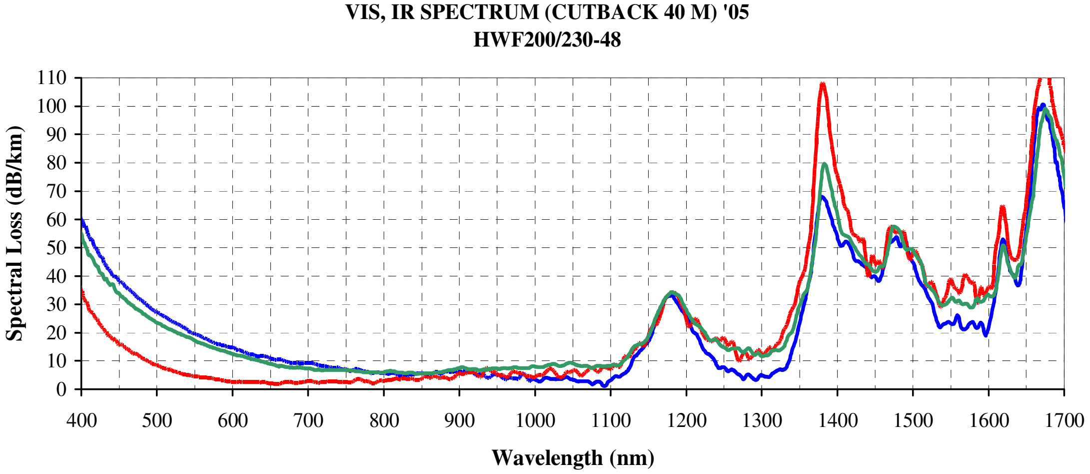

Figure 3: Overlaid spectrums three lots of low-OH fiber, NA = 0.48

In Figure 4 is presented comparison spectra from Optran[2] and two competitors fibers. The spectra are essentially the same in the 500-1100 nm wavelength range.

As a measure of the reliability of these fibers, we present dynamic strengths measurements for fibers make over a 5 year period and including a fiber tested and retested during this period. In Figure 5 the Weibull plot compares fibers drawn in 1999 [left points black], and in 2004 [right points, shaded] Note that log S = 2.80 is a strength of 4.35 GPa.

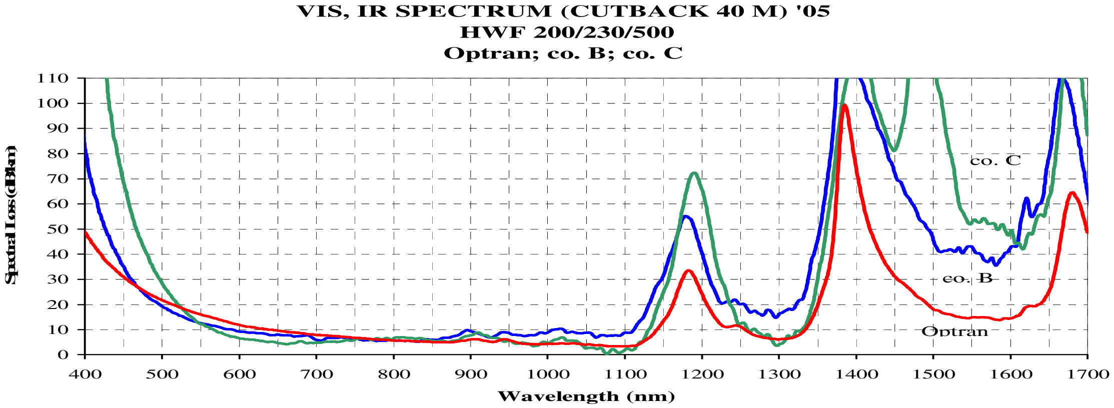

Figure 4: Overlaid spectra, Optran and competitor of HPCS fibers.

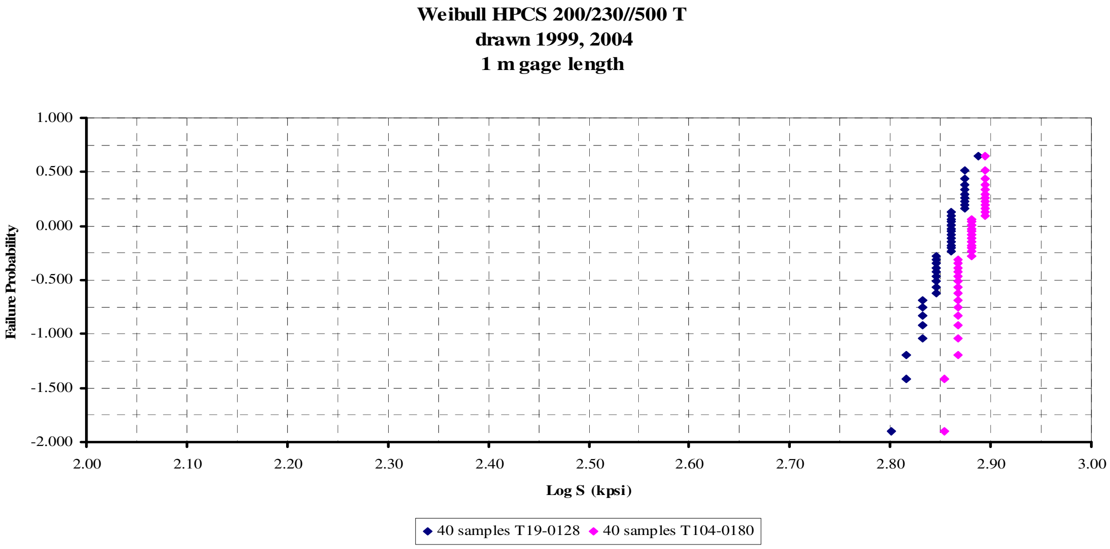

Figure 5: Weibull Plot of std. Optran HPCS fiber; drawn '99[left], drawn '04[right]

In Figure 6, the Weibull plot compares strength for a fiber drawn in 1999, tested in 2000 [circles] and again in 2004 [shaded triangles] after storage in varying humidity (10-80% RH) on spools under about 0.1 GPa (15 kpsi).

Figure 7 presents a Weibull plot of data for the new high NA HPCS fiber, but with a very thin nylon jacket. Whereas the earlier graphs were for fibers jacketed with about 135 μm thick Tefzel (® DuPont) this fiber has only about 15 μm thick nylon as its jacket. Not shown here but high NA Optran HPCS fibers with standard Tefzel jackets had Weibull plots essentially the same as for the standard NA HPCS fibers as shown in Figures 5 and 6. Note that log S = 2.75 is a strength of 3.88 GPa, log S = 2.80 is a strength of 4.4 GPa, and log S = 2.85 is a strength of 4.9 GPa.

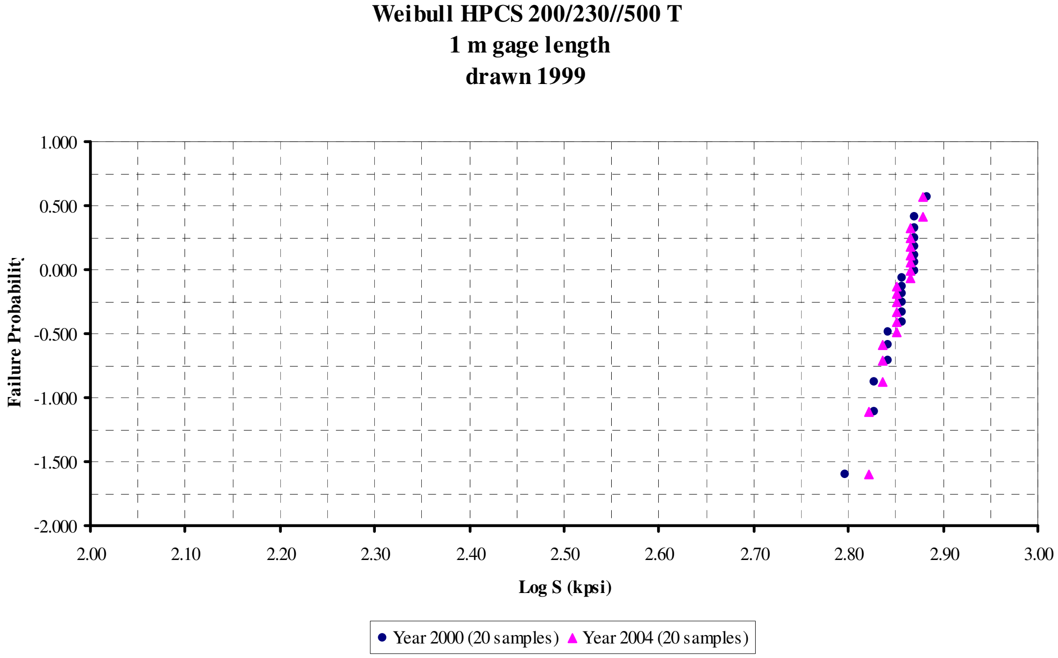

Figure 6: Weibull Plot of std. Optran HPCS fiber; test '00[circle], test '04[triangle]

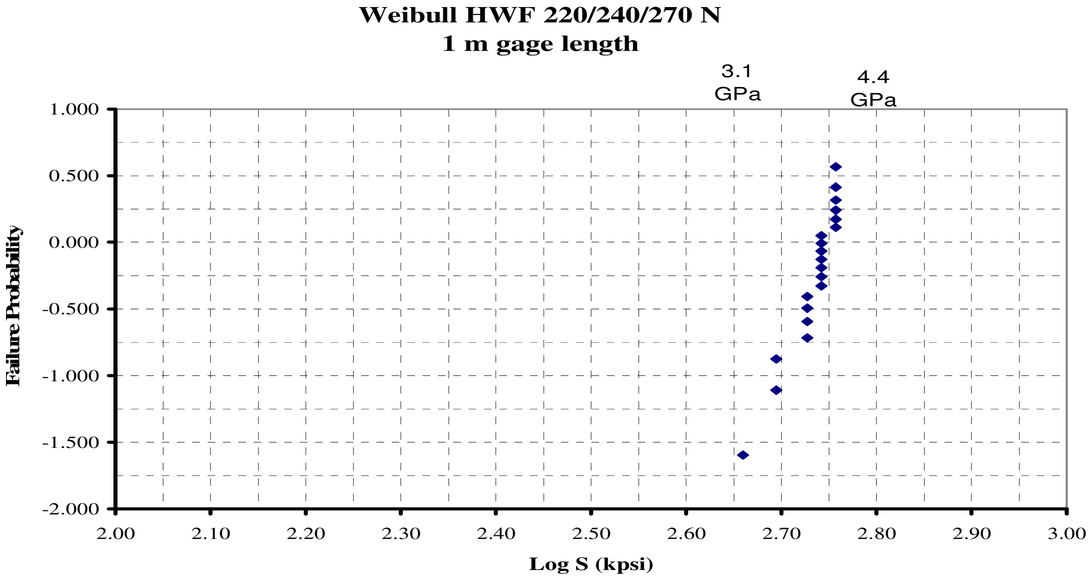

Figure 7: Weibull Plot of 0.48 NA Optran HPCS fiber with ultra-thin nylon jacket

A Weibull plot for a competitor's 0.44 NA fiber with the standard 140 thick Tefzel jacket is presented in Figure 8. Note again that log S = 2.75 is a strength of 3.88 GPa, log S = 2.80 is a strength of 4.4 GPa, and log S = 2.85 is a strength of 4.9 GPa.

Finally in Figure 9 is data representing the time to failure of wound samples of the 0.48 NA HPCS fibers with 20 µm thick nylon jacketing, which corresponds roughly to

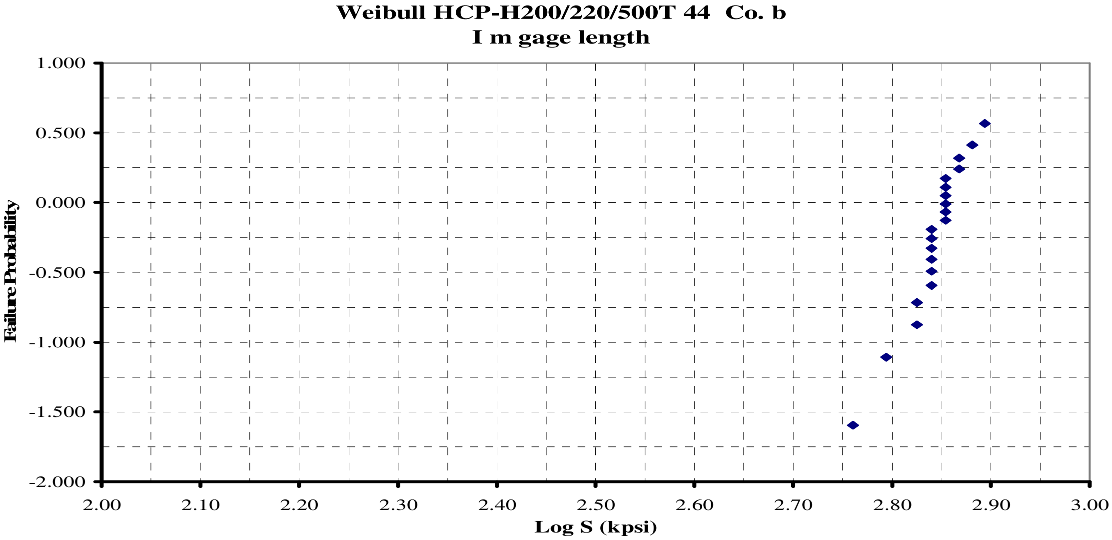

Figure 8: Weibull Plot of 0.44 NA Co. b HPCS fiber with std. thick Tefzel® jacket

the fiber whose dynamic strength data were presented in Figure 7 above. Actual fiber breaks and the average time to failure points for a given stress are plotted on the same graph. This test is ongoing with only the short to medium time failures recorded thus far.

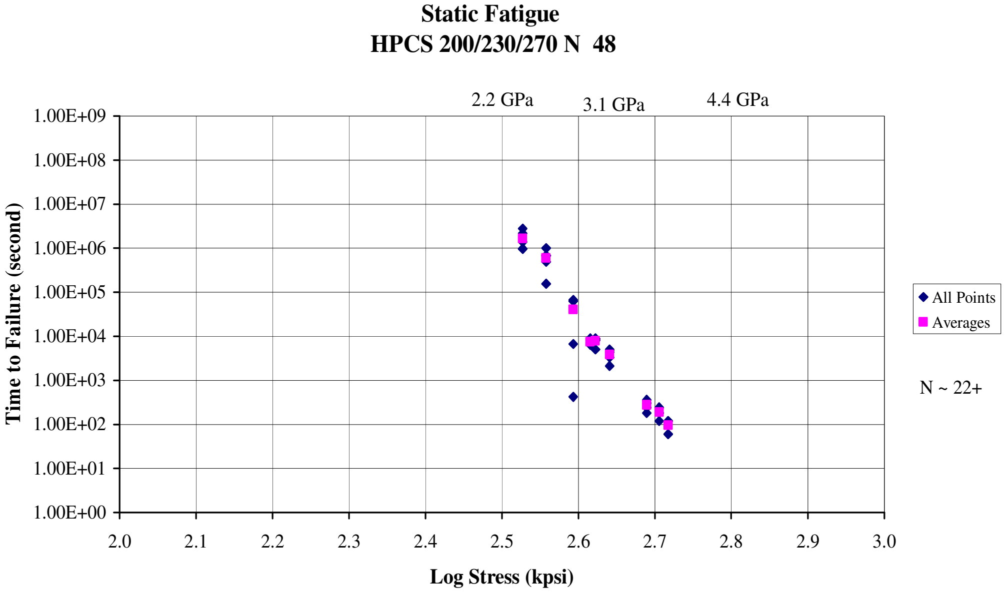

Figure 9: Power law plot of Static Fatigue for HPCS fiber, NA = 0.48

4. DISCUSSION

As implied earlier, coupling of optical components can be improved in a number of situations by the use of high NA, low loss fibers. In the design and functioning of compact laser systems, high NA HPCS fibers can be used for delivery fibers, especially for diode lasers which use bars and arrays to achieve high power, permitting a smaller dimensioned fiber to capture all the laser's power output, possibly without resort to lenses or other optical components. This reduces the size of the package and can improve reliability also by having a simpler, fewer-component system with consequently less critical parameters and less items which could cause the system to go out of specification.

In general, the output from a fiber can be used from near contact to longer distances from the exit of a fiber end. Although a higher NA beam will be more divergent, a smaller fiber diameter will project initially a smaller spot near the fiber end. In applications such as laser marking or ablation this may be critical to get the desired patterns. Laser welding may be aided by having a larger beam with a somewhat diffuse edge. Stronger better welds can result by having thermal distribution around the seam which diminishes slowly at first from the seam, permitting some adjustment in the material on both sides of the seam to enhance stability.

These represent some of the benefits which become possible in photon processing systems in microelectronics and photonics when low loss, high numerical aperture, optical fibers are available to the designer and end users as is now the case with the more robust 0.48 NA HPCS fiber characterized here.

To summarize, HPCS fibers are shown to be reliable, robust having high dynamic strengths with little change in strength or distribution of flaws after storage at about 0.1-0.2 GPa [10-25 kpsi] for up to, at least, 5 years. Their dynamic strength and fatigue behavior are comparable to all-silica fibers. Weibull mean strengths are above 4.4 GPa [>600 kpsi]. Prior studies have indicated a static fatigue parameter of > 22. Power capacity approaching 1GW/cm2 under proper conditions. Their lighter weight can be of some benefit for non-stationary high power laser stations.

A new high NA HPCS with spectral and strength properties similar to the standard NA HPCS fibers has been featured. It is significantly more robust than earlier versions. With the NA= 0.48, it is now possible to provide a larger target for collecting the output from multiple laser sources, e.g. diode laser arrays, and delivering high brightness power to a site, by use of smaller core size.

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1. B. J. Skutnik and H. Park, "Cladding Effects on Spectral Transmission of Optical Fibers for Medical Applications", SPIE Proc. **4616**, 180 (2002).
2. Optran is a trademark of CeramOptec Industries/Biolitec.