MECHANICAL BEHAVIOR AND B-VALUE OF AN ABRADED OPTICAL FIBER

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ABSTRACT

The mechanical behavior of high strength and abraded (proof test level) optical fibers have been tested by joint experiments at nine laboratories in a wide range of dynamic stress rates and on static stresses. The answers to the open questions about B-value magnitude, measurement method and life time estimation were found (see Conclusions). Although measurement results diverge slightly because of accuracy problems and environmental conditions, the results show that the one-region power-law model cannot describe the test results, but the two region power law theory[1-6] can. Both n- and B-values are dependent on dynamic stress rate and static stress level. For long term life time estimations of optical fibers the B and n-values of Region I shall be used, and they should be evaluated from the test results on fiber weak spots at low stress rates or from static fatigue tests, by using the two region power law theory.

1. INTRODUCTION

The European research action COST 246 was established in 1993 with the scope to provide joint work on problems of reliability and life-time estimations of optical fibers, cables, passive components and optical amplifiers. In this paper the results for one of the topics - the B-value problem and optical fiber life time estimation- are presented. Other papers, such as the ones published by S. Semjonov et. al[4] and M. Bubnov et.al[5] including the cube corner indentation-work[6] on fibers to be presented at this IWCS-conference, have been effectively stimulated by the COST 246 initiative.

The work of this paper was stimulated by the European participants of IEC standardization group on optical fiber reliability, who asked COST 246 for a recommendation for measurement methods of B-value, together with a wish to simplify and qualify the power-law based lifetime report of IEC[7] for standardization. There has been a continuing controversy in the optical fiber community over the magnitude of the B-value (strength preservation parameter). While it has been studied mainly on high strength fibers, it is of greater immediate importance for fibers with 'proof test' level flaws, because the life time is defined by the fractures at these. In order to study this, a special abraded fiber (J-fiber) was prepared by S. Glaesemann of Corning, Inc. for study by COST 246. In this paper, the round robin tests on Fiber J together with a theoretical analysis are presented.

The earlier reliability action COST 218 (1987 - 1992, A. Breuls, T. Svensson, W. Griffioen and others) started the studies on life time theories of fibes[8-9], and concluded with the suggestion that the well known one–region power law theory is appropriate, and, in particular, the Mitsunaga-approximation of it for the life time estimation of fibers in cable networks, in the case B-value is negligible. However, no final agreement was found about the B-value magnitude (whether it is negligible or not) or about a reliable measurement method for it. It was not completely understood either, why the high speed measurements on high strength fibers showed a much higher B-value (above 0.001 GPa^2s) than the values predicted from the inert strength and ambient environment fatigue tests (below 10^{-5} GPa^2s).

It was suggested that these problems be avoided by measuring the factor β (~BS^{n-2}, where S is the inert strength and n is the n-value) from static fatigue or dynamic fatigue measurements of the weak spots. This method has practical limitations.

An eight decades range of variation exists in the reported[5,2-4] values of B (fracture preservation parameter) for silica glass optical fibers, ranging from 2 * 10^{-8} GPa^2s to 0.5 GPa^2s. The high values, above 0.001 GPa^2s, have been obtained from high speed tensile tests[10,11,5] on pristine high strength fibers by direct fitting the well-known one-region power law model to the test data. On the other hands, the low values, below 10^{-5} GPa^2s, are obtained by combining the fatigue test data from ambient conditions with inert strength measurements at liquid nitrogen temperature or under high vacuum conditions, on high strength fibers[5,12,13] .

So far, five unsolved problems have existed:
- A) to decide which of these magnitude levels of B-value is correct for the long term static fatigue of the weak spots in installed fibers in cable networks.
- B) to verify whether the mechanical behavior parameters (n-value and B-value), which are measured on high strength fiber, are valid for static fatigue of weak spots.
- C) to find a reliable measurement method for B-value.
- D) to find how much larger the initial (= inert) strength is than the measured strength at room conditions, in order to know the relevant start-length of the surviving flaws after a proof test, for life time estimation.
- E) to find an explanation for why the n-value of high strength fibers is dependent on loading time, as earlier found in the round robin test of high strength fibers by COST 218[16].

Solutions to these problems are found in this work by measuring the static and dynamic fatigue of an abraded fiber at eight laboratories and comparing the data with the two- region theory.

Optical fiber life time

The controversy in the magnitude of B-value raises two questions regarding life time estimation. IEC[7] suggests that the life time t_f of optical fibers (i.e. the time–to-reach-a-given-fracture-probability of a fiber under a given small static tensile stress) can be approximated by the known Mitsunaga equation[14].

The exact one-region power-law lifetime equation has different approximations depending on the level of B-value[7-9]. Mitsunaga-approximation agrees with the exact equation[7-9], only if B-value is below 10^{-5} GPa^2s. For significantly higher B-values than 10^{-5} GPa^2s an exact equation should be used.

One approximation for the one-region power law is the so called *minimum life time equation*[1,7], which also is used to calculate the lifetime of fibers. A requirement is that the initial strength of it, S_{pmin} (~ initial length of the crack) is known. Sometimes a "rule of thumb" $t_{fmin} \approx (B/\sigma_p^2)(\sigma_p/\sigma_a)^n$ is used (σ_p is proof stress)[7].

The minimum life time equation gives very short life times, if B-value is below 10^{-5} GPa^2s, n-value is around 20 and the initial strength of the weakest crack, S_{pmin}, is approximated to be only as large as the proof test stress σ_p. --It has been proposed to solve this problem by missing out this equation from the life time standard report[7]. However, it is similar to the definition of B-value. Furthermore, it is used for the evaluation of the effect of a proof test, which is as important as life time estimation.

Definition of B-value

Strength preservation parameter, B-value, (as well as fatigue parameter, n-value) is defined[7] by equation which describes the weakening of fiber strength

$$S^{n-2}(t) = S^{n-2}(0) - \frac{1}{B}\int_0^t s^{\,n}(t)dt, \quad (1)$$

where $S(0)$ is the initial strength in the environment, $S(t)$ is the strength to which the crack has weakened under the tensile stress σ applied for a time t. Inert strength (initial strength at an inert environment) S is 1.3 - 2.5 times higher than the measured strength at room conditions depending the stress rate[5,12]. B (B - value) is[7]

$$B = \frac{2K_{Ic}^{2-n}}{(n-2)AY^2} = \frac{2K_{Ic}^2}{(n-2)V_cY^2}, \qquad (2)$$

where the parameters are given earlier. The latter, normalized formula of Eq. 2 is preferred, because they define a clear meaning for the crack growth velocity V_c. V_c is dependent on the material structure and environment[7], but the critical stress intensity K_{Ic} is independent on the environment. Y, the geometrical shape factor of the crack. The fatigue parameter n is also dependent on the material and environment. Thus B is strongly dependent on the environment and material.

2. THE TWO REGION MODEL

It has been known from studies[1,17] of silica and glass materials that the crack growth process includes three regions, however, it has been until recently assumed that the crack growth of optical fiber weak flaws can be approximated by the function of Region I, neglecting Region II. However, this assumption has raised the problem of B-value and initial strength. It has not been realized either that depending on the level of B- and n-values, which both are dependent of the environment (humidity, temperature, chemicals, etc.), the measured n- and B-values and static behaviors may not be usable for long term application, because the measurement range is too close to the transition between the regions.

In the following numerical simulations, we use the same basic formulae of the two-region power law model with the parameters used in ref.4. The two region model[4, 19] is described

$$\frac{da}{dt} = V_1\left(\frac{K_I}{K_{IC}}\right)^{n_1} \qquad \text{for } K_I \le r\, K_{IC} \qquad (3)$$

$$\frac{da}{dt} = V_2\left(\frac{K_I}{K_{IC}}\right)^{n_2} \qquad \text{for } K_I \ge r\, K_{IC} \qquad (4)$$

where V_1, V_2, n_1 *and* n_2 are the parameters of the respective regions and $V_1 = V_2 r^{(n2-n1)}$. Eqs. 3 and 4 can be rewritten in strength degradation terms for a dynamic fatigue test by using S_i is initial strength, S_r and s_r are the strength and applied stress at the transition, s_f is the fatigue strength for the stress rate:

$$S_i^{\,n_1-2} = S_r^{\,n_1-2} + \frac{s_r^{\,n_1+1}}{B_1(n_1+1)\dot{s}} \qquad (5)$$

for the crack growth through Region I, and

$$S_r^{\,n_2-2} = s_f^{\,n_2-2} = \frac{s_f^{\,n_2+1} - s_r^{\,n_2+1}}{B_2(n_2+1)\dot{s}} \qquad (6)$$

for crack growth through Region II, and where[19]

$$B_2 = \frac{2 \cdot K_{IC}^2}{(n_2-2)\cdot V_2 \cdot Y^2}\text{, and} \qquad (7)$$

$$B_1 = B_2 r^{n_1-n_2}\frac{(n_2-2)}{(n_1-2)}. \qquad (8)$$

In Figs. 1 and 2 we consider two cases: static fatigue (σ = const) and dynamic fatigue (σ = σ' t). Calculations are made both for abraded fibers (initial strength = 1 GPa) and for high strength fibers (initial strength = 12 GPa). For the static and dynamic graphs in Figs. 1 and 2 the parameters used in ref. 4 are used: $n_1 = 21$, $B_1 = 4.5 \times 10^{-5}$ GPa^{2}s, $n_2 = 4.5$, $B_2 = 0.0082$ GPa^{2}s, r = 0.645. The transition from Region I to Region II occurs $rK_I = K_\tau \approx 0.6$ MPa√m.

For high strength fibers, in particular in Region I, typically measured fracture times and strength values at ambient conditions are significantly lower than the theoretical curves shown in Figs 1a and 2a. Curves at two decades lower level, which would represent a lower B-value (or larger cracks), would be in better agreement with normal high strength fiber test results. Crack growth velocity (i.e. B- and n- value) both in Region I and II is highly dependent on the chemical environment as well as on the temperature[2,17,19]. High strength fiber parameters may also slightly differ from the parameters of large weak flaws[9,18].

3. COMPARISON OF THE ONE AND TWO-REGION MODELS

Effect on static and dynamic fatigue

Two interesting practical conclusions can be drawn from the dynamic fatigue curves (Fig. 2). A flat transition regime on the level of ~0.6 of the initial inert strength is observed for abraded fibers in the range of stress rates between 10^{-3} and 1 GPa/s. This region is normal for standard testing machines. Thus, an usual dynamic test gives incorrect fatigue parameters for abraded fibers because of the transition between the regions. Only testing machines with an extended stressing rate region can be used for measuring the correct

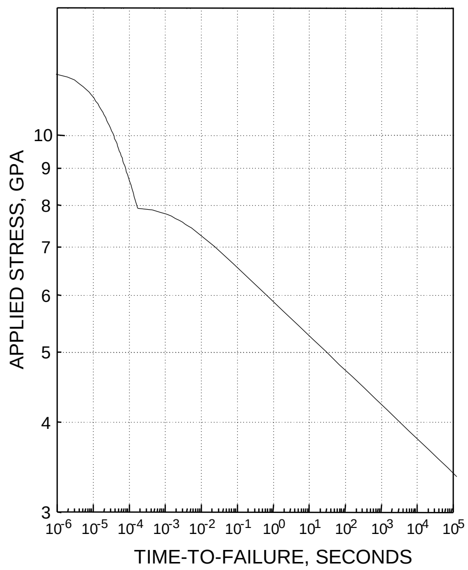

Fig. 1a. Theoretical static fatigue plot for high-strength fiber[4]. Initial strength 12 GPa is used.

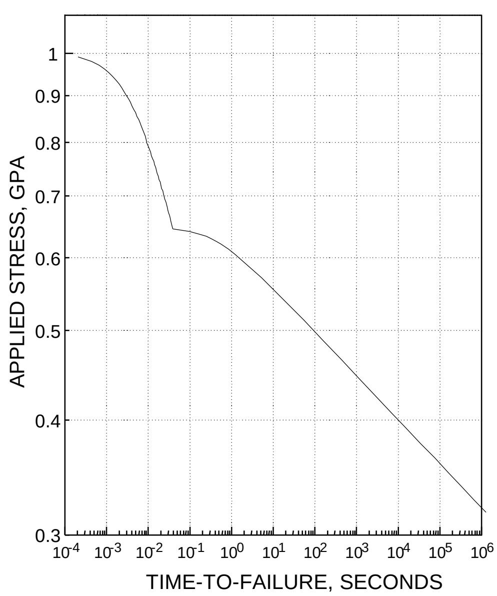

Fig. 1b. Theoretical static fatigue plot for low-strength fiber[4]. Initial strength 1 GPa is used.

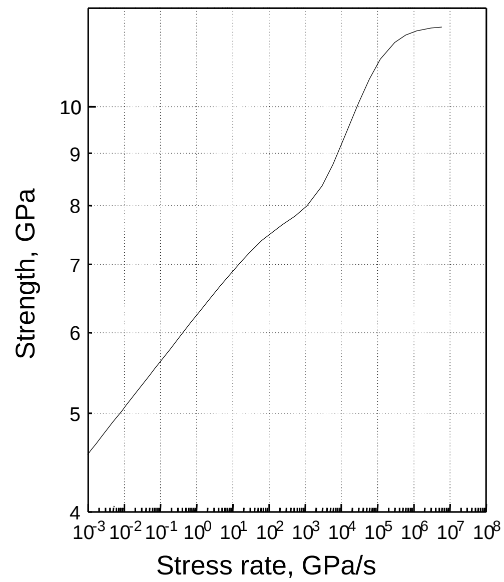

Fig. 2a. Theoretical dynamic fatigue plot for high-strength fiber[4]. Initial strength 12 GPa is used.

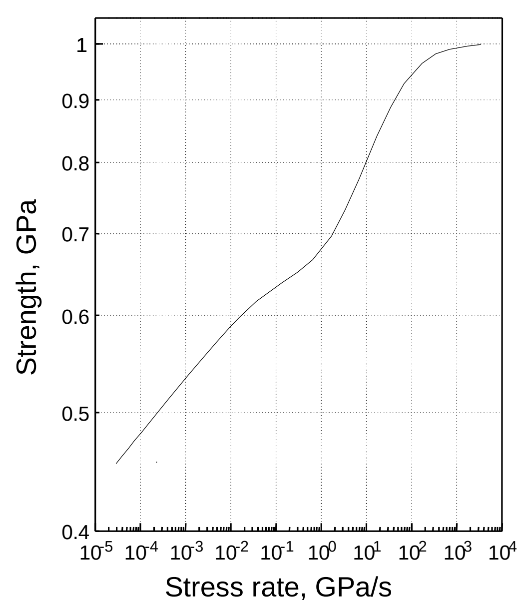

Fig. 2b. Theoretical dynamic fatigue plot for low-strength fiber[4]. Initial strength 1GPa is used.

value of n_1 and B_1. Static fatigue testing at sufficiently long times can also be used. For high strength fibers, the flat transition regime is observed in Figs. 1a and 2a at stress rates exceeding 1 GPa/s. So, for these kind of fibers a standard testing machine can be used for measuring n- and B- parameters of Region I. But in the case where B_1-value is very low and n_1 relatively high (25 - 40), the flat transition regime (and a high, intermediate n-value) can be found at the stress rates used in fatigue tests.

The transition was found by S. Sakaguchi et al[2] at the K_I = 0.61 MPa√m for fused silica rod, and very recently by G.S. Gleaseman et al[19] also at. 0.61 MPa√m (r = 0.81 with K_{Ic}= 0.75 MPa√m) in abraded fibers similar to Fiber J.

Differences between high strength and weak fibers

If we assume that the only difference in the behavior of the dynamic fatigue curves for strong and weak fibers is due to the two-region model and that the crack growth rates are the same for both fiber types, we could use the results from high-strength fiber testing to predict the lifetime of weak fibers. If this theoretical result was to hold for fibers, static fatigue testing of a strong fiber for a few months would be equivalent to static fatigue testing of an abraded fiber for 25 years, because the crack sizes in high strength fibers are smaller by about 10^2.

However, it has not been shown in this work, and to our knowledge elsewhere either, whether the results on high strength fibers are directly applicable to the behavior of weak spots of fibers. Some published test data on weak or abraded fibers[18:], as well as some theoretical studies[9], indicate that the fatigue and aging of weak spots can differ from high strength fibers.

Furthermore, it can be concluded that the high speed tests are applicable only to weak fibers, not to high strength fibers. To measure Region II for high strength fibers, tensile testing equipment much faster than 1000 GPa/s (strain rate over 1600 %/s) would be needed. The speed of voice (mechanical wave speed = maximum possible speed for elongation) in silica glass is of the order of 5000 m/s. This phenomena gives an absolute limit for the high speed testing of fibers.

Effect on weak spot distribution and life time

In Fig. 3 we qualitatively demonstrate the theoretical effect of the two-region power law to the weak spot distribution surviving a proof test[5]. The curves are strongly dependent on the n- and B-values of the fiber, but the principle is clear. At the relatively high fracture probabilities, i.e. less than 10^{-3} below the original fracture probability before proof test, the one region power law gives a too high estimation for the fracture probability.

But at the very weakest points and lowest fracture probabilities, i.e. more than 10^{-3} below the original fracture probability, the two region model gives a higher fracture probability. The crossing point of curves B (one region model) and C (two-region model) is highly dependent of the B-value and n-value at the low stress rates, i.e. in Region I.

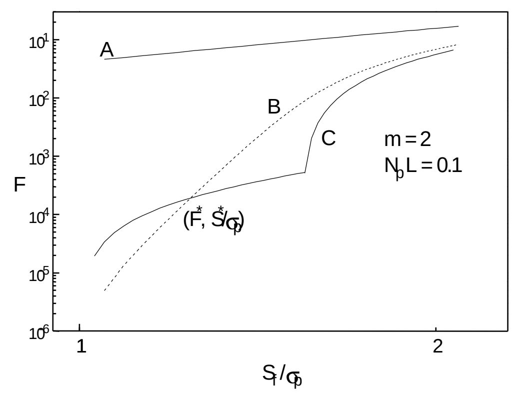

Fig. 3. Theoretical Weibull-plots of the fiber inert strength distribution before (A) and after proof testing: non-modified (B) and modified with regard for the two-region crack growth (C)[5]. B = 4.5×10^{-5} GPa^2s and n = 21 were used for non-modified plots A and B. $B_1 = 4.5\times10^{-5}$ GPa^2s; $n_1 = 21$; $B_2 = 8.2\times10^{-3}$ GPa^2s; $n_2 = 4.5$ and r = 0.645 were used for modified plot C.

4. EXPERIMENTS

The round robin test results

High stress rate measurements were carried out on this fiber at Corning, Inc., France Telecom and Telia. Also ‘normal’ and low stress rate dynamic and static fatigue measurements have been made in several laboratories. From the test results (Figs. 4 and 5) the following conclusions can be drawn for abraded Fiber J:

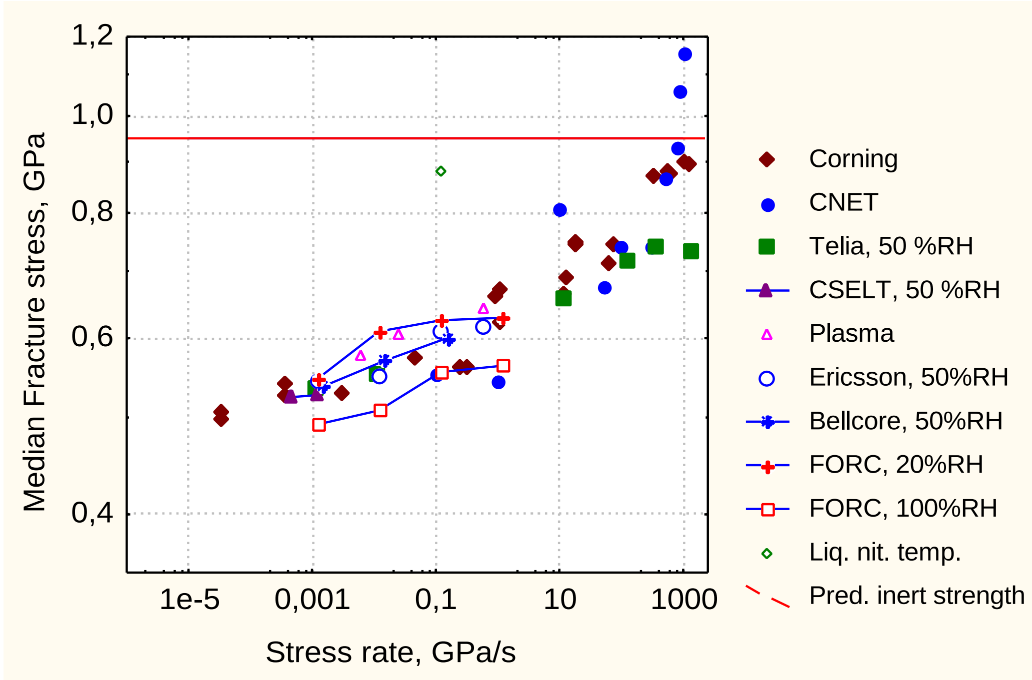

Fig. 4. The measured dynamic fatigue results of the round robin tests for abraded Fiber J measured at eight laboratories. Each point presents a median value of 20 - 30 samples. Gauge length was 500 mm except for one of the labs which had 100 mm.

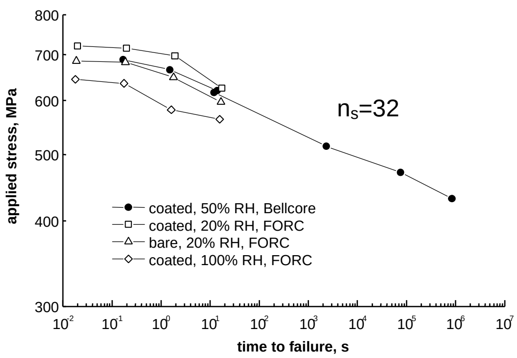

Fig. 5a. Dynamic and static fatigue of Fiber J.

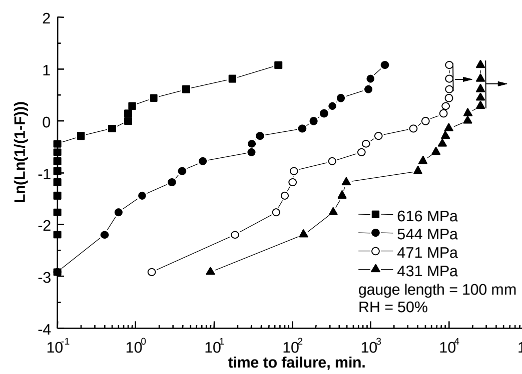

Fig. 5c. Static fatigue of Fiber J.

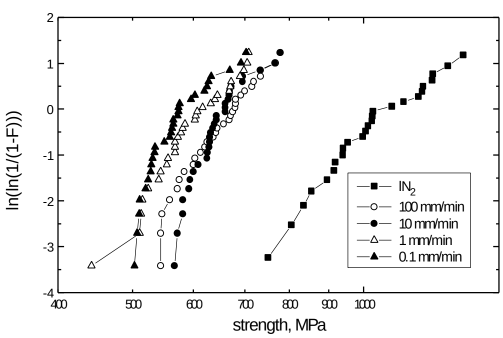

Fig. 5 b, Dynamic fatigue of Fiber J

- The low m-value (~12) makes it necessary to test a large number of samples.
- The n_1-value for Fiber J was 32 at the static tests (Fig. 5 a) and 40 at the lowest stress rates in Region I (Fig.4.); 40 - 50 at the intermediate stress rates 0.01 - 1 GPa/s, and very low, only 2 - 7, at the high stress rates in Region II.
- The predicted values by fitting the two-region power-law to the Corning data are the following: $B_1 = 1.4*10^{-10}$ GPa^2s; $B_2 = 0.0091$ GPa^2s, $n_1 = 45$, $n_2 = 2.3$ and r = 0.737 (with K_{IC} = 0 0.75 MPa√m). The prediction to the other data of Fig.4 (excluding FORC's data at 100 %RH and data from CNET) gave similar parameters.

- Inert strength 0.89 GPa was measured at liquid nitrogen temperature. Initial strength, predicted from Corning data by fitting the two region theory was slightly higher, 0.94 GPa in average.
- Thus the shift inert strength/strength at room conditions σ_I/σ_{RT} ~ 1.5 - 1.6 at the stress rate 0.01 GPa/s (~ 1%/min) and 1.3 - 1.4 at 0.1 GPa/s (~ 10 %/min).

The variation of the test results is caused partly by the different humidity of the test environment, and partly by measurement accuracy. The tensile test difference (shift) between laboratories, defined in earlier COST 246 comparisons on high strength fibers, is below ± 0.05 GPa. Also the scatter in the strength of Fiber J (low m) is causing a variation to the median values.

Comparison with other low strength fibers studied within COST 246

Different kinds of weak spots exist in optical fibers: surface abrasions caused by contact with drawing tower parts, imbedded particles of impurity materials, surface particles sublimated from oven material, crystallized particles such as silica, etc. etc. COST 246 earlier studied four types of abraded fibers[16], with imbedded chromium oxide metal particles inside the fiber glass, with zirconium particles on the fiber surface and abrasion against coating applicator dye of copper.

Fiber J of this work was abraded by drawing in contact with a crossing glass fibers. A similar fiber has been studied[16] earlier and the results are in good agreement with the results in this paper. A similar fiber has been studied by G. S. Glaesemann in ambient conditions and humid conditions[19]. The predicted parameters for ambient conditions (n_1= 28, n_2= 2.25, r = 0.81, B_1= 1.86 $10^{-7}GPa^2s$, B_2=4.39 10^{-3} GPa^2s, V_1= 0.187 m/s and V_2= 8.25 10^{-4} m/s) differed only slightly from the predicted parameters of this paper. At the 100 % RH the n-values are the same, B-values are lower and the critical crack growth velocities are higher.

Very recently dynamic and static fatigue was also measured[6] for a flat fiber which had been indented by using a cube-corner shaped diamond with an applied load of 1 gram. This fiber showed quite a narrow strength distribution (m ~ 50–70) and a very clear two- region behavior was found, with n-value ~44 (30 to 80) at intermediate stress rates and n_1 ~ 21 (17 to 25) at long times.

In addition, T. Volotinen reported at MRS Spring - 98 conference results for a test fiber abraded by drawing the bare fiber, prior to coating applicator, around small Teflon-coated wheels. The results indicated two-region behavior, similar to Fiber J of this paper.

Inert strength of weak spots

In theory, the initial strength (~ the length of a crack) at any environment is equal to the strength at inert environment. The critical stress intensity factor K_{Ic} (0.75 - 0.789 MPa√m)[15,12] is a material structure constant, which is thought to be independent of the environment. It is always reached at the border of Region 2 and 3 prior to a fracture of the fiber. However, the crack growth velocity V_c at the fracture is different depending on the environment, and the fracture can occur at different stress because of the crack growth.

The shift between inert and ambient strength is strongly dependent on the environment and both B- and n- values, as well as on the stress rate at which the inert strength and ambient strength are compared. In European countries it is usual to measure thestrength of fiber at 10 %/min strain rate (≈ 0.1 GPa/s), and in U.S. at a much lower strain rate 1%/min (≈ 0.01 GPa/s). Thus the published data must be compared with care.

Test results for fiber J show that the strength measured at liquid nitrogen temperature is only 1.3 - 1.4 times the strength at 0.1 GPa/s stress rate (≈ 10 %/min strain rate) whereas for the indented fiber it was about 1.5[6]. Other laboratories have reported shifts 1.3 - 2.0 for low strength fibers and 1.9 - 2.5 for high strength fibers. Thus, according to the worst case approximation[5], the strength of weakest surviving flaw after a quick (10 - 100 ms) proof test in ambient conditions is of the order 0.9 of proof test stress. Thus, the inert strength S_{pmin} of it is at least 1.2 - 1.4 of the proof test stress σ_p.

5. DISCUSSIONS

Limitation of the high speed measurements

The J-fiber data do not really show agreement in detail over the whole stress rate range. What they do show is that all laboratories show a reasonable agreement in the low stress rate regime and the three laboratories that did high rate testing, Corning, Telia and CNET, show that at high stress rates a second region appears. For the cube-corner indentation fiber[6], essentially the liquid nitrogen strength (~90%) was reached, at the highest rates, which is an indication that the data is close to the truth.

The very large, eight decades spread in B-values, which is continually referred to, is the result, primarily of the Telia and France Telecom data on high strength fibers. However, it can now be understood why there is this curvature in the dynamic fatigue curve at the stress rates 10 - 1000 GPa/s. The measurement data and the curvature are qualitatively correct. However, the assumption that the initial strength is at the level of the curvature is not correct. The curvature only indicates the transition between Regions I and II.

It is now clear from Fig. 2 of S. Semjonov et al[4] that obtaining inert strengths at room temperature on high strength fibers would require stress rates three decades of magnitude higher than presently available at any laboratory. We see large disagreement between the three laboratories' data at the high stress rates (Fig.4) for Fiber J. COST 246 also analyzed the technical aspects of the pieces of equipment used and the reasons for the possible accuracy problems internally.

For the determination of the B- and n-value of Region I, fatigue tests at low stress rates together with inert strength measurements can be used. In order to reach the inert strength of weak fibers by high stress rates measurements, equipment with adequate accuracy is required.

Life time estimation of optical fibers in real service environment

20 years of experience from the field all over the world with over 100 million kilometers of optical fibers installed, has shown that the fibers do not seem to fracture frequently. Partly this is due to the fact that the applied stresses in the fibers are on average significantly lower than 1/4 of proof test stress. Furthermore, this suggests that the static fatigue of fiber weak spots is not very well estimated with the one-region power-law approximation by using n-value measured on high strength fibers and B-value assumed to be negligible.

The test results of this work show that the B-value for long term static fatigue is low, below 10^{-5} GPa^2s. Therefore the first doubt regarding the Mitsunaga model is solved. However, the minimum life time equation can be used only if the accurate B- and n-value of Region I and the inert strength (= initial length of the crack after proof test) of the weakest spot are known. To calculate the effect of a quick proof test, the two-region model with Region II parameters is needed.

The two-region model can explain the delayed fatigue (the distribution of cracks after proof test is better than assumed, the n_1- and B_1-values of the weak spots can be more favorable for long life), as well as the dependency of n-value on loading time and both high and low B-values obtained.

For the life time calculation of fibers in cable networks, the n- and B- values of Region I must be used. They should be measured on weak spots in the service environment by using very long loading times, far away from the transition between Regions I and II.

The accuracy of the estimations made by using one-region model based Mitsunaga- equation is very much dependent on the distribution of the weak spots and of the B-value (assumes it being negligible) and n-value. The parameters of the surviving weak spot distributions are affected by the two region behavior, and both too conservative or too optimistic estimations can be made depending on the allowed maximum fracture probability.

There are indications[18], but it is not yet completely shown, that both B_1-value and n_1-value of weak spots are different from the values measured for high strength fibers. This subject should be studied further.

The discussion in this paper does not consider the possible long term changes in the static fatigue, which can be caused by any kind of aging, or reaching of a chemical equilibrium of the dissolution reaction of silica, or by a change of the chemical or physical environment.

6. CONCLUSIONS

The mechanical behavior of high strength and abraded (proof test level) fibers have been tested by different laboratories at a wide range of dynamic stress rates and on static stresses. This was done in order to find answers to the questions about the B-value magnitude, measurement method and about the life time estimation methods. Although measurement results diverge slightly, the results show that the one-region power-law model can not describe the test results, but the two region power law can. The differences of the results at the highest stress rates are due to the testing accuracy and the test environment rather than the fiber.

Studies on an indented and some other weak fibers also show a two -region behavior. However, studies on other specific types of weak spots should be carried on in order to draw final conclusions about general behavior of weak spots in optical fibers.

The answers to the problems are the following:

- A) The low value levels of B-value, below 10^{-5} GPa^2s are correct for the long term static fatigue of the weak spots of fibers. Also the n-value is dependent on stress rate, and thus it must be ascertained that both n- and B-values used for the life time calculations represent Region1.
- B) The mechanical behavior parameters (n-value and B-value), which are measured on high strength fibers in Region I, i.e. at low stress rates or in static tests at low stresses are probably usable. However, the very best are the values of Region I measured directly on the weak spots of the fibers.
- C) The recommended method to predict B-value of a fiber for life time estimation includes two steps: to measure inert strength of weak spots at liquid nitrogen temperature or high vacuum, and to measure dynamic or static fatigue of the weak spots at the environment of application in Region I (at very low stress rates or static stresses). The high speed measurements can also be used, if the accuracy is ascertained. The B-value of Region II of weak fibers can be obtained from the high speed tests. It is needed for estimation of the effect of proof test. None of the available instruments can reach the high stress rates necessary to reliably measure the inert strength of high strength fibers.
- D) The initial strength of fiber weak spots (the proof test level cracks) is about 1.5 times the measured strength at low stress rate, 0.01 GPa/s ≈ 1 %/min strain rate, under room conditions.
- E) The crack growth process of fiber weak flaws can be described by the two-region model, and both B- and n-value of fibers are dependent on the loading time and the environment. Because the B-value is strongly dependent on the environment, the transition from Region I to II may occur at the stress rates normally used. Thus both too low and too high n-values can be reached, if the prediction is done by assuming only one-region behavior. The intermediate transition regime between Regions I and II explains the leveling of fatigue curves measured by high-speed tests on high strength fibers, - not the reaching of the initial strength.

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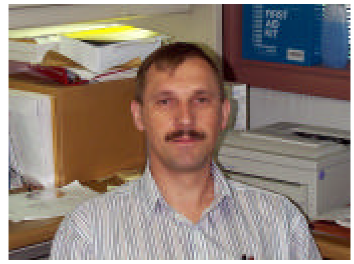

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