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TIME-DEPENDENT STRENGTH OF OPTICAL FIBERS

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The results of strength investigations of optical fibers with two-layers coat in dynamic fatigue measurements have been presented in this paper. Strength was measured at three strain rates in ambient air and aqueous solution. The results obtained were worked out using a stress-corrosion model, for which fracture mechanics laws were applied. An increase in relative humidity leads to an acceleration of flaw growth. Predicted strength of optical fibre, based on a dynamic fatigue test, agrees with static fatigue measurements.

Key words: optical fibres, fatigue, stress-corrosion model

1. Introduction

Application of optical fibers to optical communication offers numerous merits. There are some advantages of replacing traditional conductors by silica glass fibers; e.g., small cross-section, low weight, wide frequency range, low dielectric losses. However, glass is a brittle material and its strength is determined by effects of environment. Numerous flaws occur in the optical fibre. They affect fiber strength accidentally. Flaw appearing in the glass fibre propagates as a result of small strains and stresses, the fibres in the cable are subjected to. Such a fibre may be broken at some time, as an effect of constant stress (lower than the strength) acting. In the case of silica glass it was found that a decrease in its strength is caused by the stress-corrosion process with water as a predominant factor (cf Michalske et al. (1983); Wiederhorn (1975)).

During the service life in optical communication ($30 \div 40$ years), mechanical reliability of optical fibres is the basic feature ensuring their proper functioning. Strength of fibres applied to telecommunication must be known perfectly well. Moisture cannot always be excluded from the optical fibre cable, so the effect of relative humidity on the time of reliable service life should be established. Investigations of static fatigue are excessively time-consuming. Therefore, it would be helpful to establish a mathematical model for time-dependent fracture that can be used with momentary measurements of the physical parameters. The general theoretical basis is that the atomic mechanism for constant stress flaw growth is identical to that for constant stress rate flaw growth. The theory for damage prediction in glass and ceramics is deduced mainly from the theory of fracture mechanics (cf Evans et al. (1974); Wiederhorn (1978)). Analytical relations to determine the static fatigue and dynamic fatigue are based on the Charles power model of flaw growth (cf Charles (1958a,b), (1975)) and its extension in fracture mechanics terms by Evans and Wiederhorn (cf Evans et al. (1974); Evans (1974)). Among theories concerning mechanisms of glass fracture as a result of static fatigue, the most favourable is the stress-corrosion mechanism developed by Charles and Hillig (cf Charles (1958); Charles et al. (1961); Hillig et al. (1965)). It leads – like diffusion (cf Cox (1969)) and plastic flow (cf Weidmann et al. (1974)) mechanisms – to a relation between the static fatigue strength σ_s and the time-to-failure t_s.

The aim of the present paper is to examine usefulness of dynamic fatigue tests in forecasting of optical fibre durability at constant load (static fatigue). The effect of humidity on the dynamic fatigue life of optical fibres has been also investigated.

2. Experimental procedure

The optical fibre with two-layers coat made of the soft silicone rubber Sigel 600 – inner layer and the lacquer De Solit 101 – outer layer was used. The glass fibre-core and coat were made of silica glass. Characteristics of that optical fibre was inserted in Szabelski and Banaszek (1993), Szabelski et al. (1993).

Tensile strength was tested in ambient air (23°C, about 55% rh) on $L = 250$ mm – gauge length specimens. Those specimens issued from the same batch of product and were fixed in the roller handle. Three traverse speeds were used, $1.667 \cdot 10^{-4}$, $4.167 \cdot 10^{-4}$ and $8.333 \cdot 10^{-4}$ m/s, which were equivalent to the stress rates of 15.10; 37.75 and 75.50 MPa/s, respectively. At each stress rate, 25÷34 replicate tests were performed. To examine the effect of environment, the investigations were carried out in 4% solution of NaCl. In that case, at each stress rate, about 10 ÷ 13 results were obtained. Static fatigue tests were performed on the test stand designed specially for that purpose. Applied constant load produced stress $\sigma_s = 2470\,\mathrm{MPa}$. 20 measurements of durability were made in that test. Strength investigations in the inert environment were carried out in dry nitrogen atmosphere. To exclude moisture, the optical fibre was kept in vacuum before the test. Fifteen replicate tests at traverse speed $1.667 \cdot 10^{-4}$ m/s gave a median strength of $\sigma_{1c} = 4895\,\mathrm{MPa}$. Detailed description of investigations and their results were presented in Szabelski et al (1987), Szabelski et al. (1989).

3. Results and discussion

The flaw growth model of Charles (1958) assumes that the flaw velocity v is a power function of stress and an exponential function of temperature

$$v = C_1(\sigma_m)^n \exp\Big(-\frac{Q_1}{RT}\Big) \tag{3.1}$$

where

C_1, n	–	characteristic constants for a material and environment, respectively
σ_m	–	tensile stress at the flaw tip
Q_1	–	activation energy
R	–	gas constant
T	–	temperature.

In the case of constant stress σ_s at a constant temperature, the time-to-failure t_s – by virtue of Eq (3.1) – is expressed by

$$\log t_s = -n \log \sigma_s + \log C_s \tag{3.2}$$

Similarly, Charles (1958) showed that for dynamic fatigue

$$\log t_d = -n \log \sigma_d + \log C_d \tag{3.3}$$

or

$$\log \sigma_d = \frac{1}{n+1} \log \dot{\sigma} + \frac{1}{n+1} \log C_d \tag{3.4}$$

where

σ_d	–	dynamic fatigue strength
t_d	–	time-to-failure in dynamic fatigue
$\dot{\sigma}$	–	stressing rate.

The constants C_s and C_d are linked by

$$\log C_d = \log C_s + \log(n+1) \tag{3.5}$$

Fracture mechanics gives an alternative approach to description of the glass time-dependent strength. Evans (1974) also Evans and Wiederhorn (1974) using a power law for flaw velocity depending on the stress intensity factor $K_1(v = da/dt = AK_1)$, basing on fracture mechanics presented approach analogous to the Charles and Hillig stress-corrosion model (1961). The time-to-failure is expressed by

$$\log t_s = -n \log \sigma_s + \log C_s^* \tag{3.6}$$

where

$$C_s^* = \frac{2}{AY^2(n-2)} \Big(\frac{K_{1c}}{\sigma_{1c}}\Big)^{2-n}$$

and

K_{1c} – critical stress intensity factor
σ_{1c} – inert environment fracture strength
A, n – characteristic crack-growth parameters
Y – geometric constant.

Eq (3.6) is analogous to Eq (3.2) and $C_s^* = C_s$. Eqs (3.2) and (3.4) are used more often to estimate static and dynamic fatigue.

On the ground of presented relations we obtain

$$\log C_s = \log \frac{2\sigma_{1c}^{n-2}}{AY^2(n-2)K_{1c}^{n-2}} = \log\Big(B\sigma_{1c}^{n-2}\Big) \tag{3.7}$$

Eq (3.4) takes the form

$$\log \sigma_d = \frac{1}{n-1}\Big[\log \dot{\sigma} + \log(n+1) + (n-2)\log \sigma_{1c} + \log B\Big] \tag{3.8}$$

The tensile fracture strength in a dynamic fatigue test versus stress rate may be plotted. Then we read parameter n from the slope $1/(n+1)$ according to Eq (3.8). If K_{1c} and Y are unknown, the point a representing intersection of the function $\log \sigma_d = f(\dot{\sigma})$ with the coordinate axis is expressed, basing on Eq (3.8), by relation

$$a = \frac{1}{n+1}\Big[\log(n+1) + (n-2)\log \sigma_{1c} + \log B\Big] \tag{3.9}$$

Right-hand side of Eq (3.9) presents also the value of $(n+1)^{-1} \log C_d$.

Hence

$$\log C_d = \log(n+1) + (n-2)\log\sigma_{1c} + \log B \tag{3.10}$$

Calculating the flaw-growth parameter A, one can use the intersection point of $\sigma_d = f(\dot\sigma)$ plot with the coordinate axis according to

$$\log A = \log(n+1) + (n-2)\log\sigma_{1c} + \log\frac{2}{Y^2(n-2)K_{1c}^{n-2}} - \log C_d \tag{3.11}$$

Comparing the equation of least squares line at dynamic fatigue ($\log\sigma = a + b\log\dot\sigma$) with Eq (3.8), the flaw growth parameters n and B may be written

$$\frac{1}{n+1} = b \tag{3.12}$$

$$\log B = a(n+1) - \log(n+1) - (n-2)\log\sigma_{1c} \tag{3.13}$$

Introducing Eq (3.13) into Eq (3.10) and using Eq (3.5), we obtain Eq (3.2) in function of the flaw-growth parameter n and estimated value $\log\sigma_d$ for $\log\dot\sigma = 1 - a$ at dynamic fatigue test. Eq (3.2) determining its durability at a constant load in function of dynamic test parameters takes the form

$$\log t_s = -n\log\sigma_s - \log(n+1) + a(n+1) \tag{3.14}$$

In dynamic fatigue investigations the relations between σ_d and $\dot\sigma$ were analyzed (σ_d was median or mean of the strength results obtained). Taking the correlation coefficient ($r = 0.886 \div 0.881$) into account, median was chosen for further analysis (for 50% failure probability). To enhance reliability of the results obtained, apart from median, homologous stress σ_d/σ_{1c}) is introduced into Eq (3.8). As it was shown (cf Ritter et al. (1978)) that such analyses give convergent values of flaw-growth parameters.

Fig.1 shows σ_d (median) versus $\dot\sigma$ plot for ambient air and liquid, respectively. Analysis of the least squares for median in ambient air and liquid results in equations of the least squares line, respectively

$$\begin{aligned} \log\sigma_d &= 3.529 + 0.0325\log\dot\sigma \\ \log\sigma_d &= 3.323 + 0.0630\log\dot\sigma \end{aligned} \tag{3.15}$$

The flaw-growth parameters n and B are determined form Eqs (3.12) and (3.13). Fig.1 shows the values of exponent n. It is noticeable that increase in humidity leads to acceleration of flaw-growth. The value of n decreases from 29.8 in ambient air to 14.9 in NaCl solution.

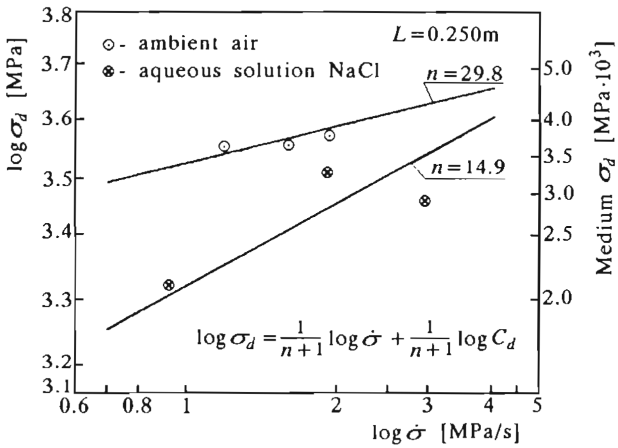

Fig. 1. Effect of relative humidity on dynamic fatigue of the optical fibre

As for fused silica optical fibres, the value of n amounts: $21 \div 24$ in the ambient air at 23°C and $14 \div 17$ in 97% rh at 23°C (cf Kalish et al. (1977)). The same authors (cf Kalish et al. (1978)) announced that in ambient humidity $n = 20 \div 25$, whereas in high humidities the value of n decreases to 15. In other investigations (cf Ritter et al. (1978)), $n = 22.33$ was obtained in ambient air at 23°C and 55% rh.

In silica glass in an ambient atmosphere (rh 60%, 25°C) in static fatigue measurements $n = 39.8$, whereas in dynamic fatigue measurements $n = 41.8$ (cf Hibino et al. (1984)). For silica fibres of low strength revealing macroscope flaws, which were examined in the air at 23°C and 60% rh, $n \approx 40$ (cf Hibino et al. (1984); Sakaguki et al. (1984)).

The values of parameters B, C_d and C_s depend on the strength in inert environment, which is property of each samples population. Their comparison does not seem advisable. Thus the parameter n is characteristic in strength investigations of optical fibres. Considerable discrepancy in the values published of n is observed. It is perceptible, that in high humidity of environment or in water optical fibres with coat reveal considerably smaller values of n in comparison with those obtained in ambient atmosphere humidity.

As for the values of n obtained in our investigations:

- $n = 29.8$ (in ambient air) – is convergent with data presented in the papers

- $n = 15.9$ (in water solution) – is very close to data presented in the papers.

They can be used to forecasting of the time-dependent strength.

The results of dynamic fatigue measurements were used to forecasting of median of optical fibre subjected to a constant stress. Prediction of static fatigue was made according to Eq (3.2) which then took the form Eq (3.14). The following parameters were assumed for calculations: $n = 29.8$; $\log(n+1) = 1.448$; $a = 3.529$ (obtained in dynamic fatigue measurements). Prediction was made for the following stresses σ_s: 2000; 3000; 3800 MPa. Fig.2 shows the predicted static fatigue curve (median line) for the optical fibre with 250 mm-gage-length.

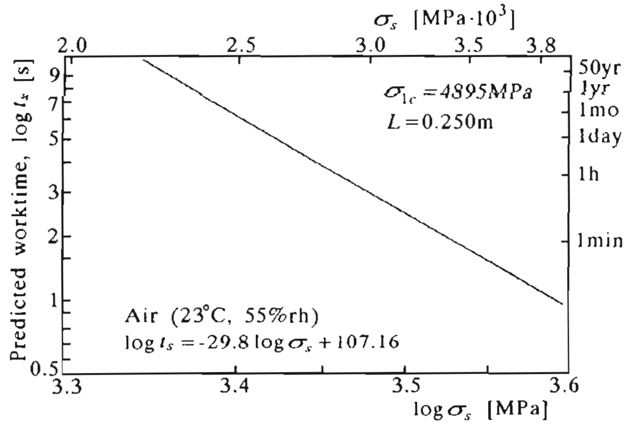

Fig. 2. Predicted static fatigue behaviour from dynamic fatigue measurements for the optical fibre made of silica glass

Assuming from the equation of least squares line for predicted durabilities (for 50% probability of optical fibre failure) under σ_s stress, the value of constant $C_s^* = 107.16$ (estimation of $\log t_s$ for $\sigma_s = 1$ MPa), Eq (3.6) of predicted static fatigue in the ambient air can be written as

$$\log t_s = -29.8 \log \sigma_s + 107.16 \tag{3.16}$$

Fig.3 is a comparison of the predicted static fatigue behaviour from dynamic fatigue and direct static fatigue measurements.

The static fatigue prediction is denoted by crosses in circles. The results of static fatigue measurements ($\sigma_s = 2470$ MPa; $\log \sigma_s = 3.393$) in twenty samples are denoted by dots in circles. Convergence of direct measurement

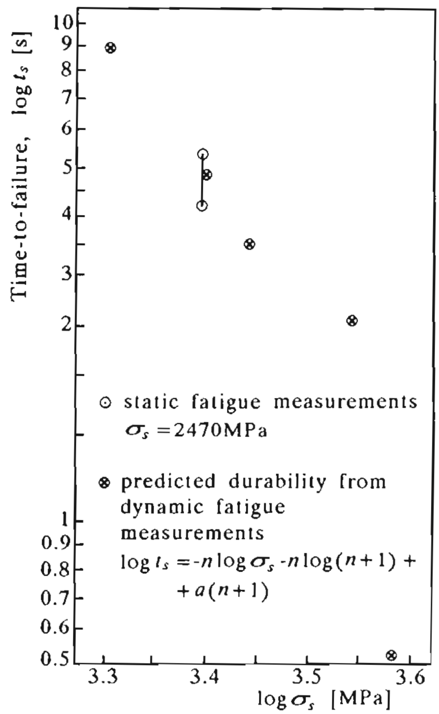

Fig. 3. Comparision of static fatigue prediction based on dynamic fatigue measurements with the static fatigue measurements

results with the predicted ones (from dynamic fatigue) is observable. Median of measurements results amounts 1388265 s — $\log t_s = 6.142$, whereas the predicted value of durability amounts 1238796 s – $\log t_s = 6.039$. It makes about 90% (89.2%) of the results obtained in direct measurements. Similar predicted and measured values prove that the values of determined parameters (n and C_s^*) are close to the real ones. One can maintain that the predicted static fatigue behaviour – with high probability determines the optical fibre time-dependent strength.

4. Conclusions

Strength investigations of optical fibres in static and dynamic fatigue measurements were carried out to check prediction possibility of the optical fibre mechanic reliability based on a dynamic fatigue test. The analytical relation between optical fibre strength obtained in both tests is very important also from a practical point of view. The problem is how to shorten time-consuming tests while determining the time-dependent strength. Parameters describing static fatigue can be determined from dynamic fatigue tests. Investigations (cf Kalish et al. (1977) and (1978)) giving good compatibility with results the obtained prove that fact. However, high precision should be kept while carrying out experiment and the flaw-growth parameters (n and a) obtained from dynamic fatigue test should be used contiously. Great scattering of durability evidence that the flaw-growth and optical fibre failure mechanisms are very complex. The flaw-growth parameters obtained from dynamic fatigue test may not correspond exactly to the results from static fatigue test. The results of presented investigations and those published in the papers prove that the described model gives sufficient reliability in preliminary determining of the time-dependent strength.

The flaw-growth parameter n characterizes the optical fibre strength both in dynamic and static fatigue. The essential effect of relative humidity on the strength of optical fibres is confirmed. The flaw-growth velocity increases as the relative humidity increases. It is due to surface energy changes. Water occurring on the flaw surface – directly from the environment or by humid air condensation – makes obstacle (screen) for interaction of atoms in glass. It results in surface energy decrease at the flaw tip. As a consequence of this, decrease in the glass strength (which is a function of surface energy) occurs.

Increase in the tensile force in the glass element, appearing in long-lasting experiment (cf Banaszek (1995)) suggests the assumption that in static fatigue measurements the whole load is transferred only by a silica fibre.

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Wytrzymałość zależna od czasu włókien światłowodowych

Streszczenie

W pracy omówiono wyniki badań wytrzymałościowych włókien światłowodowych z powłoką dwuwarstwową w teście obciążenia rosnącego ze stałą prędkością (dynamicznym), dla trzech prędkości odkształcenia w środowisku otaczającego powietrza i roztworu wodnego. Wyniki tych prób opracowano przyjmując model korozji naprężeniowej, do którego zastosowano prawa mechaniki pękania. Wzrost wilgotności środowiska prowadzi do przyspieszenia rozwoju wady. Przewidywana na podstawie wyników testu dynamicznego wytrzymałość długotrwała włókna światłowodowego jest zbieżna ze zmierzonymi czasami pękania w próbach pod obciążeniem stałym.

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