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Effect of temperature on the strength and fatigue behaviour of optical fibres

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The fatigue behaviour of a polymer-coated fibre and a silicon oxynitride-coated fibre was measured in water between 25 and 90° C by the dynamic fatigue test technique where strength is measured as a function of stressing rate. The results are analysed in terms of stress corrosion theory. It was found that the silicon oxynitride coating reduced fatigue significantly, but caused a large reduction in strength of the fibre. The implications of these results to the design of optical fibre communication cables, where a high reliability must be assured, is discussed.

1. Introduction

Considerable research has shown that optical fibres exhibit all the fatigue characteristics of bulk glass samples [1–7]. Fibres, loaded rapidly or forced to support a given load for a short time, are relatively strong, whereas fibres are relatively weak if loaded slowly or forced to support a load for a long time. Furthermore, the strength of fibres decreases as temperature increases and the relative humidity of the surrounding environment increases, fibres being weakest when tested immersed in water. Thus, reliable data on the fatigue behaviour of fibres in a moist environment as a function of temperature is needed to ensure the high reliability required for communication systems.

To evaluate the fatigue characteristics of different optical glass fibres, a test was developed whereby fracture strength of a given fibre is measured in water as a function of stressing rate over a range of temperatures. Analysis of the dynamic fatigue data gives a measure of the fatigue resistance of the fibre and the activation energy for the fatigue process. To demonstrate the effectiveness of this test the fatigue properties of a polymer-coated fibre were compared with a silicon oxynitride-coated fibre.

2. Experimental procedure

Two types of optical glass fibres were used in this study. The first was a 126 μm diameter fused silica core coated with uv-curable polyurethane acrylate and manufactured by Bell Laboratories. The second was a 140 μm diameter Suprasil^{TM} core coated "in-line" with a thin layer of silicon oxynitride followed by a thermally cured layer of silicone and Hytrel coating [8]. The silicon oxynitride coating is thought to provide a hermetic seal which minimizes fatigue effects.

The fatigue resistance of the fibres was measured in distilled water at 25, 45, 65 and 90° C by the dynamic fatigue technique [5] where fracture strength is determined as a function of constant stressing rate. The test apparatus was similar to that used by Chandan and Kalish [1] where the gauge length portion of the fibre (0.1 m) was immersed in water contained in a glass tube, closed at the bottom by a serum bottle stopper and at the top by a foam cork to prevent condensation on the fibre outside the gauge length at elevated temperatures. The fibres were threaded through the serum bottle stopper and foam cork with a hypodermic needle and gripped top and bottom by 0.1 m capstan grips fitted to a universal testing machine.* The temperature of the water was maintained by a constant temperature circulator bath† connected to the glass tube apparatus. Stressing rates for the dynamic fatigue tests ranged from

*Instron Corp., Canton, Massachusetts, USA.
†Fisher Scientific Co, Pittsburgh, Pennsylvania 15219, USA.

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0.111 to 150 MPa sec^{-1}, corresponding to crosshead speeds of 0.005 to 5 cm min^{-1}, respectively. All samples were randomized prior to the test programme to prevent any systematic error from propagating through the data. A minimum of 20 specimens per test condition were used to characterize the strength distribution.

The strength of the fibre samples was also measured at a stressing rate of 140 MPa sec^{-1} in a test environment of dry nitrogen gas to determine their strength in an inert environment, i.e. an environment where no subcritical crack growth occurs. Prior to the inert strength tests, all the samples were placed in a vacuum ($< 10^{-2}$ torr) for over 100 h to help eliminate any moisture in the coating of the fibres.

For comparison with the above glass fibre data, the strength of abraded and annealed soda-lime glass microscope slides was measured in water using four-point bending over a similar stressing rate and temperature range. The inert strength of these samples was determined with the samples wetted with mineral oil.

3. Results

Based on fracture mechanics principles, fatigue failure is caused by the stress-enhanced growth of a pre-existing flaw to dimensions critical for catastrophic failure. The crack growth model that has demonstrated the best capability for explaining the fatigue in glass systems is that due originally to Hillig and Charles [9] and later put into fracture mechanics terms by Wiederhorn and co-workers [10, 11]. Wiederhorn assumed that crack velocity is governed by the rate of chemical reaction at the crack tip and that atomically sharp cracks grow with a constant tip radius. He then derived that crack velocity is related to the stress intensity factor (K_I) by [10, 11]:

$$v = a \exp(-E^*/RT) \exp(nK_I/K_{IC}RT) \quad (1)$$

where E^* is an empirical measure of the zero stress activation energy of the stress corrosion reaction, R is the gas constant, T is the absolute temperature, K_{IC} is the critical stress intensity factor, and a and n are constants. Wiederhorn determined the constants n and E^* for a variety of glasses by fitting a series of crack velocity/stress intensity factor curves for a given glass in water over the temperature range 2 to 90° C. Table I summarizes these results.

For a given glass and temperature, Equation 1 can be numerically integrated to yield fracture strength (σ_f) as a function of stressing rate ($\dot{\sigma}$) [12]:

$$\sigma_f/\dot{\sigma} = (2K_{IC}^2/S_i^2 Y^2 A) \exp(-n\sigma_f/S_i RT) \quad (2)$$

where $A = a \exp(-E^*/RT)$, Y is a geometric constant equal to approximately $\pi^{1/2}$, and S_i is the inert strength, i.e. the strength determined in an environment where no subcritical crack growth occurs. Rearranging Equation 2 gives:

$$\ln(\sigma_f/\dot{\sigma}) = \alpha + \beta/T + \gamma\sigma_f/T \quad (3)$$

where $\alpha = \ln(2K_{IC}^2/S_i^2 Y^2 a)$, $\beta = E^*/R$, and $\gamma = -n/RS_i$. Therefore, a trivariant regression of Equation 3 with $\bar{\sigma}_f/\dot{\sigma}$ as the dependent variable ($\bar{\sigma}_f$ is the median fracture strength) and $1/T$ and $\bar{\sigma}_f/T$ as the independent variables will yield the constants α, β and γ from which the constants E^* and a can be determined knowing the median inert strength ($\bar{S}_i$). Table II summarizes the inert strength data which was fitted to a two parameter Weibull function:

$$\ln\ln(1/1 - F) = m \ln(S_i/S_0) \quad (4)$$

where F is the cumulative failure probability and m and S_0 are the Weibull slope and scale parameters, respectively. The median inert strength ($\bar{S}_i$) is obtained from the appropriate Weibull relationship where $F = 0.5$.

A summary of the dynamic fatigue data for the

TABLE I Summary of the stress corrosion constants in water as determined from [10]

Glass	E	E^* (kJ mol^{-1})	n (kJ mol^{-1})†
Silica		138.6 (4.2)‡	170.4 (4.7)
Aluminosilicate I		121.4 (2.9)	125.3 (2.7)
Aluminosilicate II		126.0 (2.5)	148.9 (2.7)
Borosilicate		128.9 (3.4)	155.6 (3.9)
Lead-alkali		105.5 (5.0)	98.2 (4.1)
Soda-lime-silica		108.8 (4.6)	82.4 (3.0)

†It should be noted that the constant n used in this paper is related to the constant b used in [10] by $n = bK_{IC}$.
‡Number in parentheses represents one standard deviation.

TABLE II Inert strength data as measured in dry nitrogen gas

Fibre	Weibull parameters		Median strength (MPa)
	m	S_0	
Polymer-coated	27.1	5697	5620
Silicon oxynitride-coated	41.1	3307	3278

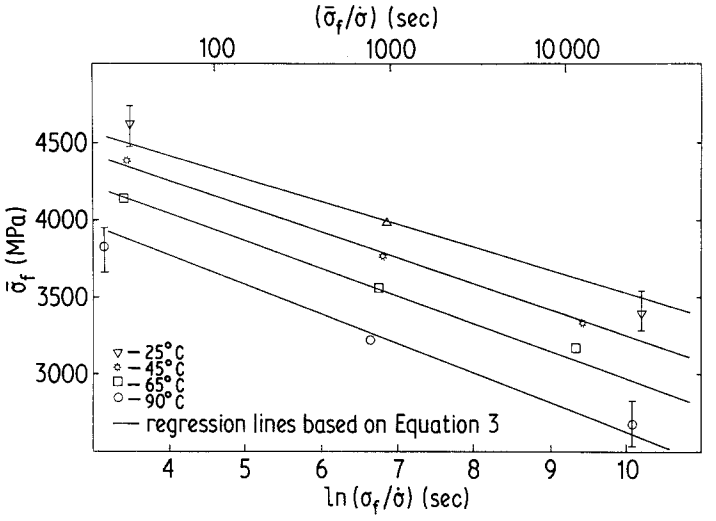

Figure 1 Dynamic fatigue data of a polymer-coated optical glass fibre in water as a function of temperature. Error bars represent one standard deviation.

polymer and silicon oxynitride-coated optical fibres is given in Figs. 1 and 2, respectively. It should be noted that the solid lines in these figures represent the overall best fit of the data considering simultaneously both temperature and stressing rate as given by Equation 3. From the data it can be seen that the silicon oxynitride-coated fibre is considerably weaker than the polymer-coated fibre. This lower strength has been attributed to a deposition-induced residual stress in the surface of the glass fibre that is brought about by a non-equilibrium atomic arrangement within the silicon oxynitride coating [8]. This residual stress has been estimated to be equal to 300 to 1300 MPa, depending on the elastic modulus of the silicon oxynitride coating [8]. To properly analyse the stress corrosion constants, the residual stress must be added to the fracture strength before the data are analysed. Taking the residual stress to be 500 MPa, which corresponds to an elastic modulus of the coating of 172 GPa [13], the data for the silicon oxynitride-coated fibre were analysed in terms of Equation 3 and the results are summarized in Tables III and IV, along with those obtained from an analysis of the data for the polymer-coated fibre. The lines fitted through the data shown in Figs. 1 and 2 are those obtained from Equation 3. Also included in Table IV are the stress corrosion constants determined from the dynamic fatigue data of abraded and annealed soda-lime glass microscope slides.

4. Discussion

Based on crack velocity measurements, Table I

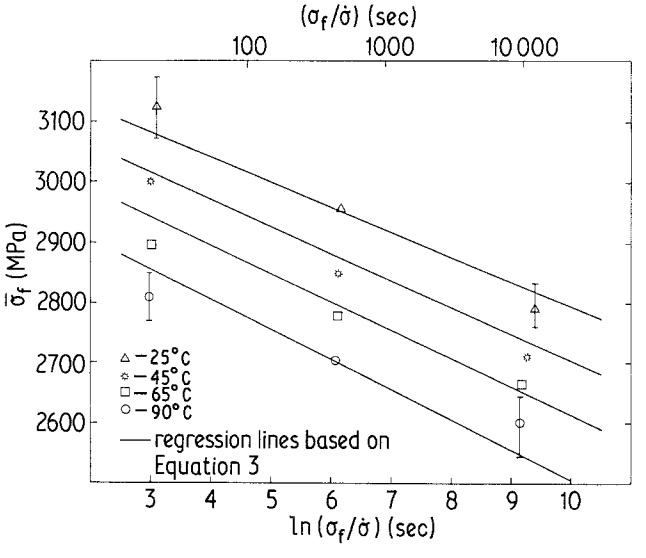

Figure 2 Dynamic fatigue data of a silicon oxynitride-coated optical glass fibre in water as a function of temperature. Error bars represent one standard deviation.

TABLE III Summary of the trivariant regression constants as determined from fatigue results in water using Equation 3

Glass	α (ln sec)	β ($\times 10^3$ K)	γ (K MPa^{-1})
Polymer-coated fibre	−16.02 (2.90)†	14.38 (1.19)	11.87 (0.11)
Silicon oxynitride-coated fibre	−22.24 (5.73)	33.01 (4.06)	7.10 (0.81)

†Number in parentheses represents one standard deviation.

shows that the stress corrosion constants depend strongly on glass composition. Values for activation energy at zero stress range from 109 to 139 kJ mol^{-1} and the stress intensity coefficient, n, varies by nearly a factor of 2. Higher values of n indicate a greater fatigue resistance and higher values of E^* imply a lower sensitivity of the fatigue process to temperature. Thus, fused silica represents the best glass in terms of resistance to fatigue and soda-lime glass the worst.

From Table IV it is seen that there is reasonably good agreement in the stress corrosion constants n and E^* for soda-lime glass obtained from dynamic fatigue strength measurements and those determined directly from crack velocity measurements (Table I). The polymer-coated glass fibre has stress corrosion constants n and E^* similar to lead-alkali but most important is the fact that stress corrosion constants for the polymer-coated fibre are in the range of those observed for a variety of commercial glasses. Thus, it is believed that the role of the polymer coating is primarily to prevent strength degradation due to mechanical abasion and not to minimize fatigue effects. On the other hand, the significantly higher values of the stress corrosion constants E^* and n for the silicon oxynitride-coated fibre suggests that the coating significantly reduces the fatigue susceptibility. The superior fatigue resistance of this fibre has been attributed to the silicon oxynitride coating acting as a hermetic seal which effectively limits the availability of moisture to the glass surface [8]. Unfortunately, this silicon oxynitride coating causes a large reduction in the fibre strength due to the residual tensile stress. Thus, the greater fatigue resistance of this fibre is somewhat counterbalanced by its lower strength.

TABLE IV Summary of the stress corrosion constants determined in water

Glass	E^* (kJ mol^{-1})	n (kJ mol^{-1})
Polymer-coated fibre	119.5 (9.9)†	87.65 (6.56)
Silicon oxynitride-coated fibre	274.5 (33.8)	223.13 (26.20)
Soda-lime glass	77.9 (28.1)	91.8 (22.08)

†Number in parentheses represents one standard deviation.

The contrasting fatigue results discussed above for the two optical glass fibres can be better understood in terms of lifetime prediction diagrams. Lifetime diagrams give the required strength for a given lifetime and applied for a fibre in a given test environment. From the required strength the probability of failure can be calculated knowing the appropriate strength distribution for the fibre. For constant stress (σ_a) loading, Equation 1 can be integrated to give the time-to-failure as [12, 14]:

$$t_f = \frac{2K_{IC}^2}{\sigma_a^2 Y^2 A}\frac{RT}{n}\left[\exp\left(-\frac{n}{RT}\frac{\sigma_a}{S_i}\right)\right]\left(\frac{\sigma_a}{S_i}+\frac{RT}{n}\right) \quad (5)$$

Rearranging Equation 5 gives:

$$\ln \sigma_a^2 t_f = \ln\left(\frac{BRT}{n}\right) + \frac{E^*}{RT} - \frac{n}{RT}\left(\frac{\sigma_a}{S_i}\right) + \ln\left(\frac{\sigma_a}{S_i}+\frac{RT}{n}\right) \quad (6)$$

where $B = 2K_{IC}^2/Y^2 a$ is a constant that can be determined from the dynamic fatigue data since $B = \bar{S}_i \exp(\alpha)$. Fig. 3 gives the lifetime diagram based on Equation 6 for the polymer- and silicon oxynitride-coated fibres using the stress corrosion constants obtained at 25 and 90° C (Table IV).

From Fig. 3 it can be seen that for a given lifetime and applied stress in service, the required strength increases as the temperature in service increases. For example, for a 40 yr lifetime at 1100 MPa the required inert strength for the silicon oxynitride-coated fibre at 25° C is 1519 MPa and at 90° C it is 1789 MPa. Under these same service requirements the required inert strength of the polymer-coated fibre at 25° C is 3971 MPa and at 90° C is it essentially infinite. The lower required strength for the silicon oxynitride-coated fibre is simply a reflection of its superior fatigue

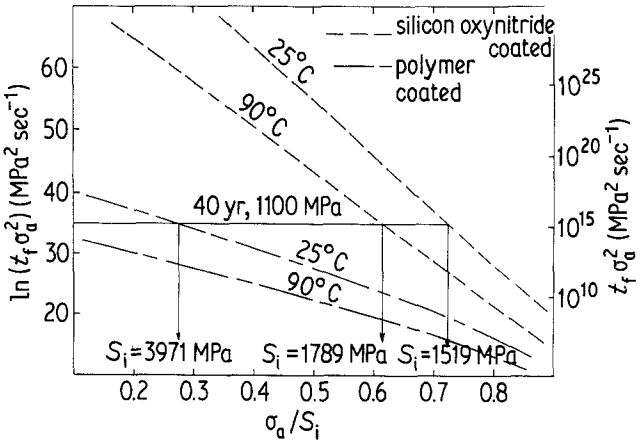

Figure 3 Lifetime diagram for polymer- and silicon oxynitride-coated fibres based on dynamic fatigue data in water at 25 and 90° C.

resistance. To ensure that the fibres have this required strength, proof testing can be used [6,15, 16] or, alternatively, the probability of failure associated with this required strength can be calculated.

The probability of failure in service can be determined from the appropriate inert strength distribution for the fibres, accounting for the fact that the strength of the small laboratory test specimens (0.1 m) is much stronger than the actual fibres in communication cable. Assuming that the single Weibull scaling law [17] is valid, the Weibull parameter for a long length fibre is related to that of the test samples by:

$$S_{01}/S_{02} = (L_2/L_1)^{1/m} \quad (7)$$

where the subscript 1 refers to the long length fibre and the subscript 2 refers to the short length test specimen. Based on a fibre 1 km long, the corresponding Weibull scale parameter for the polymer-coated fibre is 4056 MPa and for the silicon oxynitride-coated fibre 2638 MPa. Using these scale parameters the failure probability at a given required strength level can be calculated from Equation 4. For the required strengths cited in the previous paragraph, the failure probability of the silicon oxynitride-coated fibre under the given service conditions is 1×10^{-10} at 25° C and 1.2×10^{-7} at 90° C. For the polymer-coated fibre the associated failure probabilities are 0.43 at 25° C and 1.0 at 90° C. These significantly lower failure probabilities for the silicon oxynitride-coated fibre are due to its much higher fatigue resistance as compared to the polymer-coated fibre. In fact, the only service condition where the silicon oxynitride-coated fibre is less desirable than the polymer coated fibre is where fatigue effects in the service environment are minimal. Under these conditions, the fibre with the greater inert strength, i.e. polymer-coated fibre, will be the one with the least probability of failure.

If the calculated failure probabilities for a given service condition are too high to be acceptable, the required lifetime or applied stress in service must be decreased. For example, if the required failure probability in service is 10^{-8}, then the correponding strength of a 1 km long polymer-coated fibre is 2057 MPa, and 1687 MPa for the silicon oxynitride-coated fibre. For a 40 year lifetime these strengths, associated with a failure probability of 10^{-8}, can be shown from Fig. 3 to correspond to design stresses of 638 and 255 MPa for the polymer-coated fibre at 25 and 90° C, respectively. For the silicon oxynitride-coated fibre the design stresses for this same lifetime and failure probability are 1218 and 1040 MPa at 25 and 90° C, respectively. Thus, the superior fatigue resistance of the silicon oxynitride-coated fibre allows significantly higher design stresses in service as compared to the polymer-coated fibre.

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