Journal of Optoelectronics and Advanced Materials Vol. 7, No. 3, June 2005, p. 1581 - 1587

FATIGUE TESTING PROCEDURES OF SILICA OPTICAL FIBRES

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Some manufacturing technologies of silica optical fibres are reviewed and the role of polymer external coatings underlined. Mechanical properties of some commercial optical fibres have been investigated and fatigue testing procedures were described. Experimental testing devices, results treatment and parameters comparison have been evidenced. Dynamic fatigue testing using two point bending bench at four different stress rates were carried out. Fibre strength was determined using Weibull statistical treatment, then the n-corrosion parameter was calculated on the basis of four different stress rates. Static fatigue testing were carried on winding sample fibre around alumina mandrel. Fibre time to failure was measured and the n-corrosion factor was calculated on the basis of four different stress rates controlled through the mandrel-sized calibrated diameter.

(Received May 4, 2005; accepted May 26, 2005)

Keywords: Silica optical fibres, Static and dynamic fatigue testing, Weibull plots, Corrosion parameter

1. Introduction

Optical fibres are now key components of high capacity telecommunication networks. The concept of an optical fibre is probably very old and the transmission of light through glass rods and filaments was known by glass makers of the antique Mediterranean civilizations. Due to the use of the vapour phase deposition technology, the milestone of glass fibre attenuation, lowered down to 20 dB/km, comparable to the damping undergone by an electric current in a copper wire, was reached in 1980, resulting in the spectacular decrease of the fibre loss [1]. Today the commercial optical fibre shows an attenuation lower than 0.25 dB/km for an information transport of 65000 times faster than a copper wire. As already known, optical fibres consist of two concentrically cylinders of silica.

Even if drawing a fibre from a glass rod might be a simple exercise, manufacturing an optical fibre requires the rigorous control of any contamination factor. Silica fibres are made by drawing at 2000 °C high purity preforms as previously described [1]. Preforms are rods in which the central part consists in core glass of higher index of refraction while the external part is made from cladding glass. These preforms are prepared by vapour phase process in which silicon chloride reacts with gaseous oxygen. This results in a very high purity material which contains extremely low levels of metal impurities and hydroxyl. Variation of refractive index is achieved by the modification of the vapour composition: germanium, phosphorous and fluorine can be incorporated in this way. High quality preforms can be made using other chemical processing, for example sol-gel.

Optical fibres may also be drawn directly from the melt using the double crucible method. Both core and cladding glasses are heated in two concentric crucibles at a temperature for which melt viscosity is large enough. Then a step index fibre may be drawn from the bottom of the double crucible [1].

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Special glasses are sometimes difficult to draw into fibre because of their tendency to devitrification. These problems are solved by adjustment of glass composition and processing optimization.

An external polymeric coating is applied to protect fibre from scratches, to limit chemical attack of water and to increase mechanical strength. Usual coatings are epoxyacrylate resins, but other polymers such as silicones and polyimide may be used, too.

The reliability of the optical fibre depends on various parameters that have been identified: time, temperature, applied stress, initial fibre strength and environmental corrosion. The major – and usually unique – corrosion reagent is water, either in the liquid state or as atmospheric moisture. Glass surface contains numerous defects, either intrinsic – the so-called "Griffith's flaws" – and extrinsic, in relation to fabrication process. Under permanent or transient stress, microcracks grow from these defects, and growth kinetics depends on temperature and humidity. Although polymeric coating efficiently protects glass surface from scratches, it does not prevent water to reach glass fibre and consequently to damage the fibre.

For better protection to moisture or water / chemical etching, metallic or inorganic coatings are deposited. If possible to deposit on the optical fibre surface a hermetic coating so as to prevent water to cross the polymeric "sponge-type" structure, fibre's reliability to reagent etching should be much improved even if, to some extent, a mechanical properties loss is registered.

2. Fatigue testing – experimental procedures

Testing have been implemented using different commercial single mode silica fibres of 125 µm in diameter with a 62.5 µm thick epoxy-acrylate polymer coating (Alcatel and Verrillon). For comparison the as-tested fibres were noted F1 – Alcatel fibres and F2, F3 and F4 – Verrillon fibres. The difference between the Verrillon fibres is reflected by different perform surface treatment. From the experimental point of view, three references of the fibre rollers were noted. The F3 noted Verrillon fibre presented a thin hermetic carbon coating.

The current work presents the experimental procedures for fatigue testing of silica optical fibres. Once the methodology established, the dynamic and static fatigue testing have to be implemented and the experimental results statistically treated in order to compare the statistical parameters and the fibre's strength values. More advanced testing of aged fibres in severe or harsh conditions will be reported further.

2.1 Dynamic fatigue measurement using a two-point bending testing apparatus

As-received fibres were subjected to dynamic fatigue tests using a two-point bending testing device (Fig. 1). The samples of 10 cm in length are bent and placed between the grooved face plates of the testing apparatus (see detail Fig. 1), in order to avoid the fibre slipping during the face plates displacement and to maintain the fibre ends in the same vertical plan.

Series of 30 samples were tested for four different faceplate constant velocities. The measurements were performed in the normal ambient laboratory environment, the temperature and the relative humidity being noted for each of the testing series.

The stress to fracture applied to the fibre was calculated from the distance separating the faceplates, using the Proctor and Mallinder relation, improved by Griffioen [2]. So, for each tested sample was determined the stress to fracture, and then the results were treated through a statistical approach using the Weibull theory.

The classical Weibull plots of the logarithm function of the cumulative failure probability related to the logarithm of the stress to fracture ($\boldsymbol{\sigma}$) has allowed to calculate the statistical parameters [3,4]. On the basis of the experimental values for four different constant stress rates, the $\boldsymbol{n}$-stress corrosion parameter was calculated and the regression coefficient (R^2) given.

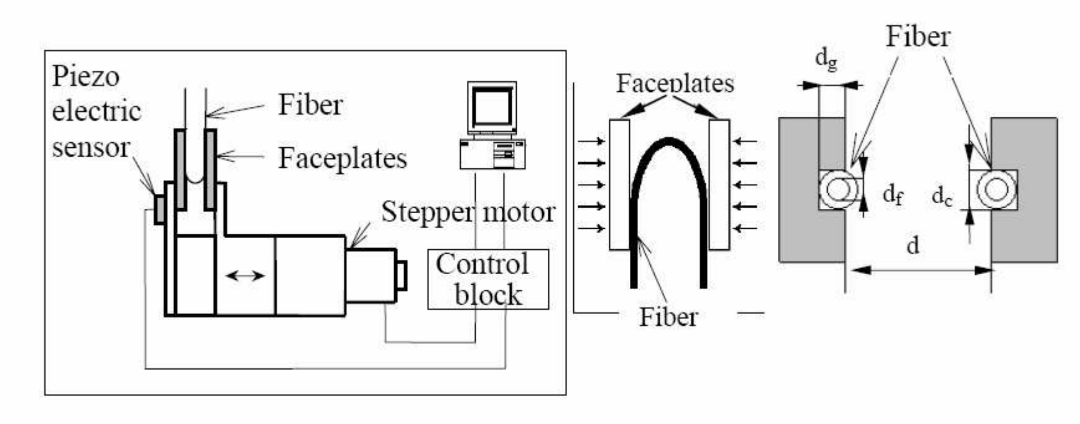

Fig. 1. Two point bending bench and detail of the position of the fibre in the graved faceplates.

2.2 Static fatigue measurement

The static fatigue parameters were measured by a static bending test accordingly to the international standard IEC 793 [5]. As received fibres, one meter in length, were subjected to bending stresses by winding around alumina mandrel with calibrated diameter sizes. The constant level of the applied stress can be adjusted by the proper choice of the mandrel size. The time to failure is measured, and this corresponds to the time required for the fibre strength to degrade until it equals the stress applied through winding round the mandrel. The time to failure is measured by optical detection when the ceramic mandrel moves out of the special holder (Fig. 2). When fibre breaks, the mandrel rocks from its vertical static position and the time to failure is directly recorded with an accuracy of ±1 s. The testing setup consists of a large number of vats containing 16 holders each (Fig. 3).

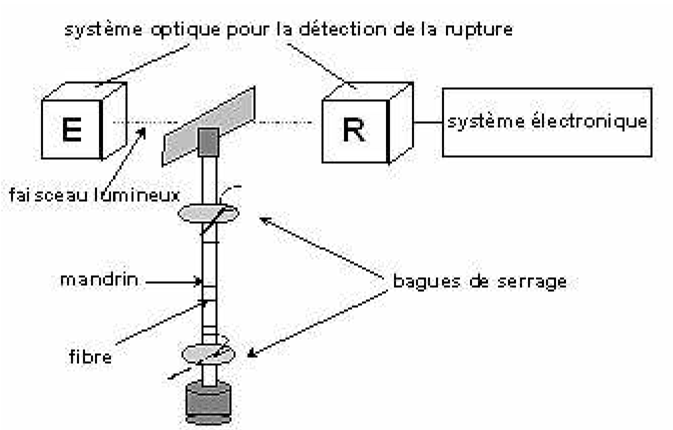

Fig. 2. Principle of fiber time to failure optical detection – the energy liberated by the breaking fiber damages the equilibrium vertical position of the mandrel which is pushed out of the handler.

The applied stress on the fibre depends on the mandrel diameter accordingly to the Mallinder and Proctor relation [4], as follows:

$\sigma = E_0 . \varepsilon \left(1 + \frac{\alpha' . \varepsilon}{2} \right)$ where: σ : applied stress (GPa); E_0 : Young modulus (= 72 GPa for the silica); ε : relative deformation of the fibre; $\alpha' = \frac{3}{4}\alpha$; α : constant of elasticity non-linearity (=6).

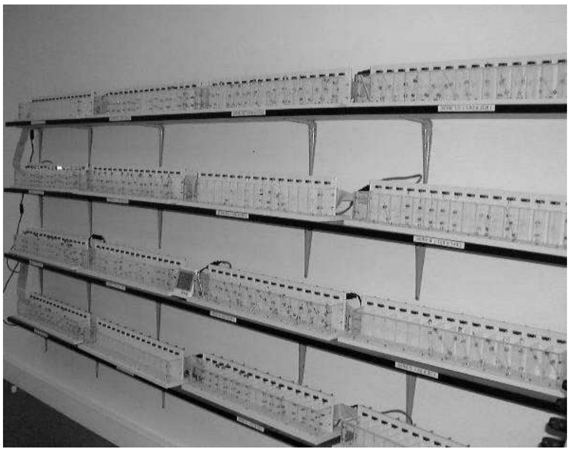

Fig. 3. Photo of the static fatigue testing setup.

The relative deformation of the fibre depends on the mandrel calibrated diameter, as follows: $\varepsilon = \frac{d_{core}}{\phi + d_{fibre}}$ with ϕ the mandrel diameter (in µm); d_{core}= 125 µm, the glass fibre diameter; d_{fibre} = 250 µm, the fibre diameter, including polymer coating.

This leads to the corresponding stress of 3.92, 3.76, 3.34 and 3.22 GPa for the calibrated diameter mandrel of 2.3, 2.4, 2.7 and 2.8 mm, respectively. The testing environmental conditions during static fatigue measurements has slightly ranged between 18.5-20.5 °C, in temperature and 30 to 45%, in relative humidity.

The ***n***-stress corrosion parameter of fibres was determined as the reverse of the slope of the linear function relating logarithm (failure time, in hours) to logarithm (applied stress, in GPa), directly related to the mandrel sized diameter.

3. Results

The stress to fracture, σ, of the as-received fibres were determined and the correspondent Weibull plots are given in Fig. 4 (Alcatel fibres, noted F1) and Fig. 5 (Verrillon fibre, noted F4) for four different testing faceplates velocities chosen for the two-point bending testing.

The cumulative failure probability ($\ln(-\ln(1-F_k))$) in function of the logarithm stress σ, (ln(stress, MPa)), has allowed to evidence the influence of testing parameters on fibres subjected to fatigue deformation. The corrosion stress parameter was calculated on the basis of the linear interpolation of the dynamic plot, respectively the stress at 40% fibre fracture, ln (stress, MPa), in function of velocity gradient, ln (velocity, µm/s), are given in Fig. 6. The n-corrosion parameter for the Alcatel (F1) fibre has a value of 13.16 with rather a good interpolation (0.98). The Verrillon fibre (F4) has a 14.06 n-corrosion factor with a better linear interpolation (0.998).

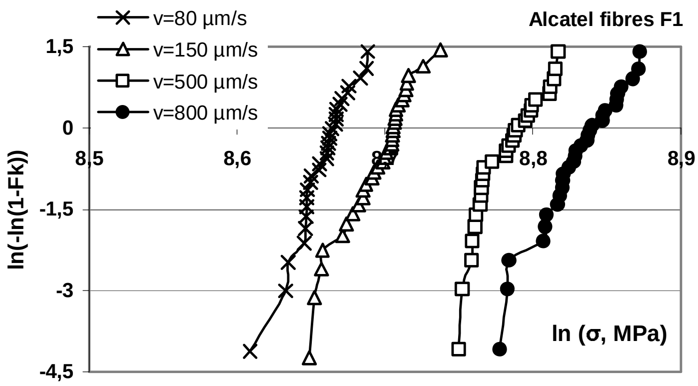

Fig. 4. Results of two point bending testing for different faceplates velocities v, in µm/s (in axes: Fk cumulative failure probability, in % and σ stress, in MPa) for Alcatel fibres.

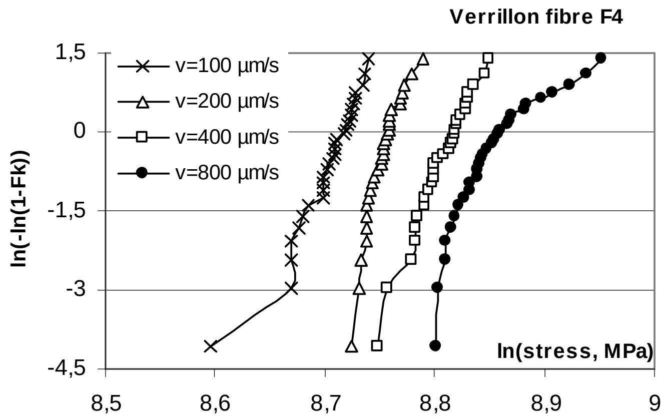

Fig. 5. Dynamic fatigue testing results for the as-received Verrillon fibre (F4).

As seen in Fig. 4 and 5, the medium strength of Alcatel fibres ranged between 5700 and nearly 7000 MPa, while the Verrillon fibres exhibit slightly higher values. Similar dispersion of strength for both fibres was noticed with steeper in the case of central faceplates velocities and broader for very low or very high stress rates. This tendency appeared clearer in the case of Verrillon fibres.

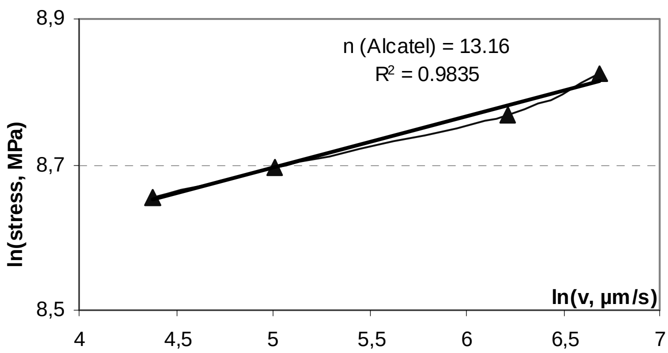

Fig. 6. Stress corrosion parameter of Alcatel fibre (F1) – dynamic fatigue testing.

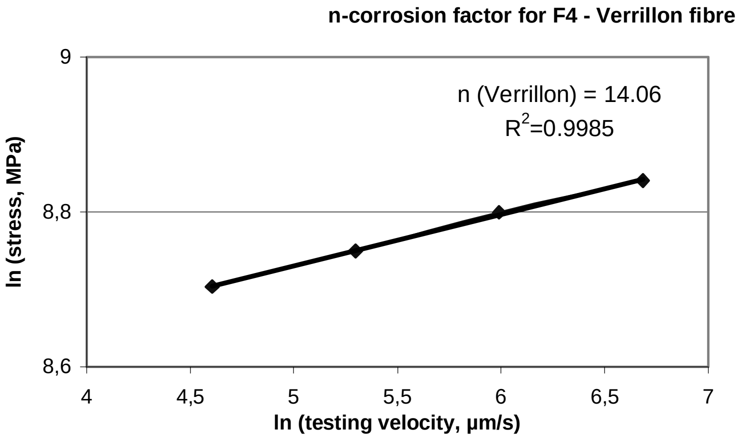

Fig. 7. Stress corrosion parameter of Verrillon fibre (F4) – dynamic fatigue testing.

The comparison of the as-received fibres, tested in static conditions, shows increasingly initial strength values in the order F1 (Alcatel), F2 (Verrillon) and finally F3 (Verrillon), as reported in table 1. Moreover, the F3 noted fibre has a three times higher failure time. Note that the applied stress (through the mandrel diameter) was higher for the Verrillon fibre.

Table 1. Failure time of as-received fibres (static fatique testing).

Fibre reference (as-received)	F1 Alcatel fibre	F2 Verrillon fibre	F3 Verrillon fibre
Failure time, hours	2.1	10.7	33.4
Correspondent applied stress, GPa	3.223	3.757	3.757

In order to calculate the stress corrosion parameter, n-factor, four different mandrel sized diameters were used ranging between 2.3 and 2.8 mm. The n-stress corrosion parameter is given by the linear interpolation of the failure time median values (noted ***Ft*** in figures legend) in a logarithm representation of the fibre failure time (ln(failure time, hours) in function of the uniform bending stress σ (ln(stress, GPa). The experimental results are seen in Fig. 8. For the F2 noted fibre (Verrillon), a 26.3 value of n-stress corrosion parameter was found, with a regression coefficient of 0.999, in comparison with the F3 noted fibre (hermetic coating) of a 18.77 n-corrosion parameter, with a regression coefficient of 0.992.

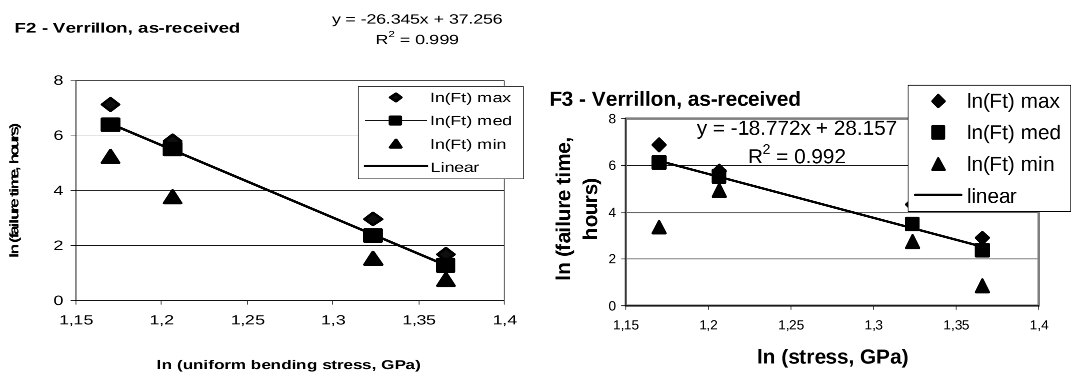

Fig. 8. The n-factor calculus of Verrillon fibres noted F2 and F3 – static fatigue testing.

4. Conclusion

Taking into account, on one hand, the huge fibre applications emerging in other fields than telecommunications and, on the other hand, the complexity of phenomena and mechanisms related to the optical fibres reliability and overall characterization, a lot of testing are still required in current and harsh conditions.

Once the methodology established, the dynamic and static fatigue testing has to be implemented and the experimental results statistically treated in order to compare the statistical parameters and the fibre's strength values. So, the fibres in as-received state or aged in different aging conditions (more or less drastic) have to be tested using a two point bending bench at a given stress rate.

If the interest is to compare different types of fibres or, further, different aging conditions, with a fixed stress rate, a series of at least 30 testing in dynamic fatigue testing conditions have to be implemented. The Weibull plots allow to find the statistical parameters and to compare the strength and the curve's slopes indicating the defects distribution along the fibre.

For the n-corrosion parameter, the testing at four different stress rates are required so the four series of at least 30 testing are necessary in order to find the n-factor. The linear interpolation of fibres median strength determined for four different stress rates in logarithmic representation gives the n-corrosion factor.

Similar procedure is required for the static fatigue testing. A series of mandrel sized diameter has allowed compare different fibres or different aging treatment previously applied. In order to find the n-corrosion parameter, four different mandrel sized diameter have to be used, so for each series the minimum number for the statistical treatment is necessary.

The merit of the paper is to describe the experimental procedure to test optical fibres in dynamic and static fatigue conditions.

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