OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 3, No. 7, July 2009, p. 659 - 663

Failure mechanisms of silica optical fibre

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When silica fibres are aged in severe conditions, their mechanical resistance is lowered and their lifetime is shortened. However, the influence of water is more complex than assumed; work has been carried on for better understanding of involved phenomena. Single-mode fibres were aged in hot water at 65 and 85°C for different aging durations. In a first step, fibres were tested after successive 3 months periods, up to 27 months. A second series of experiments was implemented on a shorter time scale, from one day to 3 months. Lifetime evolution of fibres subjected to static stress revealed an oscillatory evolution, while fibre strength in the dynamic mode decrease. These observations have led to further experiments, in which series of fibres were aged in hot water for a few days and subsequently put under static stress and finally characterized. Tensile dynamic testing does not exemplify an anomalous behaviour. Similar results were observed for fibres aged in water under a limited permanent stress. The current study has revealed that failure mechanism of aged fibres involves surface phenomena, in relation to water activity. It is anticipated that the relaxation phenomenon control could also lead to the fibre strength increase when subjected to dynamic fatigue.

(Received March 28, 2009; accepted July 20, 2009)

Keywords: Silica optical fibres, Failure mechanisms, Static and dynamic fatigue testing, Structural relaxation

1. Introduction

Optical fibres are key components for telecommunication networks. In addition the availability of inexpensive and high quality fibres has induced other applications in various areas such as sensing, laser power delivery and fibre lasers. In this respect, reliability issues have been studied carefully and much work has been achieved on this matter. The common requirement is that the fibre lifetime should be larger than the expected system operation time. Even if telecommunication networks have not faced yet major problems in relation to fibre failure, certain aspects of fibre aging are not fully understood.

The reliability issue remains more than ever a topical question for several reasons. Firstly, the impressive increase of the bit rate is accompanied by a power increase which is supported by the fiber core and can generate catastrophic failure phenomena and generate damage of the fiber ends or losses in the connectors. Secondly, current models include humidity, applied stress and temperature as major aging factors, but their accuracy for lifetime prediction is questionable. The reliability of the optical fibers depends on various parameters that have been identified: time, temperature, applied stress, initial fiber strength and environmental corrosion [1-4].

One must separate the case of the fatigue static behavior where fibers are subjected to a permanent strain, e.g. bended fibers, and the dynamic fatigue corresponding to an unexpected tensile stress arising from environmental changes. Failure mechanism involves surface phenomena, raising fundamental questions [5-8].

2. Experimental

The aging behaviour of different commercial silica optical fibers (with epoxyacrylate and fluorinated coating) was studied. Single mode silica fibres of 125 µm in diameter with a 62.5µm thick polymer coating were rolled under a bending radius of 20 mm and aged in deionized water in large tanks at temperatures of 65 and 85 °C for a maximum aging time of 27 months. The strength was measured after aging by static and dynamic fatigue tests. Samples were removed from water every three months and dried in ambient air prior to mechanical testing.

The second series of tests subjected fibres to aging in water for shorter aging periods. Fibres were plunged into large tanks containing deionised hot-water at 65° and 85°C temperatures for different durations ranging between 3 to 70 days. A number of 18 to 20 samples per series, each 1 meter in length, were carefully arranged into the hot-water tanks, so that that they remain stress-free and temperature was constant all over the aging treatment. At the end of the immersion time, the series of aged fibres were removed from hot-water and simply laid to dry into the laboratory environment on absorbent paper for at least 3 days. Some groups of fibres were subjected to static fatigue measurement and their behaviour was compared to that of the non-aged fibres. Other fibres were tested in dynamic fatigue conditions for a constant strain rate of 400µm/s.

The static fatigue parameters were measured by a static bending test accordingly to the international standard CEI [9]. The aged and subsequently dried 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. For the calibrated diameter mandrel of 2.4 mm, the corresponding stress is of 3.76 GPa. 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. 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. 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 dynamic fatigue tests using a two-point bending testing device subjected to testing fibre samples of 10 cm in length, bent and placed between the grooved faceplates of the testing apparatus, in order to avoid the fibre slipping during the faceplates displacement and to maintain the fibre ends in the same vertical plan [10]. 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, so for each tested sample one determined the stress to fracture, 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 (σ) has allowed calculating the statistical parameters. On the basis of the experimental values for four different constant stress rates, the ***n***-stress corrosion parameter may be calculated and the regression coefficient (R^2) given.

The third series of testing consisted of experiments in which fibres were aged in hot water at 65° for a few days (up to one week) and subsequently put under static stress and finally characterized. Tensile dynamic testing was used looking for an anomalous behaviour as in previous experiments. Similar testing was implemented for fibres aged in hot water under a limited permanent stress.

3. Results and discussion

Single-mode fibres were aged in hot water at 65 and 85°C temperatures for different aging durations. In a first step, fibres were tested after successive 3 months periods. While fibre strength measured under tensile stress was found to decrease, as one could expect, the lifetime of the fibres subjected to static stress was greatly increased. However this unexpected effect did not follow a regular evolution versus time, but was rather cyclic.

In the case of epoxyacrylate coated fibre, the maximum failure time in static fatigue test under uniform curve was reached for an aging period of three months for fibers aged at 65 °C, respectively ranging between 3 to 6 months for fibers aged at 85 °C. Beyond these maxima, the mechanical fiber strength rapidly decreased towards rather low values (fig. 1). This phenomenon is compared to a kind of 'cure' of surface defects due to the water action on the glass surface.

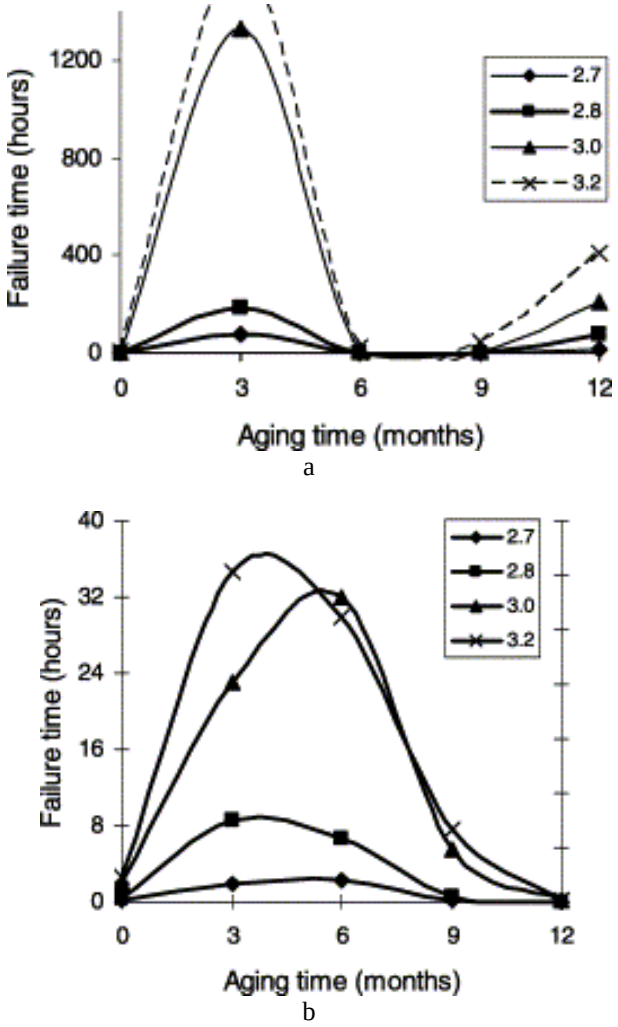

Fig. 1. Failure time versus aging time for aged fibers (epoxyacrylate coating) at 65 °C (a), respectively 85 °C (b). Results from static test under uniform bending (legend – mandrel calibrated diameter, in mm).

In the case of fluorinated coated fibre, failure time presents a cyclic evolution with an increase in amplitude and a maximum reached for an aging time of 24 months for the fiber aged at 65 °C. For fibers aged at 85 °C, the maximum failure stress was reached for an aging time of three months respectively (fig. 2).

The cyclic change of the failure time of aged fibers was unexpected since the chemical action of water is known to decrease the fiber strength. From these measurements, the aged fibers appear stronger under permanent stress than the as-received ones. However dynamic fatigue measurements do not lead to the same conclusion as an overall decrease of the failure stress was observed. This behavior may have practical consequences as it suggests that the lifetime of fibers subjected to permanent stress in wet environment is likely to be much

larger than previously assessed. However, it has raised questions about the failure mechanism in relation to failure.

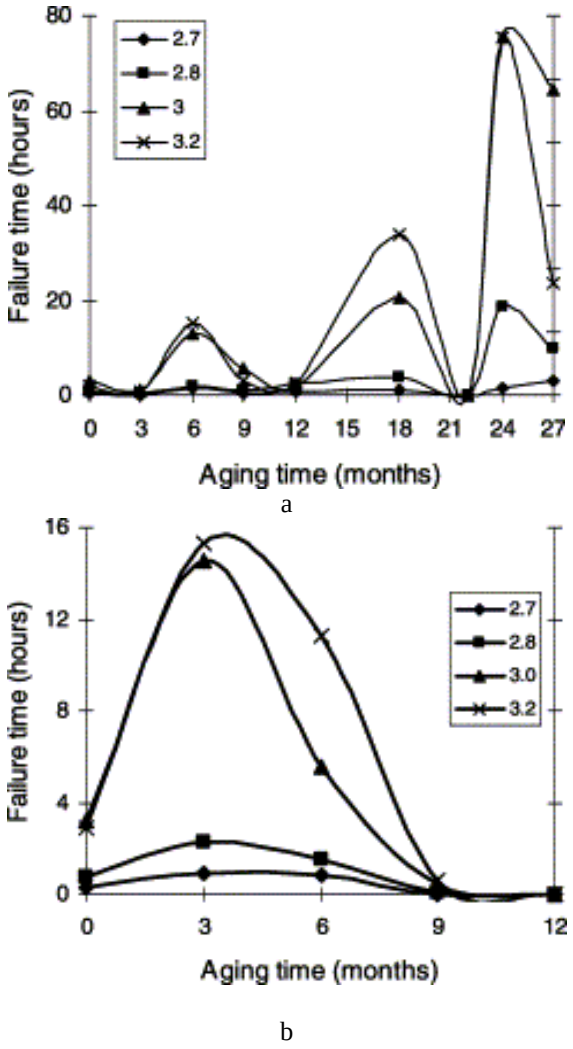

Fig. 2. Failure time versus aging time for aged fibers (fluorinated coating) at 65 °C (a) respectively 85 °C (b). Results from static test under uniform bending (legend – mandrel calibrated diameter, in mm).

The cyclic evolution of the failure time versus aging time in static fatigue tests implies that there are also cyclic changes at the fiber surface. A possible explanation for these changes lies in the formation of a hydrated silica layer which implies chemical change and exchange at the polymer–glass interface with respect to the aging time. As this layer grows, fiber is reinforced when put under static stress – that is under stresses smaller than those used in dynamic fatigue measurements. To some extent, this hydrated layer inhibits the pre-existing surface flaws. As it contains water, it also accelerates structural relaxation, decreasing the effective stress. When the thickness of the hydrated layer reaches a critical value, it starts diffusing into the polymeric coating and its thickness decreases towards a very small value. Then a new hydrated layer is formed.

On the track of our hypothesis, a second series of experiments were implemented for on a shorter aging periods scale, from one day to 3 months, at same aging temperatures. In this case also lifetime evolution of fibres subject to static stress revealed a oscillatory evolution, while fibre strength in the dynamic mode was reduced.

One may notice a similar oscillatory evolution of failure time in static fatigue conditions (fig. 3), but with decreasing amplitude and without reaching maxima exceeding values of as-received fibres. Polymer coating has appeared quite severely damaged in high temperature aging environment. The dynamic fatigue testing revealed, as in previous case, a continuously decrease of fibre strength. The comparison of the fibres prior to same aging treatment has shown slightly monotonous decrease of strength values for all tested samples. For comparison, the medium stresses, measured for a constant face plate of 400 µm/s of the dynamic fatigue-testing bench, were considered. The noticed decrease remains in the interval of 200-300 MPa for the fibres aged at a 65°C aging temperature, respectively approximately 550 MPa for the fibre aged at the 85°C aging temperature.

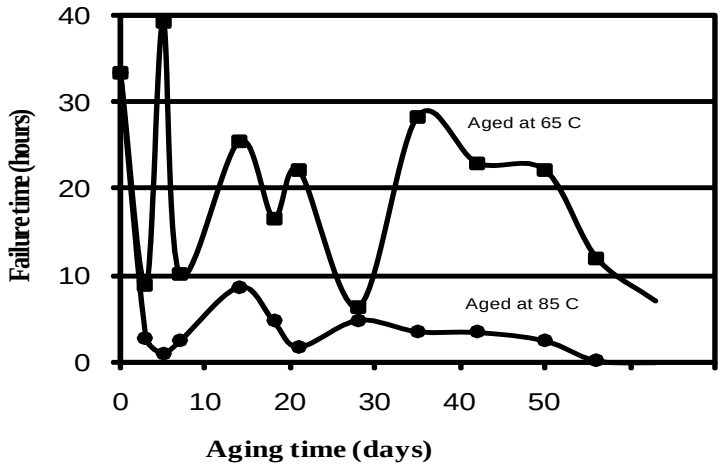

Fig. 3. Failure time versus aging time for aged fibers (epoxyacrylate coating) at 65 °C, respectively 85 °C. Results from static test under uniform bending (mandrel calibrated size 2.4 mm).

These observations have led to further experiments, in which series of fibres were aged in hot water for a few days and subsequently put under static stress and finally characterized using dynamic tensile testing. In this case, no anomalous oscillatory behaviour was noticed. Similar results were observed for fibres aged in water under a limited permanent stress.

For several silica fibers subjected to vertical static tensile testing (Fig. 4) under various loadings, one can notice that more the suspended mass value is high; more the time of rupture is large. For weak loads (15 N), two families of cracks are present, a slope break indicating the dispersion of the micro-crack shapes.

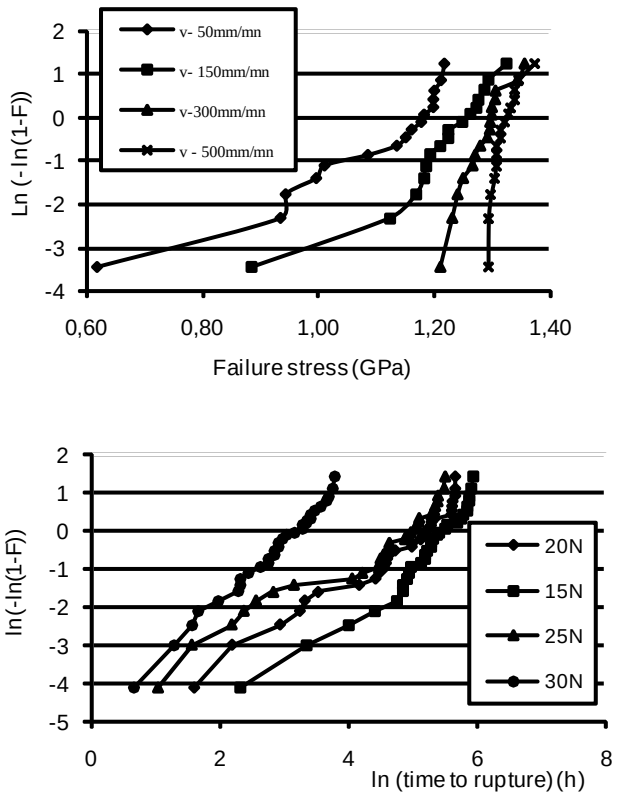

Fig. 4. Dynamic tensile testing - Time to fracture evolution for different loadings (F represents the cumulative failure probability; in legends v represents the strain rate, in mm/min, respectively the loading in N)

4. Conclusions

The current study has revealed that failure mechanism of aged fibres involves surface phenomena, in relation to water activity.

The cyclic evolution of the fibre failure time subjected to static fatigue was normally unexpected taking into account the fibre strength decrease induced in time by water chemical action. This behaviour in static fatigue conditions may present some practical consequences suggesting that in wet environments, in some particular cases (temperature and exposure duration), the as-aged fibre lifetime has exceeded the expected one, respectively the non-aged fibre failure time.

As already known, the micro-cracks smoothing due to the curing effect of water molecules on silica resulted in stress intensity factor decrease and thus, in fibre failure strength increase. This explanation may satisfy the strength increase observation after a certain aging duration. The unexpected conclusion appears in fact the cyclic variation of the fibre strength. The smoothing effect might not be the only responsible for an oscillatory process of the fibre failure time while increasing the aging duration.

The cyclic evolution of failure time versus aging duration in static fatigue should be explained through the cyclic changes at fibre-polymer interface due to the structural relaxation phenomenon. The polymeric coating is permeable [10] so the exchanges through the polymer may occur during aging. In the same time, the polymer hinders, in a certain manner, the water diffusion to the silica surface decreasing the hydrolyze reaction rate.

A layer of hydrated silica is likely to be formed at fibre surface. This layer inhibited, in some extend, the micro-surface flaws. This vitreous hydrated phase may relax under stress at room temperature, which partly compensates the external applied stress in static fatigue. Once the cycle finishes, a new process initiation allows the water attack of the glass-polymer interface.

The oscillatory behaviour of the optical fibres lifetime may be explained through the "competition" between two reactions: firstly, the water diffusion through the polymer coating towards the silica surface and secondly, the reverse sense reactions of the hydrated silica at the polymer / silica interface. The measurement of silicium concentration (fig. 5) in the polymer coating reveals the significant concentration of silicium at the interface level. This profile hasn't been registered in the case of non-aged fibres.

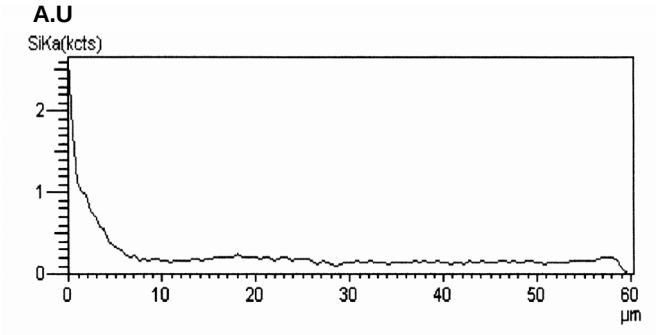

Fig. 5. The profile of silicium diffusion on a 10 µm distance from the silica / polymer interface of an aged optical fibre.

On certain aged fibres (65°C water aging temperature), stripped samples were subjected to AFM measurement on a 1µm^2 testing surface. A variation of the RMS roughness between 0.218 and 0.291 nm has been found, in agreement with other authors' results reported on fibre or plain silica testing [11]. The relationship between the strength and the silica fibre roughness hasn't been accurately proportional, but the results have allowed concluding the consistency of our hypothesis to explain the oscillatory fibre behaviour, even if more testing should be necessary. Series of testing consisting in overlapped effects of mechanical applied stress during aging in water of silica optical fibres and subsequent static elongation have revealed the strength increase up to a maximum of 18% of the as-received fibre mean strength, as reported elsewhere [12].

One has anticipated that the control of the relaxation phenomenon could also lead to the increase of the fibre strength when subjected to dynamic fatigue.

Acknowledgments

The work is part of the research project PAI Egide Brancusi Programme 2007-2008 entitled "Amélioration de la fiabilité des fibres optiques monomode à base de silice" and research grant no. 36/02.06.2006 (CNCSIS code 68, theme 27).

Authors express their gratitude to Verrillon Inc. Boston, USA for delivering fiber sample for testing.

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