The influence of water and temperature on the strength of optical fibers

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1. Introduction

The optical fiber may be considered as a composite material composed of two parts greatly different in their physicochemical properties: the inner part is a glass core and the outer one – organic polymer protective coating. The reliability of optical fiber depends on the quality of its glass part, the properties of polymer and on the interaction on the glass/polymer interface. Progress in the preform manufacturing and fiber drawing as well as in the protective coating design has resulted in the production of long highstrength optical fibers. High-strength fibers show normally unimodal strength distribution with strength of the order 4.5 to 6 GPa. However, this last value is much smaller than the theoretically calculated strength of the fused silica glass, equal to 14 GPa [1]. The presence of flaws and microcracks on the glass fiber surface is a generally accepted reason for the decrease of the fiber strength exposed to the stress and cause its destruction. Probably, the defects growth (stress corrosion) is associated with water presence, because the mechanical strength of the fiber increases with the temperature increase, i.e., when the relative humidity decreases [2,3]. This relationship may be explained by the fact that the polymer protective coatings of optical fibers are rather highly permeable for water. The water diffusion coefficients through the UV-cured polymers, commonly used as the protective coatings, are from 10 to 200 $\mu g \cdot m/m^2$ sec [4,5], thus, the protective coatings do not hinder the water molecules from reaching the glass surface. Water adsorbs first of all on the surface defects and reacts with SiO_2 forming the silanol groups [6,7]. This process can follow up till the creation on glass surface the water layer, the properties of which are similar to those of bulk water. As a consequence the process of SiO_2 dissolution in water may start. The rate of this reaction depends on temperature, therefore the temperature is, besides the water presence, another factor determining the fatigue corrosion of optical fibers.

An excellent review of extensive investigations on optical fiber reliability was given by Kurkijan and Innis [8]. The reported data provided much information concerning the optical fiber behaviour under the conditions of high humidity, however, the problem if the changes of mechanical properties of optical fibers caused by water are reversible is rather open. This work is an attempt to answer this question.

2. Experimental

The fused silica optical fiber 125 μm in diameter, covered with the UV-curable epoxyacrylic polymer ADGD 2,5 was used in all the experiments. Thickness of ADGD 2,5 coating was equal to 50 mm. The fiber was intentionally drawn in the laboratory atmosphere (without protection, e.g., against the dust) in order to detect all possible defects influencing its mechanical strength.

The strength of the fiber was measured under ambient laboratory conditions using TIRATEST 2000 (Germany), an universal testing machine. The gauge length was 0.2 m and the strain rate 10 mm/min. In each series of measurements 100 samples of the fiber were broken. The optical fiber was divided into a few parts which were treated with water and temperature:

1. The fiber was placed in the climatic chamber at 50°C and 97% of relative humidity for 24 hours. The strength of the fiber was measured just after water vapour treatment, the second half of the fiber was investigated after drying in air (24 hours at 50°C).
2. The fiber was placed in twice-distilled water at 50°C for 24 hours. The fiber strength was measured immediately after soaking in water and after drying at 50°C for 24 hours. Another sample was soaked in liquid water for 24 hours at 20°C and dried at 20°C for 168 hours in laboratory atmosphere.
3. The fiber samples were thermally treated for 24 hours at 58, 95, 120 and 220°C. The fiber strength was measured immediately after heating.

The mechanical properties of epoxyacrylate polymer ADGD 2,5 were determined as follows: The liquid composition of ADGD 2,5 was placed in the PTFE matrix 120 × 10 × 0.5 mm. Next, the UV curing process was carried out in argon atmosphere. Four series of the samples, each comprising 10 cured strips, were prepared. Three of them were heated 24 hours at 50, 120 and 220°C. The Young modulus, relative elongation and breaking strength of untreated and heated samples were determined using the TIRATEST 2000 testing machine.

3. Results and discussion

Ta Sheng Wei [3] showed that the strength of optical fiber was affected by adhesion properties and by low water absorption of polymer protective coating. This is the reason that epoxyacrylate composition ADGD 2,5 was chosen as the coating of investigated fiber. We demonstrated previously that the adhesion of ADGD 2,5 to fused silica surface is the highest in comparison to the coatings commonly applied in our Laboratory [10] and that the coefficient of water diffusion through this polymer is rather low [4].

Table 1 presents the data, expressed in per-cent of untreated fiber average tensile strength, showing the changes of the mechanical properties of fiber treated with water and temperature. As expected soaking of fiber in liquid water results in decreasing of its strength. The decrease of fiber strength clearly depends on the soaking temperature, but, after drying, the strength of the fiber becomes higher than that of the untreated fiber. The effect of the fiber treatment with water vapour at 50°C is a little surprising – its strength slightly increases. The increase of the average fiber strength caused by liquid water and consecutive drying seem to be surprising as well.

The analysis of the behaviour of all 100 fiber samples treated with water and temperature gives some details of the above

Table 1. The influence of water and temperature treatment on the mechanical strength of optical fiber coated with epoxyacrylate polymer ADGD 2,5 (in %; 100% is the average strength of untreated fiber)

Fiber	Temperature of water treatment, °C		Temperature of drying or heating in air, °C					
	20	50	20	58	95	120	203	222
Untreated			100	107	111	116	123	130
Treated with water vapour	105		108					
Treated with liquid water	93	82	103 *		102			
* fiber was dried 7 days at room temperature								

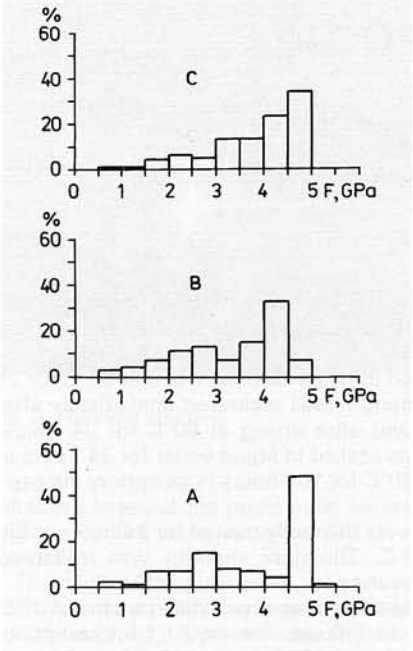

Fig. 1. Strength distribution of optical fiber coated with epoxyacrylic polymer ADGD 2,5. A – untreated fiber; B – fiber A soaked in water 24 hours at 50 ŞC; C – fiber B dried 24 hours at 50°C.

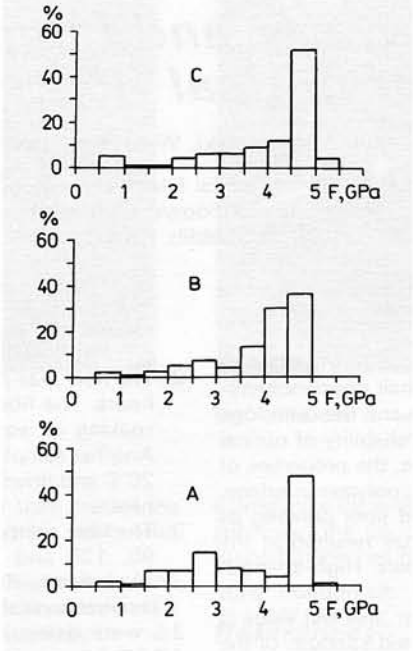

Fig. 2. Strength distribution of optical fiber coated with epoxyacrylic polymer ADGD 2,5. A – untreated fiber; B – fiber A treated 24 hours with saturated water vapour at 50°C; C – fiber B dried 24 hours at 50°C.

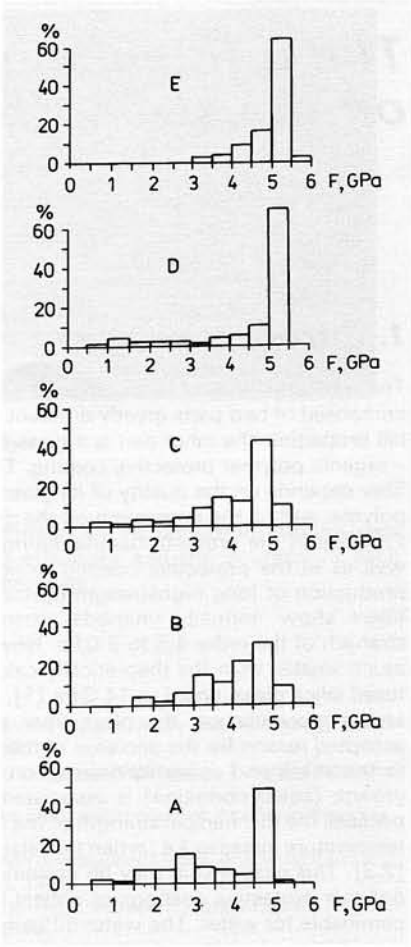

Fig. 3. Strength distribution of optical fiber coated with ADGD 2,5 heated 24 hours at: B – 50°C; C – 95°C; D – 203°C and E – 223°C. A – untreated fiber.

mentioned phenomena. In Fig. 1 the results of liquid water influence on the fiber strength are presented. Diagram A in Fig. 1 shows the histogram of the mechanical strength of untreated fiber. This diagram reveals the bimodal strength distribution with the maxima about 2.75 and 5 GPa. It means that there are two kinds of fiber defects leading to its destruction when the fiber is loaded. Soaking of the fiber in liquid water at 50°C results in the shift of the second maximum to a lower strain value. At the same time the number of the samples broken in the range 3 ÷ 4.5 GPa increases. The shape of the histogram for the fiber soaked in water and dried in air at 50°C (diagram C) radically changes: the strength distribution becomes unimodal with the maximum at about 5 GPa and the number of the samples destroyed in the region of low (up to 3 GPa) loading decreases.

The influence of saturated water vapour at 50°C on the mechanical strength of optical fiber is different from that of liquid water. The action of water vapour causes the increase of average strength of the fiber (Table 1) and leads to the homogenization of the strength distribution (Fig. 2B). This last effect, probably relevant to the disappearance of one kind of fiber defect, is still greater after fiber drying.

The results presented in Figs. 1 and 2 show the simultaneous influence of two parameters – water and temperature – on the investigated fiber strength, since both liquid water and water vapour acted at 50°C. The fiber was also dried at this temperature. The answer to the question how these factors influence the fiber strength separately is given by the data in Table 1 and Fig. 1: the liquid water at room temperature explicitly decreases the fiber strength, but, after slow drying also at room temperature, one may observe even a small increase of the strength. The influence of temperature on average strength of the fiber is equally clear (Table 1): the strength increases proportionally to the fiber heating temperature. The mechanism leading to this increase can be deduced from the histograms

Table 2. The influence of the thermal treatment on the mechanical properties of ADGD 2,5

Temperature, °C	20	50	120	220
Young modulus, N/mm²	2389	2586	2366	2674
Relative elongation, %	1.9	2.2	1.3	0.9
Breaking strength, N/mm²	42.2	49.7	31.4	20.0

presented in Fig. 3. Similarly to the case of soaking the fiber in liquid water and drying one may observe the process of the homogenization of the strength distribution. Also, the maximum in the histograms in Fig. 3 shifts to the greater value of the stress causing the fiber break (5.5 GPa). The increase of the average fiber strength cannot be explained by the change of the polymer properties caused by the thermal treatment. The data in Table 2 show that the maximum of the breaking strength of the ADGD 2,5 sample is observed after heating at 50°C. Higher temperatures of the heating lead to the decrease of both the breaking strength and relative elongation and to the increase of the Young modulus of the polymer investigated. It means that the protective coating of the fiber becomes more and more fragile with the baking temperature increase. Therefore, the increase of the Young modulus of the protective coating cannot influence the fiber strength so explicitly (Table 1). Thus, taking into account that the bimodal histogram of the strength distribution for the untreated fiber shows that there are two kinds of fiber defects causing its destruction, one can conclude that both water and thermal treatment lead to disappearance of one kind of defects. These defects can occur in the glass part of optical fiber, in its polymer coating as well as on the glass – polymer interface.

It seems that neither water nor temperature treatment influence the defects in the bulk glass. However water, especially at higher temperatures, can generate the hydroxylation of the

fused silica surface and, as a consequence, improve the adhesion of polymer protective coating to this surface. The explanation of the temperature influence on the homogenization of the strength distribution (Fig. 3) of the fiber is more troublesome. Probably this effect is connected with the change of the properties of bulk polymer – its rigidity increases with the increase of the heating temperature (Table 2). Some experiments carried out in our laboratory show also that the shrinkage of UV-cured polymers increases after heating. Therefore, the strength of optical fiber should depend not only on the adhesion of protective coating to the glass fiber surface but also on the strictly mechanical influence of protective coating on the properties of the fiber. Perhaps, the increase of the Young modulus and decrease of the volume of polymer protective coating caused by the heating process lead to the better binding of the edges of the defects on the polymer – fused silica glass interface by the coating and to the improving of the mechanical strength of optical fiber.

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References

1. *F.V. DiMarcello, J.C. Wiliams*: Fiber Drawing and Strength Properties; in: Optical Fiber Communications, vol.1., ed. by T. Li. Academic Press, New York 1985.
2. *W.J. Duncan, P.W. France, S.P. Craig*: The Effect of Environment on the Strength of Optical Fiber, in: Strength of Inorganic Glass, ed. by C.R. Kurkijan. Plenum Press, New York, 1985.
3. *Ta-Sheng Wei*: Effect of Polymer Coatings on Strength and Fatigue Properties of Fused Silica Optical Fibers. Adv. Ceram. Mat., **1** (1986) p. 237.
4. *J. Rayss, W.M. Podkoscielny, A. Walewski*: Diffusion of Water Vapour Through Protection Coatings of Optical Fibers. Proc. SPIE, **1085** (1989) p. 288.
5. *J.Rayss, W.M. Podkościelny, J. Widomski*: The Properties of Polymer Protective Coatings of Optical Fibers. I. The Influence of Active Diluent Concentration on the Properties of UV-Cured Epoxyacrylate Coatings. J. Appl. Polym. Sci., **49** (1993) p. 835.
6. *L.T. Zhuravlev*: Surface Chracterization of Amorphous Silica – a Review of Work from the Former USSR. Colloids and Surfaces A., **74** (1993) p. 71.
7. *K.J. Huttinger, S. Hohman-Wien, G. Krekel*: A Method for the Determination of the Acid-Base Interactions and the Work of Adhesion at a Solid-Liquid Interface. J. Adhesion Sci. Technol., **6** (1992) p. 317.
8. *C.R. Kurkijan, D. Innis*: Understanding Mechanical Properties of Lightguides: a Commentary Optical Egineering, **30** (1991) p. 681.
9. *J. Rayss, W.M. Podkościelny, J. Widomski, J. Ryczkowski*: The Properties of Polymer Protective Coatings of Optical Fibers II. The Influence of Curing time on Adhesion of UV Curable Coatings to Fused Silica Surface. J. Appl. Polym Sci., in press.
10. *J. Rayss, W.M. Podkościelny, J. Widomski, A. Gorgol*: Determination of Adhesion of UV-Curable Protective Coatings of Optical Fibers. J. Appl. Polym. Sci., **53** (1994) p. 1833.
11. *S. Wu*: Polymer Interface and Adhesion, Marcel Dekker Inc., New York 1982, p. 337.
12. *A.W. Adamson*: Physical Chemistry of Surfaces. J. Wiley, New York 1990.