PHOTO-THERMO-ELASTIC BEHAVIOR OF A PMMA-CORE POF

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Abstract
The use of fiber optic sensing systems of mechanical elements are based, among others, on light variations versus strain. This paper shows the results of tensile tests on a PMMA-core POF with simultaneous measurement of both optical intensity and temperature changes.

1 INTRODUCTION

An optical fiber, or light guide, is made of two concentric layers, core and cladding, which can propagate light through total internal reflection phenomenon. Optical fiber cores are typically made of glass (GOF) or polymeric materials (POF), with core refractive index being always slightly larger than the cladding counterpart. Elastic-plastic properties of the polymer make the fiber an element with a high strain limit. This fact facilitates their use in applications where the fiber is glued or embedded in the structural elements being subjected to deformational states of the surrounding material. The mechanical deformation of a fiber consists on simultaneous axial elongation and diameter decrease. Moreover, if a ray of light propagates through the fiber, its optical path may be altered both due to the fiber elongation and the refractive index change [1-4]. The aim of this work is the mechanical characterization of a PMMA-core POF through tensile tests with simultaneous measurements of the received optical power and the temperature increase due to the elastic and plastic deformations.

2 EXPERIMENTAL TECHNIQUES

The optical fiber used in this work is a standard step index POF. The cable diameter is 2.2 mm and consists of three concentric layers: a 0.98 mm diameter core section composed of polymethylmethacrylate (PMMA), a fluorinated polymer cladding with 0.01 mm thickness, and a polyethylene coating with 0.6 mm of thickness.

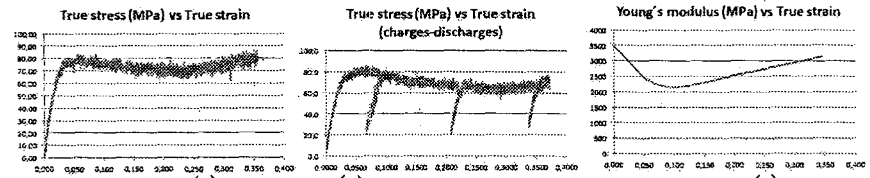
Quasi-static tests controlling the displacement of uncoated fiber specimens were performed. The POF fiber true stress-true strain (σ-ε) relation, Young's modulus, E, yield strength, σ_y, tensile strength, S_m, and the strain to failure, ε_{fai} were obtained from the different tests performed. Statistically insignificant differences between the results of conducted tests under the same conditions were observed. To analyze the deformation effect on the optical power transmission along the fiber, light was simultaneous launched into the fiber. The received optical power was measured by using a photodiode in a signal conditioning circuit. An infrared camera FLIR SC600 was used for measuring the temperature increase in the specimen surface associated with material plastic deformation.

3 RESULTS AND DISCUSSIONS

Mechanical behavior

Figure 1-a shows the σ-ε relation obtained in a test under a strain rate of 0.0005 s^{-1}. By increasing the load value, the molecular chains begin to separate reaching stable relative positions that derive in permanent (plastic) deformation in the polymer. It can be seen that the curve is decreasing until a strain value ε≈0.2. This fact is attributed to the progressive failure of the bonds of the molecular chains and the corresponding separation of the latter. From ε≈0.2 the curve is increasing, so it can be considered that at this deformation the progressive straightening, and consequent increase of

strength, of the molecular chains prevails over their separation. After averaging the measured values from the different tests, failure strain ε_{fai}=0.35, tangent Young's modulus (initial) E_{tan} = 3577+/-215 MPa and yield stress σ_y=79.3 MPa were obtained. The tensile strength was estimated by applying the Considére criterion thus obtaining a value σ=85 MPa corresponding to a strain ε=0.324.



a) $\sigma(\varepsilon)$ b) $\sigma(\varepsilon)$ *with charge-discharge processes* c) $E(\varepsilon)$

Figure 1: σ-ε relation obtained in tests without, a) and with charge-discharge processes, b)

To know the Young's modulus evolution, tests were carried out with charge-discharge processes. Figure 1-b shows the σ-ε relation obtained in a test with discharges. Figure 1-c shows the graph of a polynomial function obtained by interpolation in the (E,ε) values obtained from the charge-discharge steps. There is a rapid initial decrease of the Young's modulus associated with the breakage of the bonds between the molecular chains and their corresponding separation. The tensile stress applied to the fiber then causes the progressive straightening of the molecular chains, which tend to align themselves along the fiber axis. When the chains are straightened, the Young´s modulus of the deformed material reaches its maximum value.

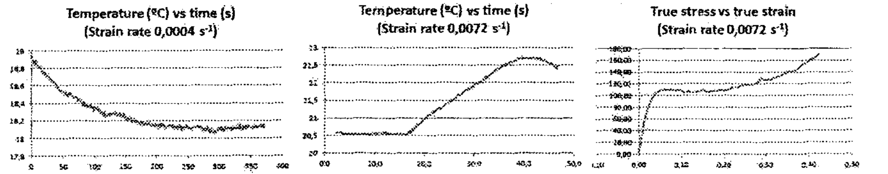
To analyze the influence of the strain rate on the mechanical behavior of the fiber material, tests were carried out under different velocities of the testing machine. Table 1 shows the values of the Young´s modulus, yield strength, tensile strength and strain to failure obtained through the tests. These parameters increase clearly with increasing strain rate, except for the Young's Modulus, which is almost strain rate independent.

Table 1: Mechanical parameters versus strain rate

Strain rate	$\dot{\varepsilon} = 0{,}0005 s^{-1}$	$\dot{\varepsilon} = 0{,}0023 s^{-1}$	$\dot{\varepsilon} = 0{,}0068 s^{-1}$
Young´s modulus MPa	3820	3850	3930
Yield strength MPa	78	85	105
Tensile strength MPa	85	120	150
Strain to failure	0,35	0,38	0,32

Temperature increase measurement during the deformation process

Figure 2-a show the temperature-time relation obtained from a test at strain rate 0.0004 s^{-1} interrupted before reaching yield stress. Figure 2-b show the same relation and figure 2-c shows the true stress-true strain relations both obtained from a test at strain rate 0.0072 s^{-1}.



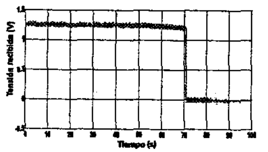
a) T-t ($\dot{\varepsilon}$=0,0004 s^{-1}) b) *T-t* ($\dot{\varepsilon}$=0,0072 s^{-1}) c) *σ-ε* ($\dot{\varepsilon}$=0,0072 s^{-1})

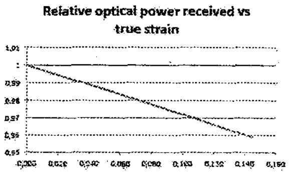
Figure 2: T-t relation from tests at $\dot{\varepsilon}$*=0,0004* s^{-1}*, a), and T-t relation, b), and σ-ε relation, c) from tests at* $\dot{\varepsilon}$*=0,0072* s^{-1}

The temperature evolution until t=40s (as shown in figures 2-a and 2-b) is in agreement with analytical predictions that take into account the different nature of the contribution of elastic and plastic components of strain to temperature variation. For t>40s, however, figure 2-b shows an unexpected decrease in temperature. From the synchronizing device, t=40s corresponds to a level of strain equal to ε=0,3. From this strain point, figure 2-c shows hardening in the form of a sustained increase in the stress carried by the fiber. This is possibly due to the fact that, from this point, most of the molecular chains are almost straightened and, thus, mainly elastically strained, which would, in turn, explain the temperature decrease seen from t>40s.

Optical intensity measurement during the deformation process

Figure 3 shows both the voltage measured at reception stage (proportional to the received optical power) versus time, a), as well as the true strain versus time, b). Both figures were tested under a strain rate 0.0021 s^{-1}. Figure 3-a shows that the received optical power underwent a slow decrease that, although being small in magnitude, can be considered significant. It is also shown that after 71 s, there is no signal detected, showing the fiber breakage. By correlating the evolution of deformation with the evolution of output voltage, the relative optical power variations with strain can be obtained, see Figure 3-b.





a) Voltage measured at reception vs time *b) Relative optical power vs true strain*

Figure 3: Voltage measured at reception vs. time, a), and relative optical power vs. true strain, b)

4 CONCLUSIONS

Tensile tests of a PMMA-core POF with simultaneous launching of light have been carried out. The main mechanical parameters, the optical power variation due the material deformation, and the temperature increase associated with the material deformation have been measured. These preliminary results demonstrate that cost-effective optical intensity-based measurements with this fiber type can be suitable as part of Structural Health Monitoring (SHM) systems. This work is a starting point for future developments.

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