

Failure Case Study for Loose Tube Jacketed Optical Fibers

H. Nagata

Optoelectronics Research Division, New Technology Research Laboratories, Sumitomo Osaka Cement Co., Ltd., 585 Toyotomi-cho, Funabashi-shi, Chiba 274-8601, Japan

K. Ooto

Sumicem Optoelectronics Ltd., The National Technological Park, Plassey, Ireland

and

M. Shiroishi and J. Ogiwara

Optoelectronics & Electronics Division, Sumitomo Osaka Cement Co., Ltd., 585 Toyotomi-cho, Funabashi-shi, Chiba 274-8601, Japan

Received March 18, 1998

In fiber optic devices, the 250 to 400- μm diameter tight jacketed fibers are sometimes jacketed additionally by loose tube-type materials. However, the loose tube jacketed fibers fail possibly due to the shrinkage of the loose tubes, if the tubes are not stabilized enough by preheat aging, etc. Although such phenomena are empirically known, here when the loose tube shrinks, the inner fiber is found to relax by being helically deformed. As a result, commercial fibers could endure at least 1-1.5% longitudinal shrink without a mechanical break, but exhibited excess optical propagation losses due to the bending. © 1998 Academic Press

1. INTRODUCTION

Engineering problems related to mechanical integrity in optical fiber devices have been investigated to estimate and ensure the long-term reliability of the devices during ordinary use. More severe demands from marine and terrestrial fiber communication systems, and recently from satellite systems, have resulted in the present highly reliable and stable states of optical fiber devices [1-4]. Standards

for such devices are also established based on huge amounts of experimental data from device and system manufacturers [5]. However, there is still the possibility that unexpected failure might occur due mainly to a lack of information on characteristics of the constituent device materials. Although the optical fibers themselves have been investigated enough and have been systematically standardized, the design requirements for the jacketing materials have not yet been established, except for the materials used in undersea cables [6]. In fact, fiber pigtailed in the devices fail sometimes due to defects in jacketing materials, assembling structures, handling, etc.

The problem of fiber extruding from tightly jacketed commercial fibers was reported previously with respect to the significant difference in thermal deformation of the outer jackets, which is dependent on the type of material [2]. Here, the failure in the loose tube jacketed fibers was investigated. The wavelike deformation of the inner fibers due to the longitudinal shrinkage in the loose tubes was empirically known, and the preaging of loose tubes at temperatures higher than device operating temperatures is commonly performed to suppress the shrinkage in the tubes during the service [7]. However, because the initial characteristics of the loose tube materials possibly fluctuate depending on the manufacturing and handling history, we consider that the failures could not be completely eliminated. Therefore, we investigated again the failures due to the loose tube shrinkage. Especially, the inner fibers were found to deform into a helix shape, not into a simple wave shape, enduring over 10-15 mm shrinkage per 1m loose tube without any fiber breaks.

2. FAILURE CASE STUDY

Figure 1 shows an example of the fiber deformation caused by longitudinal shrinkage of the loose tube. The fiber was a 250- μm -diameter UV radiation curable resin-coated single mode fiber, while the loose tube was a commercial FEP (tetrafluoroethylene / hexafluoropropylene copolymer) tube having 500 μm inner diameter and 900 μm outer diameter. In this case, because both terminals of the

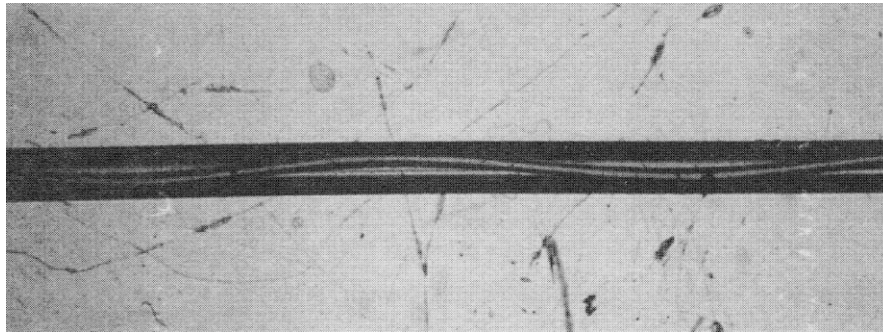


FIG. 1. Typical failure observed in loose tube jacketed fibers: a fiber wavelike deformation caused by longitudinal shrinkage of the loose tube. Outer and inner diameters of the loose tube are 900 and 500 μm , respectively. Outer diameter of the fiber is 250 μm .

oose tube were tightly bonded to the optical devices such as optical connectors with the inner fiber, thermally induced shrinkage in the loose tube induced the wavelike deformation of the fiber.

In order to investigate the relationship between the shrinkage length and the deformation in the optical fibers, 14 samples consisting of 1-m-long FEP loose tubes from multiple manufacturing lots with the 250- μm -diameter single mode fibers terminated with conventional fiber connectors at both ends were prepared and heated in an oven at 80°C for 12 h. The loose tubes had been assembled without any preaging treatments. The typical longitudinal shrinkage of the tube was described in the catalog to be less than 1%. After the heat treatment, the wavelength and waveheight of the deformed fibers were measured using an optical projector to calculate the magnitude of the deformation. The waveheight was measured to be almost 500 μm , suggesting that the radial shrinkage of the tubes was negligibly small. Then, both the loose tube and the fiber were cut at the position where the connector device was bonded, and the fiber length extruding from the tube was measured to estimate the longitudinal shrink length of the tube. The magnitude of the shrinkage was scattered from 3.5 to 12mm, indicating that mechanical characteristics of the tubes fluctuated greatly.

The experimental results are exhibited in Fig. 2 as open circles; in this figure, the vertical axis denotes the measured loose tube shrinkage and the horizontal axis denotes the wavelength of the deformed fibers averaged for more than 10 measurements in each sample. Similar relationships calculated for possible fiber deformations into the helixlike and the simple wavelike are represented by closed circles and triangles, respectively. The results indicated that due to the loose tube

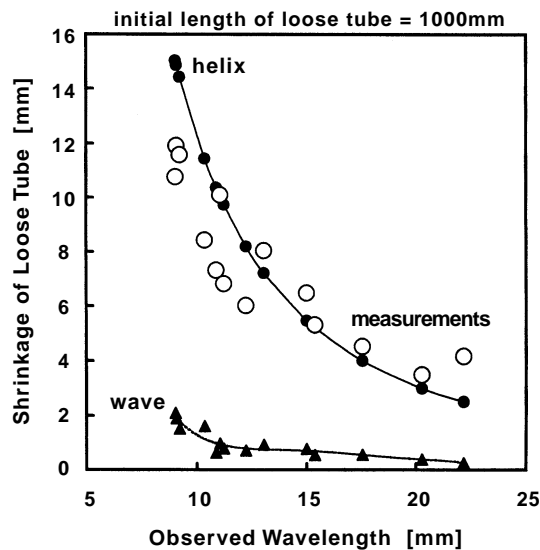


FIG. 2. Relationship between the longitudinal shrinkage measured for the 1-m-long loose tube and the wavelength measured for the deformed fibers after the heat treatment at 80°C. Open circles denote the experimental results. Closed circles and triangles denote the calculation results assuming the helical deformation and wavy deformation of the fibers, respectively.

shrinkage, the fibers deformed helically in the narrow space of the tube. Here, the calculation was done by substituting the measured wavelength, L , of the deformed fibers into the following equations. From a geometrical consideration, the length for helical fibers, L_{helix} is given by following the equation using the inner diameter, D , of the loose tube; here $D = 0.5\text{mm}$:

$$L_{\text{helix}} = [L^2 + (\pi D)^2]^{1/2} \quad (1)$$

Then, the shrinkage length of the loose tube was estimated simply by subtracting the length of the loose tube from the total length of the helically deformed fibers. Because the observed shrinkage of the tube was only 12mm in maximum for the 1-m-long tubes, here the total fiber length was calculated by $L_{\text{helix}} \times (1000 / L)$ as an approximation, and the tube length was fixed at 1000mm. On the other hand, the length for wavelike deformed fibers, L_{wave} is given by the following equation using the radius, R , of the deformed fibers and the center angle, θ , in radian for the sectors with the radius R and the cord $L/2$:

$$L_{\text{wave}} = 2R \theta \quad (2)$$

The R was derived by the following equation using the measured wavelength L of the deformed fibers; the inner diameter, $D (= 0.5\text{mm})$, of the loose tube; and the outer diameter, $d (= 0.25\text{mm})$, of the fibers:

$$R = [L^2 + 4(D - d)^2] / [16(D - d)]. \quad (3)$$

The shrinkage length of the loose tube corresponding to the deformed fibers was similarly estimated using the total fiber length, $L_{\text{wave}} \times (1000 / L)$.

The results indicated the fibers could deform helixlike in the loose tube and accept larger longitudinal shrinkage in tubes, e.g., 1-1.5% in Fig. 2, without any fiber breaks. On the other hand, the strength of the commercial fibers has been significantly improved, and the mechanical criterion for residual strain has proven to be 0.43% for 1-m-long fibers with the assumption of a predicted lifetime of 25 years, a failure probability of 1×10^{-5} per length, and fibers proof tested with 1% strain [8]. The 0.43% strain corresponds to the 15mm bending radius. In this regard, as a simple estimation, the maximum shrinkage length approved for the 1-m loose tube was calculated to be 20 mm by using Eq. (3) with $R = 15$ mm and Eq. (1) with the derived L for $R = 15$ mm. Note that the above consideration is with respect to only mechanical failure and the actual strain induced in the helically deformed fiber is more complex. The effect of twisting was not considered here, in spite of the fact that the strength of the twisted fibers was less than that of simply bent fibers. Concerning a similar problem occurring in the coiling up of slack fibers, Kiss recommended an assembly method to eliminate twisting in fibers [9].

At last, the optical propagation losses for the deformed fiber samples of Fig. 2 were evaluated using light with a wavelength of $1.55 \mu\text{m}$. Figure 3 shows the relationship between the loose tube shrinkage and the excess loss measured for the

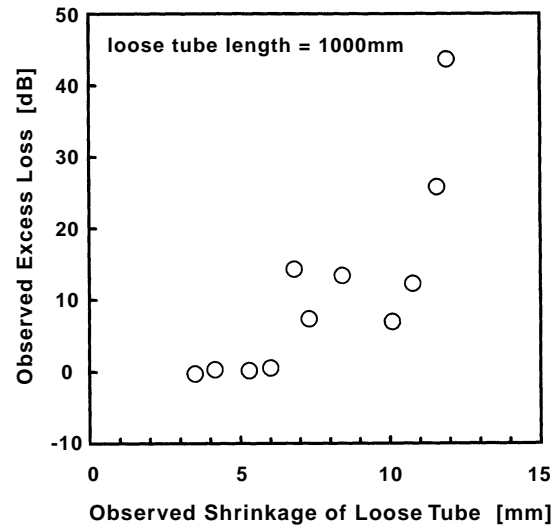


FIG. 3. Relationship between the loose tube shrinkage and the excess loss measured for the samples of Fig. 2.

corresponding samples. The excess loss was simply calculated by subtracting the initial loss value from the loss measured for deformed fibers after the heat treatment. Although all fibers might not have failed mechanically, a significant increase in propagation loss was detected for samples with the greatest tube shrinkage. By cutting the loose tubes to remove the deformation in the fibers, however, the excess losses were measured to be almost completely eliminated, indicating that observed losses were due to the fiber bending.

Figure 4 is a replot of Fig. 3, showing the relationship between the radius R of the deformed fibers, which was calculated using Eq. (3), and the normalized excess loss. Here, the measured excess losses were reduced per unit wind for each fiber coiled with the radius R . The numbers of coils appearing in the total fiber length, as a sum of the deformation with the wavelength L , were estimated by comparing the circumference length for the circle having radius R with the partial arc length L_{helix} by Eq. (1) within the gap L . In Fig. 4, open circles and error bars denote average and \pm , respectively, and was a standard deviation for R corresponding to \bar{E} for the measured L values. The closed circles show other experimental results obtained for 1-m-long fibers coiled up around mandrels having various radii (mandrel test [10]). The results for the deformed fibers (open circles) seemed to be like those given by the mandrel test, although the data were largely scattered. The larger deterioration in optical propagation losses for the deformed fibers is considered to be due to the influence of the fiber bent with a smaller R , which appeared possibly at some positions in the deformed fibers, and of the twisting caused by the helical deformation.

As a result, even though the fibers might not break until approximately 2% of the longitudinal shrinkage in the 1-m-long loose tube, in order to prevent a large increase in optical propagation losses, the loose tube shrinkage should be com-

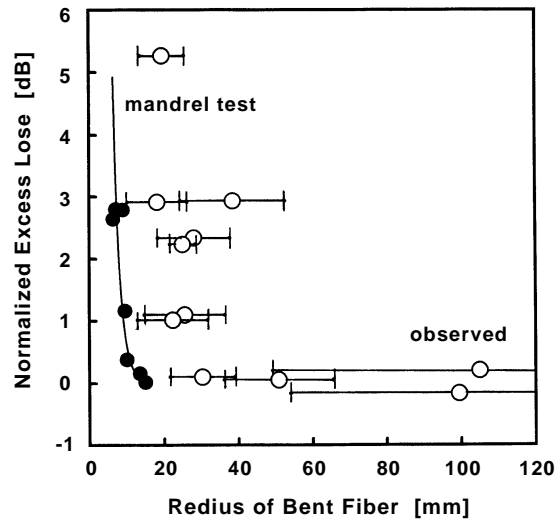


FIG. 4. Replot of Fig. 3 as a relationship between the radius R of the deformed fibers and the normalized excess loss. Open circles denote the data of Fig. 3, and closed circles denote the results of the mandrel test performed using other fiber samples.

pletely eliminated. In this regard, we also recommend simpler component designs excluding the loose tube jacketing of the fibers, and such designs have been commonly adopted. However, if the loose tube jacketing is necessary, the tubes should be divided into multiple elements so as not to deform the inner fibers by the shrinkage in the tubes. Although the preaging of the tubes seems to be effective in reducing the magnitude of the shrinkage, we consider that such treatment could not exclude completely the failure for the reason described in the following section.

3. EVALUATION OF LOOSE TUBE CHARACTERISTICS

As loose tubes, hytel (polyester) and fluorocarbons, such as FEP and PTFE (polytetrafluoroethylene), seem to be commonly used. In our experience, the hytel loose tubes were soft and reliably applied to devices operated under ordinary office conditions [4]. However, for critical devices used under a severe environment, fluorocarbon tubes are recommended. In our experience, for instance, after 1000 heat cycles between -40 and 100°C for devices with the hytel loose tube jacketed fibers, the tubes became harder and stuck to the inner fiber surface. Fortunately, because only 10-cm tubes had been installed at the fiber ports of the tested devices, the observed deterioration in the loose tube did not cause any damage to the optical characteristics of the devices. Such thermal deterioration in the hytel jacketing material could be predicted from the fact that the glass transition temperature (T_g) of the material was only approximately 50°C and changed largely depending on the environmental conditions, as previously reported [11].

Concerning the fluorocarbon tubes, too, there is a possibility that their mechanical characteristics are influenced by problems in the manufacturing, handling processes during the device assembly, etc. Figures 5a and 6a show results of

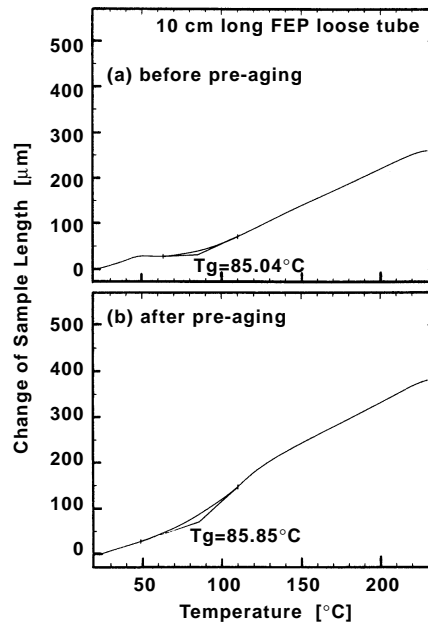


FIG. 5. Results of TMA tests for the 10-cm-long FEP loose tubes (a) before the preaging and (b) after the preaging at 100°C. The T_g is measured at 85.04°C. for (a) and at 85.85°C. for (b).

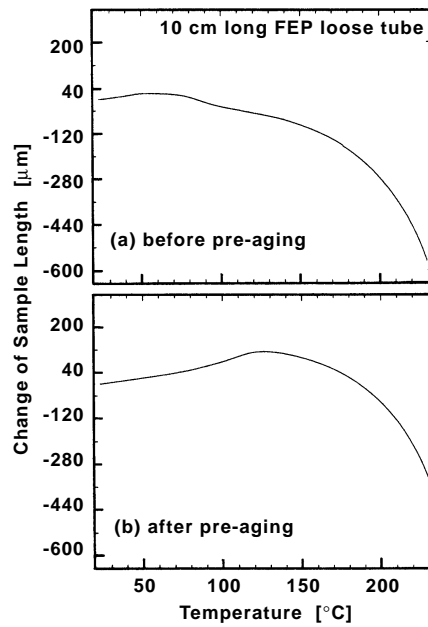


FIG. 6. Results of TMA tests for the other 10-cm-long FEP loose tubes (a) before the preaging and (b) after the preaging at 100°C.

thermomechanical analyses (TMA) for two FEP tubes supplied from two different fabrication batches. The 10-cm-long sample was suspended with a 10-g weight in an oven (N_2 atmosphere), while the temperature was increased from the room temperature to 230°C at 10 K/min . The change in the sample length was recorded as a function of the temperature. In the vertical axes of the figures, the positive and negative directions denote elongation and shrinkage of the sample, respectively. As is seen, the behavior in thermal deformation was very different depending on the sample. The sample in Fig. 6a shrunk considerably, even though the tensile force was applied to the sample by the weight. Although reasons for the observed difference in the thermomechanical behavior are not known, such analyses should be useful in rejecting undesirable materials and fabrication lots of the processed tube before assembly, at least.

Differential scanning calorimetry (DSC) analyses were also performed for the same FEP loose tube samples. The melting temperatures (T_m) were measured for the samples of Figs. 5a and 6a and found to be 267.0 and 266.1°C , respectively. The detected slight difference in T_m indicated a possible fluctuation in the material characteristics, because the T_m measured for the samples from the same lot was similar within 0.1°C .

Figures 5b and 6b show the TMA results for the preaged tube samples. The preaging was carried out at 100°C for 5 h. Concerning the sample of Fig. 5, the magnitude of elongation at lower temperatures (below approximately 120°C) increased while the T_g was kept almost the same at 85°C . The origin of the increased elongation was considered to be the shrinkage induced by the preaging of the tube at 100°C before the TMA test. Similar results were shown for the sample of Fig. 6, although the stability of T_g could not be checked for this sample because of its intrinsic anomaly in thermomechanical characteristics. Melting temperatures (T_m) were measured by DSC for the samples of Figs. 5b and 6b to be 267.74 and 265.5°C , respectively, and changed from the initial values, suggesting that the material characteristics were modified by the preaging.

A supplied PTFE tube was also evaluated and shown to have T_m at 328°C by DSC analysis. The result from the TMA test was also ideal, as shown in Fig. 7,

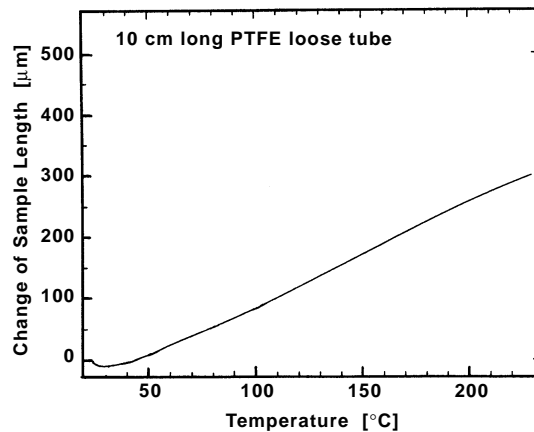


FIG. 7. Results of TMA tests for the 10-cm-long PTFE loose tube..

without a certain T_g . Within ordinary temperatures for the optical device operation. Even after 1000 heat cycles between - 40 and 100°C, no significant deterioration in mechanical dimension and color was observed for the PTFE loose tube. The PTEF is considered to be a promising material for the loose tubes, which could be used under severe heat conditions.

4. CONCLUSIONS

The mechanical failure in optical fiber devices induced by the thermal shrinkage of the loose tube materials was analyzed. Although the phenomena have been empirically known, we revealed here that the optical fibers deformed helixlike in the loose tube due to longitudinal shrinkage of tubes. As the result of such a flexible deformation, the fibers might endure approximately 2% in the shrinkage without any fiber breaks (1-m-long fibers), although a large deterioration in optical propagation appeared due to fiber bending. In order to know the thermal stability of the loose tube materials, some commercial tubes were evaluated by TMA and DSC methods, and fluctuation in the mechanical characteristics, possibly due to the material and handling history, was shown. From the viewpoint of long-term reliability of the devices, the results recommended the assembly designs without loose tube jacketing, which are commonly adopted, rather than designs having fibers completely jacketed with loose tubes.

ACKNOWLEDGMENTS

The authors are grateful to staff members of UBE Analysis Laboratory Co., for TMA and DSC analyses, and to Dr. Honda, Mr. Totani, and many staff members of Sumitomo for useful discussions and help with the experiments.

REFERENCES

- [1] C. R. Kurkjian, R. A. Frantz, and H. H. Yuze, "Light guide fibers: Problems and Prospects," *Opt. Photon News*, vol. 8, no. 7, 35 (1997).
- [2] H. Nagata, N. Mitsugi, M. Shiroishi, T. Saito, T. Tateyama, and S. Murata, "Elimination of optical fiber brakes in stainless steel packages for LiNbO₃ optical modulator devices," *Opt. Fiber Technol.*, vol. 2, 98 (1996).
- [3] N. Mitsugi, H. Nagata, M. Shiroishi, N. Miyamoto, and R. Kaizu, "Optical fiber breaks due to buckling: problems in device packaging," *Opt. Fiber Technol.*, vol. 1, 278 (1995).
- [4] H. Nagata and N. Mitsugi, "Mechanical reliability of LiNbO₃ optical modulators hermetically sealed in stainless steel packages," *Opt. Fiber Technol.*, vol. 2, 216 (1996).
- [5] for example, Bellcore GR-1221-CORE "Generic reliability assurance requirements for fiber optic branching components," TR-NWT-20 "Generic requirements for optical fiber and optical fiber cable," and TR-NWT-357 "Generic requirements for assuring the reliability of components used in telecommunication equipment."
- [6] D. R. Biswas, "Optical fiber coatings," *SPIE Critical Rev. Ser.*, vol. CR50, 63 (1994).
- [7] Private communication from Mr. Akira Wada, manager of Optical Fiber Technology Department, Optics and Electronics Laboratory, Fujikura Ltd.

- [8] Application Note AN3 Strength of Optical Fibres, technical report from OPTICAL FIBERS (Deeside, UK).
- [9] G. Kiss, "Reliability of optical splices," SPIE Critical Rev. Ser., vol. CR50, 118 (1994).
- [10] M. J. Matthewson, "Optical fiber mechanical testing technique," SPIE Critical Rev. Ser., vol. CR50, 32 (1994).
- [11] H. Nagata, "Thermal analysis of jacketing materials for commercial optical fibers," Opt. Fiber Technol., vol. 3, 87 (1997).