MECHANIKA TEORETYCZNA
I STOSOWANA
Journal of Theoretical
and Applied Mechanics
2, 31, 1993

THE RESEARCH INTO THE FIBERS STRENGTH WITH REGARD TO THE CONSTRUCTION AND TECHNOLOGICAL FACTORS

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The results of scanning electron microscope and tension strength examinations of experimental optical glass fibers have been presented in this paper. In the results analysis, influence of the fibre glass composite technological and constructional parameters on the immediate strength of different types of fibers, have been considered. Such good mechanical features figure out the fibers ability to carry on loads during manufacturing, installing and maintaining.

1. Introduction

The great ability of information transfer is the most useful propriety of optical glass fibers, the fibre materials cost less then copper as well. These features are the main reason of using optical glass fibers in telecommunication. Such application demands high mechanical reliability of optical glass fibers; the operation life of several score years should be concerned.

The optical glass fibers should be projected the way, they could be able to carry on some loads during production, installation and exploitation of telecommunication lines. The operating conditions of their work have a serious influence upon their mechanical reliability. There is the strength decrease because of moisture influence, thus protective coat is an internal part of the glass fibre, determining the strength and the resistance against the medium influence. The coat consists of one or two-layers, depending on the optical fibre glass construction.

The most reliable method of the optical glass fibre strength determination, considering the scale effect, is the fibre whole length tension test. One of the supplementary methods is the examination of great quantity of short samples.

The first papers in the optical glass fibers research in telecommunication, published by Mauer (1975) concerned the short fibers (0.6 m). The low fibers strength was explained as the result of surface defects appearing during production. The results of the tension strength research into the silicate fibers 0.04, 0.75 and 20 m long were presented as histograms and Weibull diagrams (cf Kurkijan et al., 1976); they did not present the only one, single mode type of distribution – one type of defect is not crucial for the optical fibre strength. For examination purpose the strength, 1 km long optical fibre was divided into 20 meters pieces (cf Kurkijan et al., 1976; Schonhorn et al., 1976). According to the "weakest link" model, the lowest strength sample represented the whole fibre strength.

It was stated that the laser usage as the source of heat during the fibre pull out and the flame polished surfaces preform application caused the narrow, single mode strength distribution with sufficiently high strength of the long fibre. Other scientists examined 1 km and 0.6 m long samples, respectively. The weak correlation between the results of the short and long samples was obtained. The single mode strength distribution for the short samples versus the long ones seemed to be one of the main reasons for such results Kalish and Tariyal (1977), Tariyal and Kalish (1977).

The knowledge of the insantaneous strength distribution and its repeateability for produced fibers can entitle to carry out the resistant tests of the small number of short samples to make sure that a given fibre has the similar strength characteristics.

The results of the optical fibre strength obtained in the research program in Maria Curie-Sklodowska University of Lublin (UMCS) in 1986-1990 have been presented in this paper (cf Szabelski et al., 1987, 1988, 1989, 1990). That program concerned all techniques of manufacturing the new types of the optical glass fibers. The achievement of appropriately high fibre tension strength was the main purpose of the mechanical properties examination.

2. Characteristics of tested optical glass fibers

Nine types of the optical glass fibers were subjected to the tension test. Five of them had one layer coat, the rest was protected by two-layer coating. All types of the optical fibers were produced of the quartz glass with the amorphous central core structure coated with high purity outer layer. The glass fibre diameters (core and coat) were changed within 103.5×10^6 to 129×10^6 m, while the Young modulus was $E = 7.5 \times 10^5$ MPa. The one layer protective coats were made of epoxy-acrylic varnish cured by the UV radiation, while the type A fibers were covered with thermally cured polyurethane varnish.

The one layer coat Young modulus was $E = 0.10 \times 10^4$ MPa, while for two-layer coat with soft silicon rubber inner layer the Young modulus was $E = 0.0001 \times 10^4$

MPa. The outer shell was made of the UV cured epoxy-acrylic varnish. The external fibers diameters were changed within $(126 \div 329) \times 10^6$ m.

3. The research conditions

The pseudo-randomly chosen samples were tested repeatedly for different constructional and technological parameters. The fibers with two-layer protective coat with soft inner layer demanded the usage of especially made roller grips with the diameter of about 100 mm. The one layer hard varnish coated fibre samples were fixed after special preparation in the flat grips. The tested quantities of fibers pieces were 25 or 50 samples, of $L = 250$ mm length each. The examinations were carried out on the ZM40 machine with dynamometer range to 200 N and the stretching velocity $V = 25$ mm/min in the surrounding air medium at 23° temperature and relative humidity of 55 %. The elongation and breaking force were measured for each tested sample. The scanning electron microscope was used to find the probable causes of sample crack.

4. The results analysis of the strength and scanning electron microscope researches

The tension research results were shown as histograms and Weibull diagrams. If in dependance

$$P(s) = 1 - \exp[L - \sigma(s)] \tag{4.1}$$

we take $\sigma(s) = \sigma^m$, then after double repeated natural logarithm finding by sides we obtain the following equation

$$\begin{gathered} \ln\ln[(1-P)^{-1}] = m\ln\sigma + \ln L \\ m \cong \frac{1}{\nu} \qquad\qquad \nu = \frac{S}{R_m} \end{gathered} \tag{4.2}$$

where

m – shape distribution parameter

ν – variation coefficient

The Weibull dependance is valid for the fibers with similar strength level. Then m can be obtained from the experimental straight line slope. The occurrence of various defects in the fibre causes maximum peaks on the strength distribution lines, research results fit to curve line.

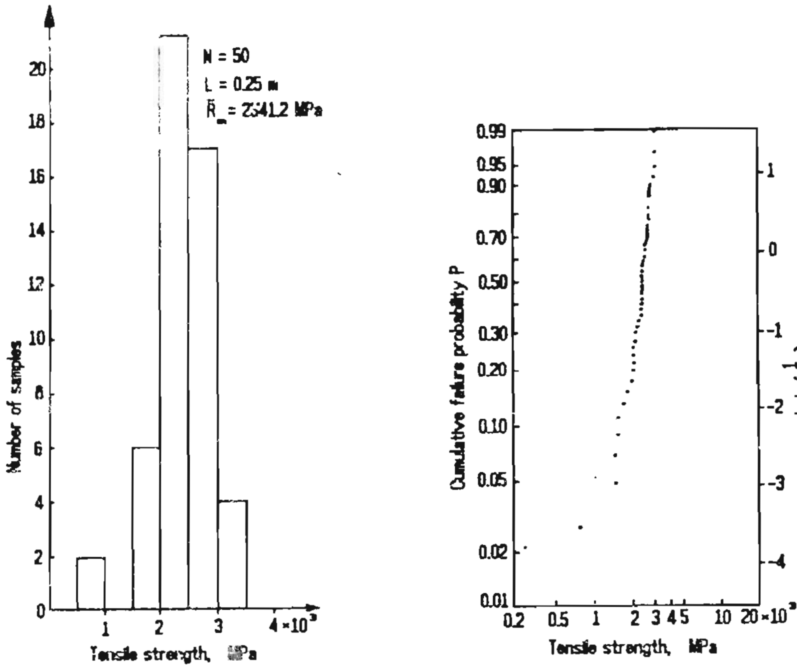
N = 50
L = 0.25 m
$\bar{R}_m$ = 2541.2 MPa
Number of samples
Tensile strength, MPa
Cumulative failure probability P
$\ln\ln\left(\frac{1}{1-P}\right)$
Tensile strength, MPa

Fig. 1.

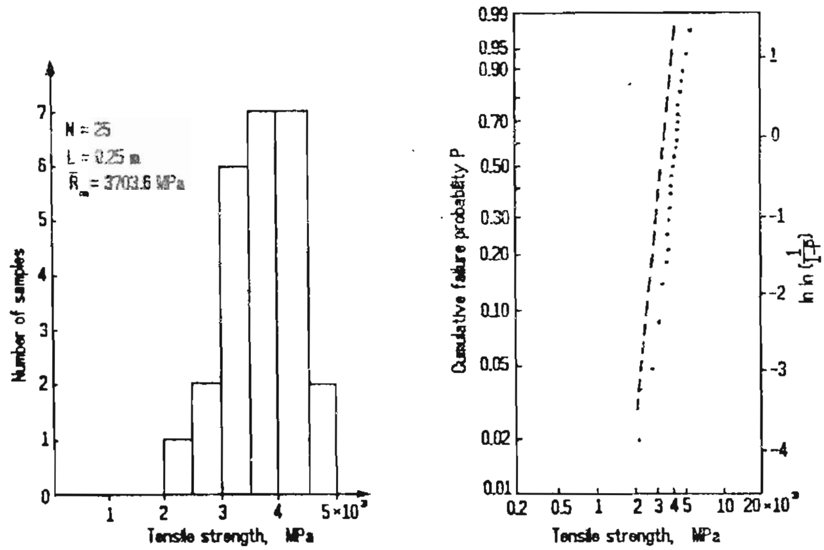
N = 25
L = 0.25 m
$\bar{R}_m$ = 3703.6 MPa
Number of samples
Tensile strength, MPa
Cumulative failure probability P
$\ln\ln\left(\frac{1}{1-P}\right)$
Tensile strength, MPa

Fig. 2.

The optical glass fibers with one layer coat (type A, B, D, UA, W) were characterized by quite significant results distribution with low value of strength; in general they did not display the single mode distribution. As far as the UA, A and B types of fibers were concerned, the distribution of strength proved that fibre crack was not caused by one type of defect. In the UA and the A type fibre, where the great number of samples were characterized by the low strength ($500 \div 2000$ MPa), detected defects were not only on the glass fibre surface but on the fracture and coat, as well. The B type fibre with its strength much higher than types previously mentioned, did not show the superficial fracture defects. The shell and the quartz coat defects have the most important influence on fibers strength. The highest strength of the one layer protected fibers has had the type D with values mainly from 3000 to 5000 MPa, which could be approximated with slope $m = 7$ line.

Only the type W (Fig.1) fibre has had almost single mode Weibull distribution with its approximating line slope coefficient $m = 11.4$ within average and high strength values.

The two-layer protective coat fibers (type C, E, OA, Z) were characterized by smaller strength distribution (Fig.2), except for the type E fibre with the lowest strength in this group. Slightly more than 30% of the samples has had over 2000 MPa strength. The Weibull diagram shows that the causes of decohesion were similar only for the small amount of samples near average strength. The low strength of a considerable number of fibers was mainly caused by the quartz coat and the shell defects. Fibers C, OA, Z were characterized by the lower strength distribution closely to Weibull single mode distribution, testified by a steep slope of the chart with $m = 11.5$ for the C and OA types, $m = 9.5$ for the type Z. The negative influence of the superficial defects was reduced by filling them with the inner layer coat material due to the good adhesive features of shell and quartz fibre (type C). There were not detected any defects in quartz casing structure in the type OA and Z fibers. The research results of $L = 0.25$ m length pieces of fibers have been extrapolated to 1 m sections in Weibull chart (Fig.2). This approach demands, however, the experimental verification of the obtained results. Based on Weibull chart, it is possible to say that only in a few cases the same kind of defects caused optical glass fibers decohesion. The complex of various defects has had usually influence on fibre strength with its source in technological process, preform quality, fibre fullering process or fibre covering with protective coat.

The examination of the fibers fracture and microstructure became essential to take closer look at the reasons of fibers strength reduction as well as their analysis. About 100 samples were fractographicaly examined in the electron microscope. The scanning electron microscope research of the superficial defects of the coat before and after strength tests were carried out. Many fractures had transverse and superficial defects with its origin in fullering fibre process in preform. The defects $0.002 \div 0.010$ mm depth became technological micronotches, causing stress concentration. The low strength values have been usually caused by fibre glass surface defects. The defect of different depth $0.003 \div 0.005$ mm and serious defects filled with soft, inner shell material and bubble shaped defects were stated in that case. The crack propagation was started in these places, moreover numerous surface sand holes, outer surface shell irregular and regular longitudinal scratches, irregular pits and joggles were observed. The fibers containing mentioned defects were characterized by the low breaking force value. The fibers with outer surface shell, casing and core defects of fracture were characterized with the lowest strength. Such fractures were usually flat, perpendicular to fibre axis (Fig.3). Samples which became broken at the highest forces were characterized by complicated, usually smooth surface fractures.

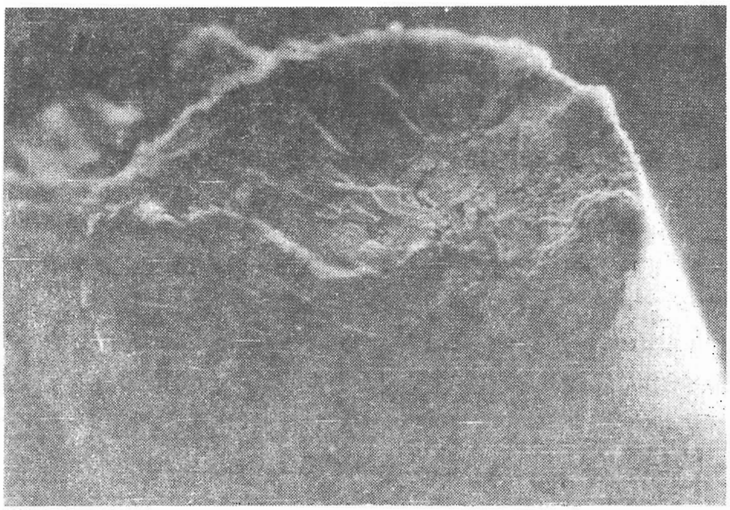

Fig. 3.

Various defects with random distribution of the optical glass fibers had influence on their strength and the destruction causes. Figure 3 presents the fibre (type A) fracture perpendicular to its longitudinal axis. The visible, big superficial defect was the crack propagation source. On the fracture surface there is an internal defect crack. All the defects mentioned above and the shell scratches, respectively have caused the low breaking strength.

Figure 4 presents fibre fracture with cracking process originated from the superficial defect; negative influence has been reduced due to the good adhesion of viscous inner layer filling the gap in the quartz casing. The shell inner layer has good adhesion with glass, but there is not good coherent joint with hard, brittle outer layer. The sample became broken with quite high breaking force.

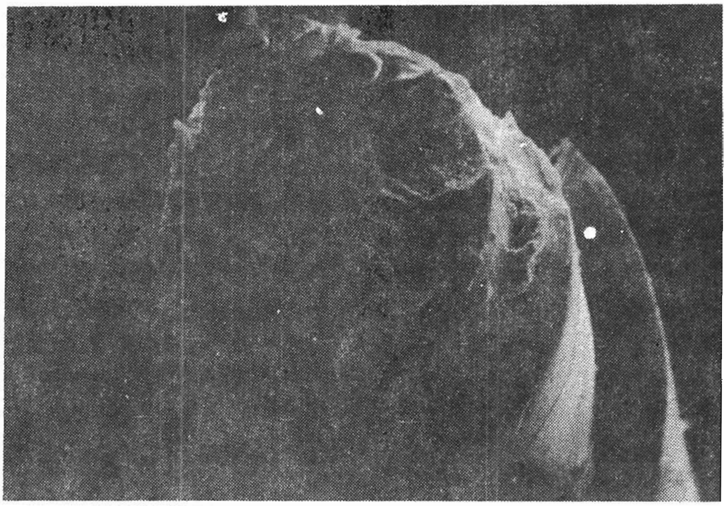

Fig. 4.

The analysis of various coat and fibre defects pointed at the necessity of the technological process improvement. The fracture analysis gave approximate mapping of the cracking propagation process inside the fibre. The crack initiation and propagation, determined by the stress gradient around defect, arise from the fibre outer mechanical loads and internal tension stresses.

Table 1

	Fibre type description		Coating layers number	Average strength R_m [MPa]	Confidence interval of average strength $\alpha = 0.05$ [MPa]	Probability R_m [MPa] the basis of empiric distribution function	Average strength variance
1	UA	I	1	1695.4	1335.9÷2054.9	$P(R_m \geq 750) = 0.76$	78371.1
2	A	II	1	1969.9	1709.9÷2230.0	$P(R_m \geq 750) = 0.86$	880248.4
3	W	III	1	2341.2	2201.8÷2480.6	$P(R_m \geq 1750) = 0.84$	252926.7
4	E	IV	2	2674.6	2232.5÷3116.7	$P(R_m \geq 1250) = 0.80$	1147148.5
5	B	V	1	2890.6	2580.7÷3200.5	$P(R_m \geq 1750) = 0.86$	1250089.0
6	C	VI	2	3319.3	3144.1÷3494.5	$P(R_m \geq 2250) = 0.89$	399445.8
7	OA	VII	2	3703.6	3437.6÷3969.7	$P(R_m \geq 2750) = 0.88$	415445.5
8	D	VIII	1	3835.5	3415.3÷4263.6	$P(R_m \geq 2750) = 0.84$	1055754.7
9	Z	IX	2	4094.0	3754.0÷4433.0	$P(R_m \geq 750) = 0.89$	766085.0

The obtained tension strength results displayed significant deviations. The normal distribution model of the immediate strength was taken (confirmed with χ^2 test). Calculated mean values are placed in Table 1. F-Snedecor's test was used for testing the two variances similarity. The significant difference between two mean values in similar and non similar variances were examined with Student's t test. In the case of different variances and different sample size to verify the null hypothesis C-Cochran and Cox's test was used.

The conclusions based on carried out tests are

- there is the significant strength difference between some types of optical glass fibers,
- there is the positive influence of the two-layer coats on the fibre strength.

The average strength of tested fibers lies within 1695.5 ÷ 4094.0 MPa. The significant difference of average fibre strength (significance level $\alpha < 0.005$) was found between optical glass fibers V vs VI and VI vs VII. In the remaining cases this difference is insignificant. Moreover, the significant strength differences were found between the following fiber types: I (UA) and III (W), II (A) and V (B), III (W) and VI (C). The strength difference between the types V (B) and VI (C) was caused by the two layer protective coat for the type C. The statistically significant type VII (OA) fibre strength growth was obtained using laser as the heat source in fullering process. The visible growth in fibers strength (Table 1) was the result of the mentioned above radical manufacturing process changes, better preform surface and the material quality (low admixture quartz glass – high silica). Better smoothness and surface quality of the glass rod used in fullering process was obtained by etching or polishing in flame. The scanning electron microscope examinations proved that despite changes in manufacturing process, all strength reduction factors have not been eliminated.

The highest strength R_m = 4094 MPa had the fibre IX (type Z) with a two-layer coat. Fibers with such two-layer protective coats were grouped within the highest tension strength area, with the highest R_m values in 88 ÷ 89 % of samples. Moreover these samples were characterized by the most uniform, with relatively low deviation strength results distribution that testify to a positive influence of the inner elastic coat layer.

5. Conclusions

The results of the optical glass fibers tension strength are the basis to the mechanical reliability of the telecommunication wires anticipation. The fibers strength is determined mainly by the technological defects arising during manufacturing process. Data handling by means of Weibull graphs and additionally electron microscope examinations give information enabling the improvement of technological process. To obtain the high strength fibre strict rules concerning parameters of fullering process should be complied.

The most important meanings have

- quality of the glass to a perform production (synthetic silicon)

- perform surface quality (etched or polishing in flame)
- purity of heat source (laser beam)
- protective coat material quality
- quality of devices for coating and forming of protective shell (geometrical accuracy and quality of elements surface)

The multi layer coat is more advantageous in the optical glass fibers construction. The inner layer in two-layer coat should be soft, high adhesive with glass and with low content of stable particles. Hard outer layer should be characterized by low surface viscosity, high Young modulus E, insensitivness to external surroundings influence.

References

1. MAURER R., 1975, *Strength of optical fibers, rm Appl.Phys.Lett., 27, 220*
2. KURKJIAN C.R., ALBARINO R.V., KRAUSE J.T., 1976, *Strength of 0.04-50 m lengths of coated fused silica fibers with tensile strengths...*, Appl.Phys.Lett., 28, 586
3. SCHONHORN H., KURKJIAN C.R., JAEGER R.E., 1976, *Epoxy-acrylate coated fused silica fibers with tensile strengths...*, Appl. Phys.Lett., 29, 712
4. KALISH D., TARIYAL B.K., 1977, *Static and dynamic fatigue of fused silica optical fibers,* 79th Annu.Am.Ceram.Soc.
5. TARIYAL B.K., KALISH D., 1977, *Application of Weibull type analysis to the strength of optical fibers,* Mater.Sci.Eng., 27, 69
6. SZABELSKI K., BANASZEK J., JAŚKIEWICZ W., MALICKI A., 1987, *Badania własności mechanicznych światłowodów,* Sprawozdanie z pracy zleconej wykonanej w ramach programu resortowego RR I 02, cz.I, II. Politechnika Lubelska
7. SZABELSKI K., JAŚKIEWICZ W., MALICKI A., NEIMITZ A., 1988, *Badania własności mechanicznych światłowodów,* Sprawozdanie z pracy zleconej wykonanej w ramach programu resortowego RR I 02, Politechnika Lubelska
8. SZABELSKI K., MALICKI A., NEIMITZ A., WARMIŃSKI J., 1989, *Badania własności mechanicznych światłowodów,* Sprawozdanie z pracy zleconej wykonanej w ramach programu resortowego RR I 02, Politechnika Lubelska
9. SZABELSKI K., MALICKI A., BANASZEK J., PIEKARCZYK A., 1990, *Badania własności mechanicznych światłowodów,* Sprawozdanie z pracy zleconej wykonanej w ramach programu resortowego RR I 02, Politechnika Lubelska

Badania wytrzymałości światłowodów z uwzględnieniem roli czynników konstrukcyjnych i technologicznych

Streszczenie

W pracy przedstawiono wyniki badań wytrzymałości na rozciąganie i badania elektronooptyczne eksperymentalnych włókien światłowowdowych. W analizie wyników badań uwzględniono wpływ czynników konstrukcyjnych i technologicznych kompozytu światłowodowego na wytrzymałość doraźną różnych rodzajów światłowodów. Tego rodzaju dobre własności mechaniczne świadczą o zdolności światłowodów do przenoszenia obciążeń występujących podczas ich wykonywania, instalowania i eksploatacji.

Manuscript received June 30, 1992; accepted for print October 20, 1992