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Acoustic Location of Fracture Origin in Optical Glass Fibers

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During strength measurements on plastic-coated optical glass fibers, the positions of fracture origins were determined by an acoustic technique. For samples other than those in which fracture was initiated at or very near the fixed ends, Weibull plots of the strength data exhibited a single-mode distribution with low variability (m=20 to 25, corresponding to a coefficient of variation of 6.6 to 10.6%).

BECAUSE of the recent demand for increased mechanical reliability of glass fibers for use as optical waveguides, strength measurements for different types of optical fibers and coating systems have been reported.[1-7] According to the results of these measurements, a bimodal or multimodal distribution, rather than a unimodal distribution, is usually generated when strength data are displayed as Weibull probability plots. This multimodal character of the Weibull distributions is interpreted as the result of the combined effects of different flaw populations produced on the surfaces of optical fibers. For example, France *et al.*[7] proposed that low-strength tails in Weibull plots were due in part to particles present in the coating and in part to failure of the nonconcentric coating failing to adequately protect the fibers.

It seems almost inevitable that sample gripping during tensile tests would cause flaws on the sample surface. Apparently, however, no systematic studies have clarified whether the portions of optical fiber samples near their gripped ends are more likely to fracture than other portions; visual location of fracture origins in glass fiber samples is impracticable since they are easily fragmented by simple tension before such an observation can be made. In the present communication, the results of a study using an acoustic technique are reported; these results indicate that sample gripping has a marked effect on the deviation from linearity in Weibull probability plots of strength data for optical fibers.

EXPERIMENTAL PROCEDURE

The samples tested were typical multimode optical glass fibers.* The core and cladding (50 and 125 μm in diameter) were essentially fused silica. The glass surface was coated in-line with a thermosetting silicone resin so that the outer diameter of the samples was ≈250 μm.

Tensile strengths were measured for 600 fiber samples 20 cm in gage length with a mechanical testing machine† at laboratory ambient conditions. The crosshead speeds used, 10, 50, and 500 mm/min, were equivalent to strain rates of 8.4×10^{-2}, 4.2×10^{-1}, and $4.2\ \mathrm{s}^{-1}$. To grip the fibers, both ends of each sample were wound three times around the periphery of aluminum disks 5 cm in radius, which was sufficient to prevent a pulled sample from slipping.

Two piezoelectric sensors (PZT ceramics), one fixed to each of the aluminum disks, picked up acoustic signals generated from the fracture origin at the moment of fracture, which oscillated at a frequency of ≈160 kHz. It should, in theory, be possible to locate the origin by clocking the difference in arrival time of the signals between the two sensors. For this purpose, a distribution analyzer‡ was used. The block diagram of the system for measuring the time difference is given in Fig. 1.

Figure 2 illustrates the relation between the location of the break versus the difference in arrival times, which was obtained by elongating fibers originally 20 cm long to 23 cm and then cutting them at several predetermined points. Good linearity exists between the location and the difference in arrival time, except for breaks occurring close to the fixed ends; since the acoustic signals generated in these areas reach the nearby sensors without appreciable attenuation, the leading edges of the signal waves, rather than the peaks, were apparently high enough to trigger the time counter used.

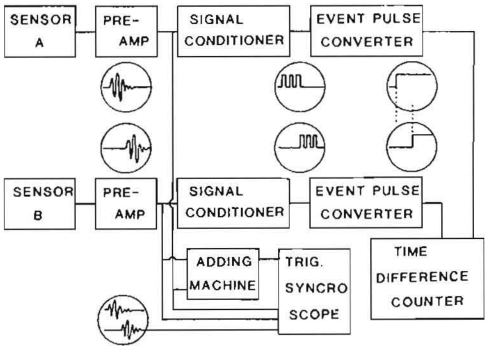

Fig. 1. Block diagram of system for measuring difference in arrival times of acoustic signals at two ends of glass fiber.

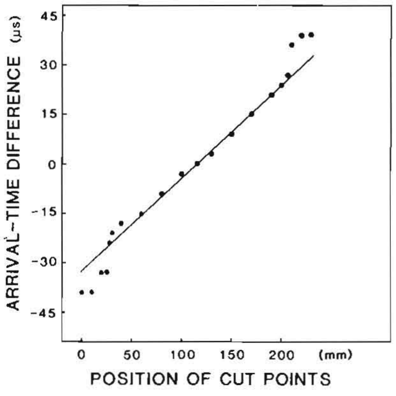

Fig. 2. Typical relation between observed time difference and location of fracture origin in glass fibers.

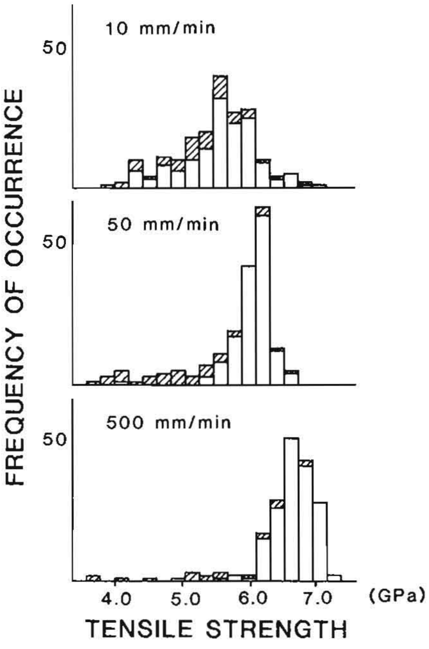

Fig. 3. Strength histograms for optical glass fibers subjected to tensile tests at loading rates indicated. *Hatched areas* represent specimens in which fracture initiated within ≈2 mm of gripped end.

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†Toyo Baldwin Co., Ltd., Tokyo, Japan.

‡Model 920, Dunegan Endevco, San Juan Capistrano, CA.

Table I. Average Strengths and Standard Deviations of Optical Fibers Tested

Crosshead Speed (Strain Rate)		Number of Trials	Mean Strength [GPa]	Standard Deviation [GPa]	Coefficient of Variation [%]
10mm/min (0.083%/s)	Total	200	5.64	0.90	15.9
	Selected	142	5.88	0.62	10.6
50mm/min (0.42%/s)	Total	200	5.72	1.12	19.5
	Selected	156	6.16	0.45	7.2
500mm/min (4.2%/s)	Total	200	6.48	1.15	17.7
	Selected	168	6.80	0.45	6.6

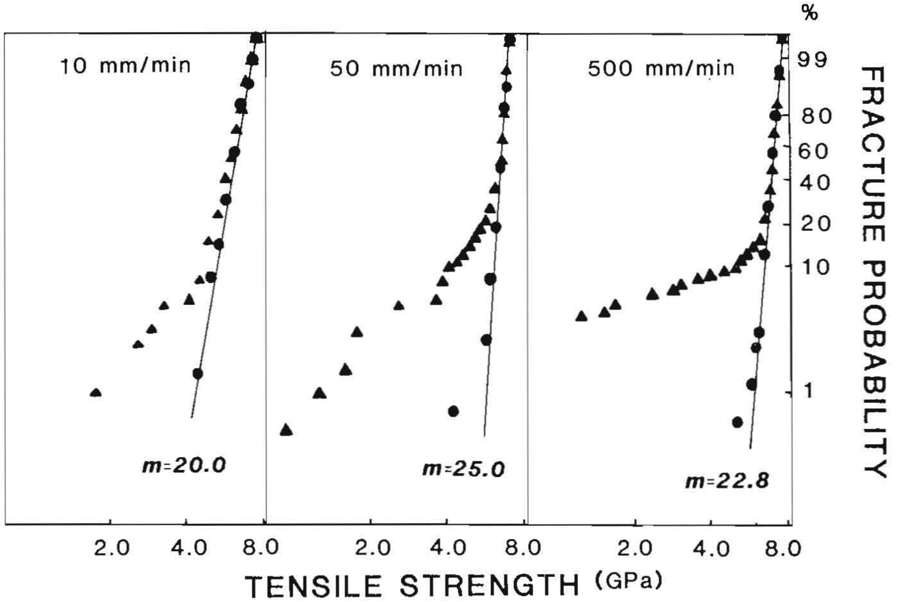

Fig. 4. Weibull plots of strength data for optical glass fibers. *Triangles* represent all data, *circles* the set of data excluding those which correspond to hatched areas in Fig. 3.

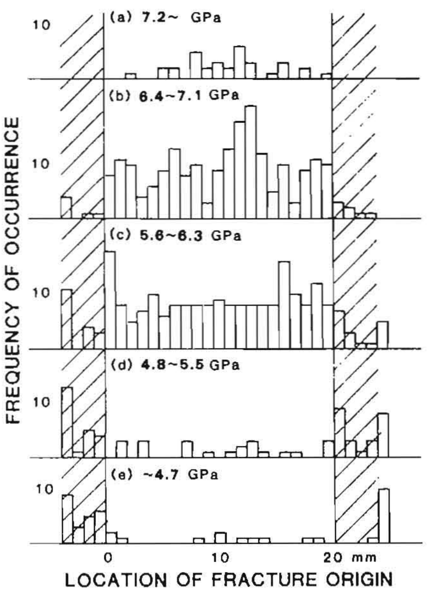

Fig. 5. Fracture origin distributions for fiber sample groups differing in strength.

RESULTS AND DISCUSSION

Figure 3 shows strength histograms for the specimens subjected to tension at the three loading rates. The results are summarized in Table I, which indicates that the average strength increased with the loading rate, a phenomenon known as dynamic fatigue. The hatched areas in Fig. 3 represent those specimens for which fracture was initiated at or very near (i.e. within ≈2 mm) a gripped end. Since most of the specimens with strengths lower than ≈5.6 GPa (or 570 kg/mm^2) fall into this category, the wide scatter in the strength distributions of optical fiber samples seems to result primarily from the gripping effect. As seen in Table I, a coefficient of variation (standard deviation/arithmetic mean) of strength as low as 10% or less was obtained when the data for the specimens corresponding to the hatched areas were excluded.

The results are plotted on Weibull probability scales in Fig. 4, in which the circles represent the set of data excluding those data corresponding to the hatched areas in Fig. 3 whereas the triangles represent all the data. As is evident from Fig. 4, as far as the circles are concerned, the data are well described by the single-mode Weibull distribution. The distribution shape parameter (characteristic of the distribution of flaw sizes),[8] m, for this case has been estimated to be ≈20 to 25 by the least-squares method.

Figure 5 shows distributions of the fracture origin locations for five groups of fiber specimens, classified by breaking strength. For low-strength specimens, fracture originated primarily in areas close to the fixed ends (Fig. 5(d) and (e)). On the other hand, for medium strength specimens (Fig. 5(c)), fracture apparently began at different places along the gage-length with equal probability. This result is certainly logical, since there is no particular reason why one position along the specimen was more likely to break than another. For higher strength specimens (Fig. 5(a) and (b)), however, it is evident that fracture originated more frequently in the middle than in other areas. Because the total frequencies in these strength regions were not very high, it is not certain if this is significant, i.e. it might be the result of a random fluctuation. In addition, the acoustic method for locating the fracture origin was not as reliable at higher strengths as at lower strengths because the calibration curve (e.g. Fig. 2) used for determining the location of fracture origin was obtained only from fibers elongated to extents corresponding to the breaking strains of medium-strength fibers.

As a final statement, note that in light of the present study, those flaws which are produced when gripping fiber samples in tensile strength tests should be greatly responsible for the weaker tail of the multimodal Weibull distribution which is usually observed in strength measurements of optical glass fibers.

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