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Optical Fiber End Preparation for Low-Loss Splices

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Cables made from brittle materials like glass require new techniques of end preparation for the purpose of splicing, especially if such splices are to be made in the field. We report here on a method of breaking fibers in a way which invariably produces flat and perpendicular end faces. We explain the underlying theory and derive optimal parameters that permit the design of a simple breaking tool. Experiments with a tool of this kind show that the tolerances for successful fracture are not critical. Laboratory splices of multimode fibers prepared by this method exhibited losses of less than 1 percent (0.04 dB) when joined in index-matching fluid.

I. INTRODUCTION

With installation and maintenance consuming an ever-larger share of system costs, simple and inexpensive splicing techniques have become a prerequisite for competitive communication systems. One bottleneck in optical fiber cable splicing is the fiber end preparation, as conventional grinding and polishing techniques turn out to be time-consuming and costly, especially in the field. It is well known that glass fibers sometimes break with flat and perpendicular end faces if they are previously scored,[1] and it has thus become common practice in the laboratory to obtain good ends in this way by trial and error. Besides being faster and simpler, this technique has the added advantage of producing perfectly clean surfaces uncontaminated by lossy residues. Such ends were recently used in fiber joining experiments to determine eventual splice losses.[2–5] The lowest losses obtained were about 10 percent for single-mode fibers[4,5] and 3 percent for multimode fibers.[2]

For such laboratory practice to become useful technology, absolute control of the breaking process and utmost reliability in obtaining a successful result are required. We report here on an approach which guarantees this reliability through control of the stress distribution in the fracture zone. The break is initiated by lightly scoring the fiber periphery at the correct point. We explain the underlying theory which allows us to predict the character of the break from the initial stress distribution. By modifying a previous design,[6] we obtained a simple tool that permits us to vary the amount and distribution of stress in the fracture zone. All 130 breaks we have made with this tool have produced the predicted fracture surface. The range within which perfectly flat and perpendicular end faces were obtained was found to be so wide that the eventual construction of a simple hand tool for this purpose should present no problem. The quality of the surfaces obtained makes this method the most promising of all the techniques investigated so far.[7–9] This notion is supported by some fiber-joining experiments which we describe in Section IV of this paper. Low-loss multimode silica glass fibers were prepared by our breaking technique and then joined in an index-matching liquid. With proper alignment, the splice losses were always less than 1 percent. Results on alignment tolerances for multimode fiber splices are also given in Section IV.

II. BRITTLE FRACTURE OF GLASS RODS AND FIBERS

It has been well documented that glass rods tend to break in such a way that the fracture face comprises three regions known as the mirror, the mist, and the hackle zones.[10,11] The mirror zone is an optically

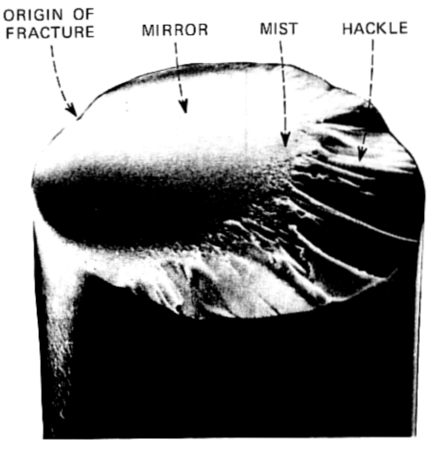

Fig. 1—A typical glass fiber fracture.

smooth surface adjacent to the fracture origin, the hackle zone corresponds to an area where the fracture has forked and the specimen is separated into three or more pieces, and the mist zone is a transition region between these two zones. Such behavior is also observed with glass fibers. Figure 1 shows the fractured end of a 125-μm glass fiber which clearly exhibits these three regions.

It has been experimentally demonstrated[11] that the distance from the origin of fracture to a point on the boundary between the mirror and mist zones, r, is given by

$$Z\sqrt{r} = K\,, \tag{1}$$

where Z is the local stress at the point in question and K is a constant for a given material.

A theoretical justification for eq. (1) can be given. Anderson[12] gives the energy balance equation for a crack of length $2c$ propagating in a brittle isotropic material subject to a plane stress, Z, as

$$\frac{d}{dc}\left(-\pi\frac{Z^2c^2}{E} + \frac{1}{2}k\rho\dot{c}^2\frac{c^2Z^2}{E^2} + 4\gamma c\right) = 0\,. \tag{2}$$

Here E is Young's modulus, ρ is the density, and γ is the surface tension of the material. The parameter k is a geometrical factor which depends on the shape of the crack. The three terms in eq. (2) represent, respectively, the released strain energy, the kinetic energy associated with the moving crack, and the surface energy of the newly created surfaces. As the crack propagates, more and more strain energy is converted into kinetic energy until the crack reaches a limiting velocity, $\dot{c} = v_f$, where v_f is roughly $\frac{1}{3}$ the longitudinal sound velocity for the material (see, for example, Reference 12). At this point the excess energy begins to be taken up by the creation of subsurface cracks (the mist zone). When the released strain energy is sufficient to create four new surfaces, a hackle zone is created. Thus, at the boundary of the mirror and mist zones,

$$\frac{d}{dc}\left(-\pi\frac{Z^2c^2}{E} + \frac{1}{2}k\rho v_f^2\frac{c^2Z^2}{E^2} + 4\gamma c\right) = 0\,. \tag{3}$$

By differentiating, we find

$$Z^2c = \frac{4\gamma E}{2\pi - k\rho v_f^2/E} = \text{a constant}\,, \tag{4}$$

which is of the same form as eq. (1). A similar derivation is given in Reference 11. The value of the constant K in eq. (1) is found experimentally to have the value 6.1 $kg/mm^{3/2}$ for soda-lime-silicate glass and 7.5 $kg/mm^{3/2}$ for fused silica, in reasonably good agreement with the value found[11] from the evaluation of the constant from eq. (4).

In order to break an optical fiber in such a way that the mirror zone extends across the entire fiber, it is necessary to have the stress at all points within the fiber low enough so that $Z\sqrt{r} < K$. The required value of Z at the origin of the fracture depends on the size of the crack or flaw from which the fracture originates.[12] The value of Z cannot be allowed to become zero or negative at any point across the fiber, or the crack will cease to propagate or propagate in a direction which is not perpendicular to the axis of the fiber. Under these conditions, a lip is formed on one fiber end. We see, then, that, to make a reliable clean mirror zone fracture, the stress distribution across the fiber must be suitably adjusted.

III. THE FIBER BREAKING MACHINE

In the preceding section, we have given the conditions necessary to create a mirror zone fracture across an entire fiber end. To determine experimentally the range of stress distributions over which clean mirror zone fractures can be obtained, an apparatus was constructed which could simultaneously bend the fiber and place it under tension. In this way, the stress distribution across the fiber can be varied, as shown in Fig. 2. For a given average tension (force per unit area), T, the stress distribution across the fiber depends on the radius, R, of the form over which the fiber is bent. (We assume no shear friction between the fiber and the form.) In fact, the stress across the fiber, $Z(x)$, is given by

$$Z(x) = T + \frac{E(a - x)}{R}, \tag{5}$$

where T is the average tension on the fiber, E is Young's modulus, and a is the radius of the fiber.

If $R = \infty$, the maximum diameter, d_M, of fiber that can be fractured with a mirror zone across the entire surface is given by

$$Z'\sqrt{d_M} = K, \tag{6}$$

where Z' is the stress necessary to initiate the break.

In the experiments to be described later using a diamond or carbide scorer to initiate the break, we find $Z' \approx 25$ kg/mm^2. Thus, for fused silica fibers we find $d_M \approx 100$ μm and for $R = \infty$, when fracturing fused silica fibers with diameters $\gtrsim 100$ μm, we expect hackle to appear.

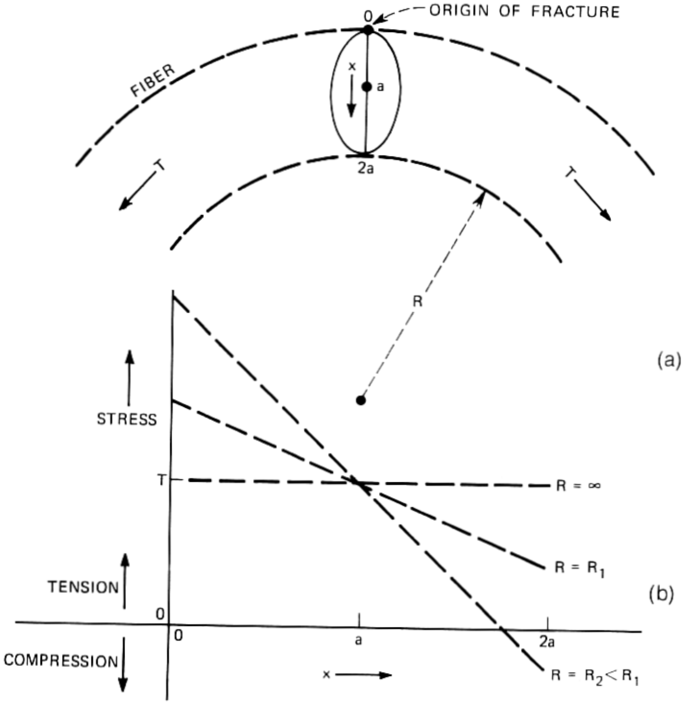

Fig. 2—(a) A glass fiber bent over a form of radius R and subjected to a tension T. (b) The stress as a function of position in the fiber for various bending radii R.

Our experiments showed this to be the case. If we compute the stress from eq. (5), assume T is adjusted so that the stress at $x = 0$ is Z', and select R $(=R_0)$ so that $Z = 0$ at $x = 2a$, we find that the maximum value of $Z\sqrt{r}$ occurs on the surface of the fiber at the position where $r = (\sqrt{4/5})a$, and if we require this product to be $<K$, we find $d_M(R = R_0) = 3.50\ d_M\ (R = \infty)$. Thus, using this technique, fused silica fibers of up to ~350 μm in diameter can be fractured with clean, mirror zone ends.

The fibers used for the experiments reported here were multimode silica glass fibers with an outer diameter of 125 μm and a core diameter of 80 μm. R_0 can be found from eq. (5), letting $Z = 0$ at $x = 125\ \mu$m, assuming the stress necessary to initiate the break, Z', to be equal to the experimentally determined value of 25 kg/mm², and using the values $E = 7.2 \times 10^3$ kg/mm²; $K = 7.5$ kg/mm$^{\frac{3}{2}}$ appropriate for silica glasses. We obtain $R_0 = 3.7$ cm.

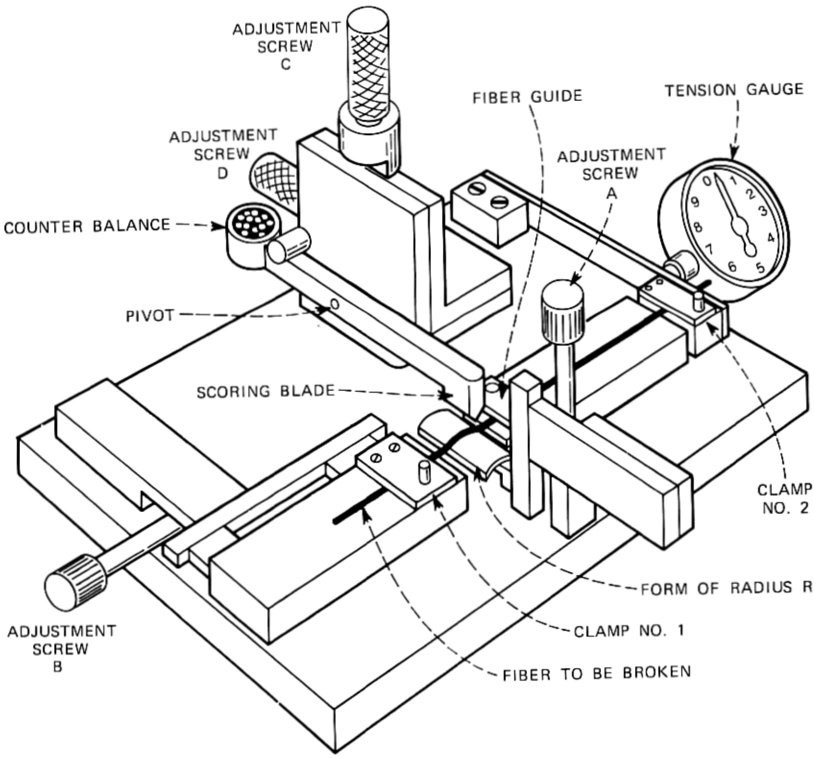

Fig. 3—A semi-schematic view of the fiber breaking machine.

Figure 3 shows a semi-schematic view of the device used to investigate the fracture properties of optical fibers. The fiber to be broken is clamped by clamps No. 1 and No. 2 and slides freely under the Teflon*-coated fiber guide. A Teflon-coated form of suitable radius R can be raised to cause the fiber to conform to the form by adjustment screw A. The tension on the fiber is measured by a tension gauge, which measures the mechanical displacement of a stiff steel bar on which clamp No. 2 is mounted. The tension can be adjusted with the adjustment screw B. A scoring blade can be lowered onto the fiber by adjustment screw C and pulled across the fiber by adjustment screw D. The pressure on the scorer blade can be adjusted by changing the weight in the counterbalance.

* Registered trademark of Dupont Co.

IV. EXPERIMENTAL RESULTS

Breaks were made on samples of a low-loss multimode silica glass fiber having a core diameter of 80 μm and a cladding thickness of 22 μm. A wide range of breaking tensions and fiber-bending radii was studied using the fiber-breaking machine described above. We used a variety of scoring techniques and attempted breaks in atmospheres of various relative humidities. The results can be summarized as follows: If the radius of curvature of the form was less than about 2 cm, a lip would be formed. When fractures were made without using a form, i.e., $R = \infty$ or negative, a hackle region was produced. "Good," clean fractures were obtained when a 5.7-cm radius of curvature form was used. These results are illustrated in Fig. 4.

Using the 5.7-cm radius of curvature form, clean fractures with no visible hackle or lip were always produced using breaking tensions in the range of 125 to 175 g and scorer pressures ranging from 1.5 to 7.5 g. The smallest scores were produced when a sharp diamond scorer* was lowered onto the fiber after the tension had been applied. We found no effect on the fracture characteristics when the relative humidity was varied from 7 to 100 percent, or even when water was applied to the point of fracture. In all, a total of 33 fractures were made within this range of conditions. *In no case was there any visible evidence of any hackle or lip.* In the worst case the disturbed region associated with the score extended over a distance of $\sim$22 μm. As the cladding thickness on this optical fiber was 20 μm, this means that in all cases a perfect mirror zone fracture occurred over essentially the entire core region of the fiber.

To establish the minimum splice loss in joining such fiber ends, we used the setup shown in Fig. 5. The joints were made from ends obtained from the same fracture, but rotated with respect to the original fracture position. In this way, the time between fracture and joining was kept at a minimum in order to avoid contamination of the ends. Moreover, utmost accuracy was achieved by comparing the losses immediately before fracture and immediately after joining. This time was typically 10 minutes, while instabilities in the setup caused a power drift at the detector of not more than $\frac{1}{4}$ percent in 30 minutes. Joining adjacent ends, of course, eliminated the possibility of diameter discrepancies which would be encountered in practical splices.

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* The diamond scorer was supplied by Victory Diamond Tool Co. of East Hanover, N. J.

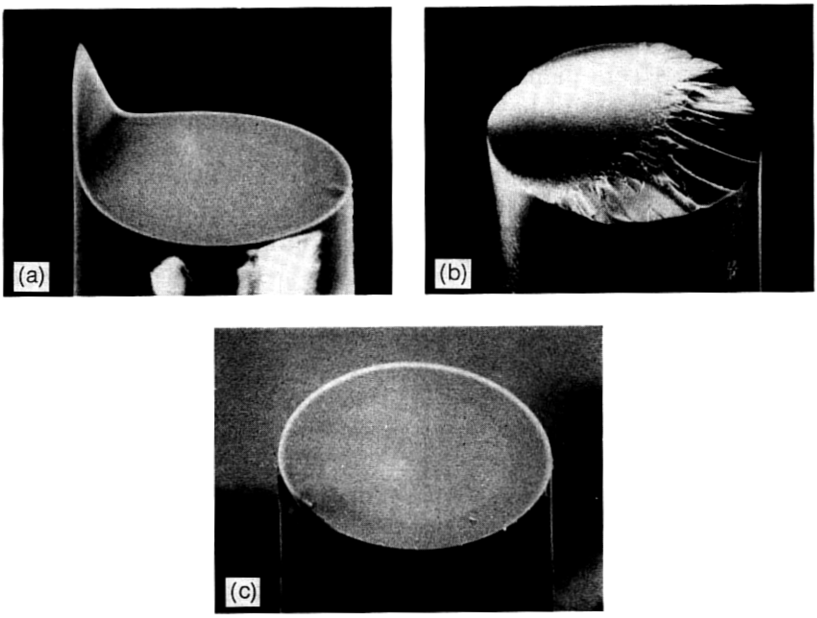

Fig. 4—Electron microscope photographs of 125-μm diameter silicate glass fibers broken using various form radii (R): (a) $R = 0.75$ cm; (b) $R = \infty$ or negative; (c) $R = 5.7$ cm.

Fibers of the type that were used for the splice loss measurements reach a steady-state power distribution after a certain distance independent of the injection conditions. This distribution was measured for the fiber in question at the end of a 1.2-km length. The power distribution in the splice should preferably be the steady-state distribution. Since a sufficient fiber length to achieve such conditions was not available for our measurements, we approximated as well as

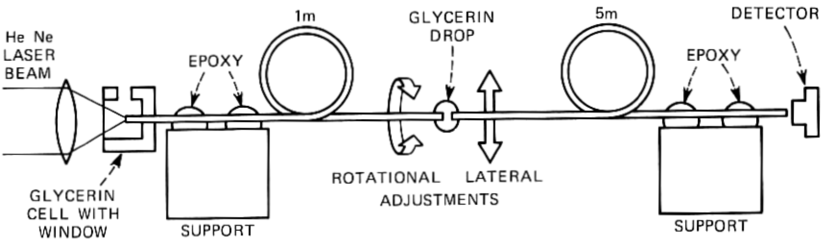

Fig. 5—Schematic of apparatus used to measure laboratory splice loss.

possible the steady-state distribution at the input by properly focusing the input beam onto the fiber front face. Specifically, we made the $1/e^2$ width of the Gaussian field distribution in the input cone equal to the $1/e^2$ width of the steady-state far-field distribution measured at the end of the long sample (0.14 rad half-width). The distance between input and splice was 1 m.

If the splice disturbs the power distribution substantially, a sufficient fiber length must be provided after the splice to allow the distribution to settle, a process which generally is associated with some excess loss. To study the magnitude of this effect, we measured several joints with fiber lengths from 1 to 5 m after the joint. We did not find a consistent increase in loss as the length was increased, although 5 m is admittedly not a sufficient length to reach the steady state. Further study is necessary to estimate the error involved.

To make a good joint, the ends were aligned using a microscope to within a fraction of a degree in angle and within 1 μm laterally, but kept apart by at least 10 μm to avoid damage of the ends by mutual abrasion. A drop of glycerin was then added, which was held between the ends by surface tension. The refractive index of glycerin is 1.473 and almost coincides with that of silica glass (n = 1.458). This procedure invariably produced a splice with a loss of less than 1 percent (typically, 0.5 percent). This result was unaffected by rotating one end with respect to the other. Note that no information on the transmitted optical signal was required to achieve this optimal alignment.

To establish the order of magnitude of alignment tolerances permissible in practical splices, we measured the increase in loss as a result of longitudinal or lateral misalignments. The fiber ends could be parted axially by 100 μm (one core diameter) before the losses increased by 1 percent. Lateral displacements were more critical. The loss increased by 1 percent for a 5-μm displacement and by 4 percent for a 10-μm displacement (10 percent of the core diameter).

V. SUMMARY AND CONCLUSIONS

We have presented a theory of glass fiber fracture which allows us to design a machine for reliably producing clean breaks which leave the fiber ends in a suitable condition for splicing. We have built such a machine and demonstrated that, with 125-μm silica glass multimode optical fibers, such breaks are consistently obtained. Laboratory splicing experiments using fibers broken with this machine always produced splices with losses of less than 1 percent (0.04 dB).

VI. ACKNOWLEDGMENTS

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