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Designation: ~~C1557 – 14~~ C1557 – 20

Standard Test Method for Tensile Strength and Young's Modulus of Fibers[1]

This standard is issued under the fixed designation C1557; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the preparation, mounting, and testing of single fibers (obtained either from a fiber bundle or a spool) for the determination of tensile strength and Young's modulus at ambient temperature. Advanced ceramic, glass, carbon, and other fibers are covered by this test standard.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard ~~may involve hazardous materials, operations, and equipment. This standard~~ does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
C1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics
D3878 Terminology for Composite Materials
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E1382 Test Methods for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis

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3. Terminology

3.1 *Definitions:*

3.1.1 *bundle*—a collection of parallel fibers. Synonym, *tow*.

3.1.2 *mounting tab*—a thin paper, cardboard, compliant metal, or plastic strip with a center hole or longitudinal slot of fixed gage length. The mounting tab should be appropriately designed to be self-aligning if possible, and as thin as practicable to minimize fiber misalignment.

3.1.3 *system compliance*—the contribution by the load train system and specimen-gripping system to the indicated cross-head displacement, by unit of force exerted in the load train.

3.1.4 *tensile strength [F/L^{-2}], n*—the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross-sectional area of the specimen.

3.2 For definitions of other terms used in this test method, refer to Terminologies D3878 and E6.

4. Summary of Test Method

4.1 A fiber is extracted randomly from a bundle or from a spool.

4.2 The fiber is mounted in the testing machine, and then stressed to failure at a constant cross-head displacement rate.

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[1] This test method is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.07 on Ceramic Matrix Composites.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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4.3 A valid test result is considered to be one in which fiber failure doesn't occur in the gripping region.

4.4 Tensile strength is calculated from the ratio of the peak force and the cross-sectional area of a plane perpendicular to the fiber axis, at the fracture location or in the vicinity of the fracture location, while Young's modulus is determined from the linear region of the tensile stress versus tensile strain curve.

5. Significance and Use

5.1 Properties determined by this test method are useful in the evaluation of new fibers at the research and development levels. Fibers with diameters up to 250 × 10^{-6} m are covered by this test method. Very short fibers (including whiskers) call for specialized test techniques (**1**)[3] and are not covered by this test method. This test method may also be useful in the initial screening of candidate fibers for applications in polymer, metal, or ceramic matrix composites, and for quality control purposes. Because of their nature, ceramic fibers do not have a unique tensile strength, but ~~rather,~~rather a distribution of tensile strengths. In most cases when the tensile strength of the fibers is controlled by one population of flaws, the distribution of fiber tensile strengths can be described using a two-parameter Weibull distribution, although other distributions have also been suggested (**2**, **3**). This test method constitutes a methodology to obtain the tensile strength of a single fiber. For the purpose of determining the parameters of the distribution of fiber ~~strengths~~ tensile strengths, it is recommended to follow this test method in conjunction with Practice C1239.

6. Interferences

6.1 The test environment may have an influence on the measured tensile strength of fibers. In particular, the behavior of fibers susceptible to slow crack growth fracture will be strongly influenced by test environment and testing rate (**4**). Testing to evaluate the maximum tensile strength potential of a fiber should be conducted in inert environments or at sufficiently rapid testing rates, or both, so as to minimize slow crack growth effects. Conversely, testing can be conducted in environments and testing modes and rates representative of service conditions to evaluate the tensile strength of fibers under those conditions.

6.2 Fractures that initiate outside the gage section of a fiber may be due to factors such as stress concentrations, extraneous stresses introduced by gripping, or ~~strength-limiting~~tensile-strength-limiting features in the microstructure of the specimen. Such non-gage section fractures constitute invalid tests. When using active gripping systems, insufficient pressure can lead to slippage, while too much pressure can cause local fracture in the gripping area.

6.3 Torsional strains may reduce the magnitude of the tensile strength (**5**). Caution must be exercised when mounting the fibers to avoid twisting the fibers.

6.4 Many fibers are very sensitive to surface damage. Therefore, any contact with the fiber in the gage length should be avoided (**4**, **6**).

6.5 Fiber diameter does, or can, vary along the length of the gage section. Therefore, the user's ability to accurately calculate and interpret tensile strength and elastic modulus is based on the use and choice of the appropriate fiber diameter through valid fractography.

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7. Apparatus

7.1 The apparatus described herein consists of a tensile testing machine with one actuator (cross-head) that operates in a controllable manner, a gripping system, and a load cell. ~~Fig. 1~~Figs. 1 and 2 ~~and Fig. 2~~show a picture and schematic of such a system.

7.1.1 *Testing Machine*—The testing machine shall be in conformance with ~~Practice~~Practices E4. The failure forces shall be accurate within ±1 % at any force within the selected force range of the testing machine as defined in ~~Practice~~Practices E4. To determine the appropriate capacity of the load cell, ~~the~~Table 1 ~~following table~~ lists the range of tensile strength and diameter values of representative glass, graphite, organic, and ceramic fibers.

7.1.2 *Grips*—The gripping system shall be of such design that axial alignment of the fiber along the line of action of the machine shall be easily accomplished without damaging the test specimen. Although studies of the effect of fiber misalignment on the tensile strength of fibers have not been reported, the axis of the fiber shall be coaxial with the line of action of the testing machine within δ, to prevent spurious bending strains ~~and/or stress concentrations:~~or stress concentrations, or both:

$$\delta \leq \frac{l_o}{50} \tag{1}$$

where:

δ = the tolerance, m, and
l_o = the fiber gage length, m.

7.2 *Mounting Tabs*—Typical mounting tabs for test specimens are shown in Fig. 3. Alternative methods of specimen mounting may be used, or none at all (that is, the fiber may be directly mounted into the grips). A simple but effective approach for making

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

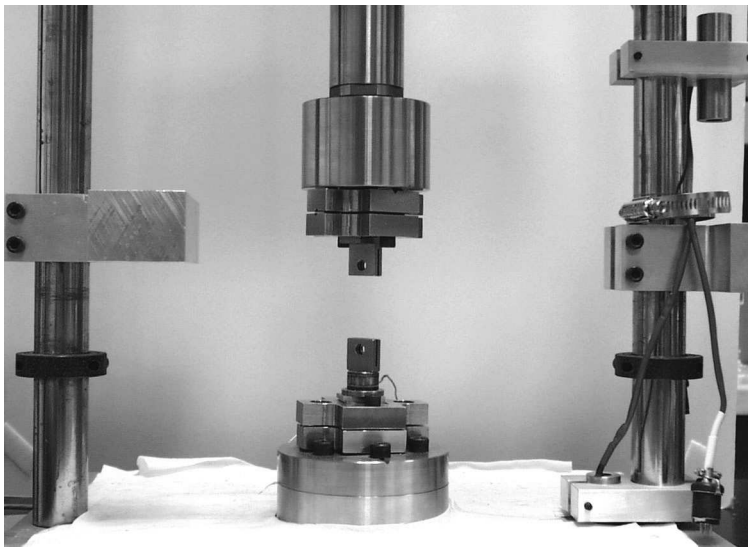

FIG. 1 ~~Typical~~ Example of Fiber Tensile Tester

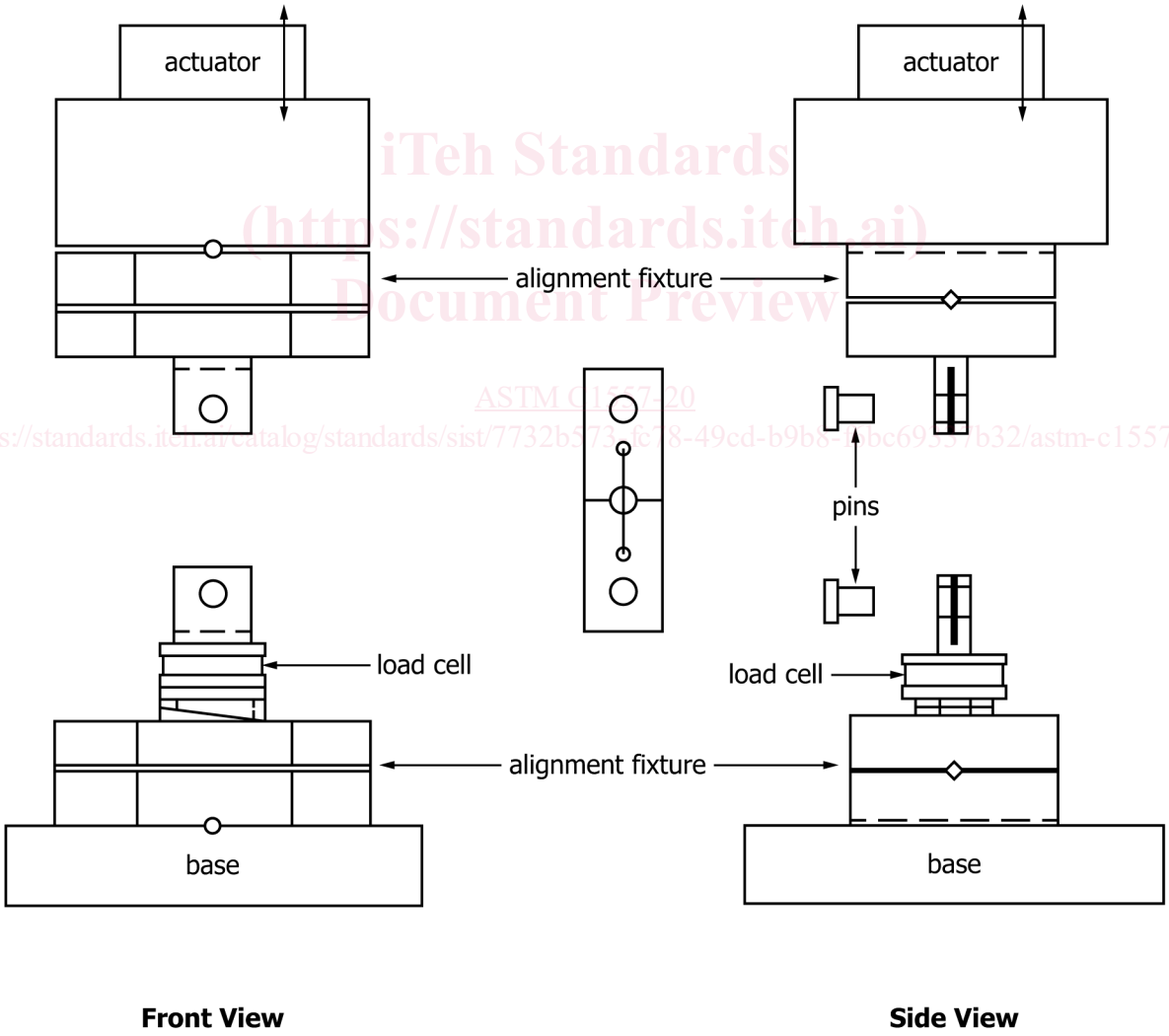

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FIG. 2 Schematic of Fiber Tensile Testing Machine

mounting tabs with repeatable dimensions consists in printing the mounting tab pattern onto cardboard file folders using, for example, a laser printer. As illustrated in Fig. 3, holes can be obtained using a three-hole punch. Fig. 3 shows a typical specimen

TABLE 1 Room Temperature Tensile Strength of Fibers (25 × 10^{-3} m Gage Length)

Fiber	Diameter, m	Strength, Pa
~~CVD-SiC~~	~~50-150 × 10^{-6}~~	~~2-3.5 × 10^{9}~~
~~polymer-derived SiC~~	~~10-18 × 10^{-6}~~	~~2-3.5 × 10^{9}~~
~~sol-gel derived oxide~~	~~1-20 × 10^{-6}~~	~~1-3 × 10^{9}~~
~~single-crystal oxide~~	~~70-250 × 10^{-6}~~	~~1.5-3.5 × 10^{9}~~
~~graphite~~	~~1-15 × 10^{-6}~~	~~1-6 × 10^{9}~~
~~glass~~	~~1-250 xx 10^{-6}~~	~~1-4 × 10^{9}~~
~~aramid~~	~~12-20 × 10^{-6}~~	~~2-4 × 10^{9}~~

TABLE 1 Room Temperature Tensile Strength of Fibers (25 × 10^{-3} m Gage Length)

Fiber	Diameter, m	Strength, Pa
CVD-SiC	50–150 × 10^{-6}	2–3.5 × 10^{9}
polymer-derived SiC	10–18 × 10^{-6}	2–3.5 × 10^{9}
sol-gel derived oxide	1–20 × 10^{-6}	1–3 × 10^{9}
single-crystal oxide	70–250 × 10^{-6}	1.5–3.5 × 10^{9}
graphite	1–15 × 10^{-6}	1–6 × 10^{9}
glass	1–250 × 10^{-6}	1–4 × 10^{9}
aramid	12–20 × 10^{-6}	2–4 × 10^{9}

mounting method. The mounting tabs are gripped or connected to the load train (for example, by pin and clevis) so that the test specimen is aligned axially along the line of action of the test machine.

7.2.1 When gripping ~~large diameter~~ large-diameter fibers using an active set of grips without tabs, the ~~grip facing~~ grip-facing material in contact with the test specimen must be of appropriate compliance to allow for a firm, non-slipping grip on the fiber. At the same time, the ~~grip facing~~ grip-facing material must prevent crushing, scoring, or other damage to the test specimen that would lead to inaccurate results. ~~Large diameter~~ Large-diameter fibers (diameter > 50 × 10^{-6} ~~m)~~ m) can also be mounted inside hypodermic needles filled with an adhesive (**7**). This is a good alternative to avoid crushing the fiber if pneumatic/hydraulic/mechanical grips were to be used. The adhesive must be sufficiently strong to withstand the gripping process, and prevent fiber "pull-out" during testing.

7.2.2 Consistent end-tabbing, specifically in the case of Young's modulus estimation, is important because system compliance is used in that calculation. Variation in end-tabbing quality and compliance could manifest itself in inaccurate system compliance estimation and consequential inaccurate Young's modulus estimation.

7.3 *Data Acquisition*—~~At a minimum, autographic records of applied force and cross-head displacement versus time shall be obtained. Either analog chart recorders or~~ Either digital data acquisition systems or analog chart recorders may be used for this purpose, although a digital record is recommended for ease of later data analysis. ~~Ideally, an analog chart recorder or plotter shall be used in conjunction with the digital data acquisition system to provide an immediate record of the test as a supplement to the digital record.~~ Recording devices must be accurate to ~~± 1 %~~ ±1 % of full scale and shall have a minimum data acquisition rate of 10 Hz, with a response of 50 Hz deemed more than sufficient.

8. Precautionary Statement

8.1 During the conduct of this test method, the possibility of flying fragments of broken fibers may be high. Means for containing these fragments for later fractographic reconstruction and analysis is highly recommended. For example, vacuum grease has been used successfully to dampen the fiber during failure and capture the fragments. In this case, vacuum grease is applied in the gage section of the fiber so that the former does not bear any force. An appropriate solvent can be used afterwards to remove the vacuum grease.

9. Procedure

9.1 *Test Specimen Mounting:*

9.1.1 Randomly choose, and carefully separate, a suitable single-fiber specimen from the bundle or fiber spool. The total length of the specimen should be sufficiently long (at least 1.5 times longer than the gage length) to allow for convenient handling and gripping. Handle the test specimen at its ends and avoid touching it in the test gage length.

NOTE 1—Because the tensile strength of fibers is statistical in nature, the magnitude of the tensile strength will depend on the dimensions of the fiber being evaluated. In composite material applications, the gage length of the fiber is usually of the order of several fiber diameters, but it has been customary to test fibers with a gage length of 25.4 × 10^{-3} m. However, other gage lengths can be used as long as they are practical, and in either case, the value of the gage length must be reported.

9.1.2 *When Using Tabs:*

9.1.2.1 A mounting tab (Fig. 3) may be used for specimen mounting. Center the test specimen over the tab using the printed pattern with one end taped to the tab.

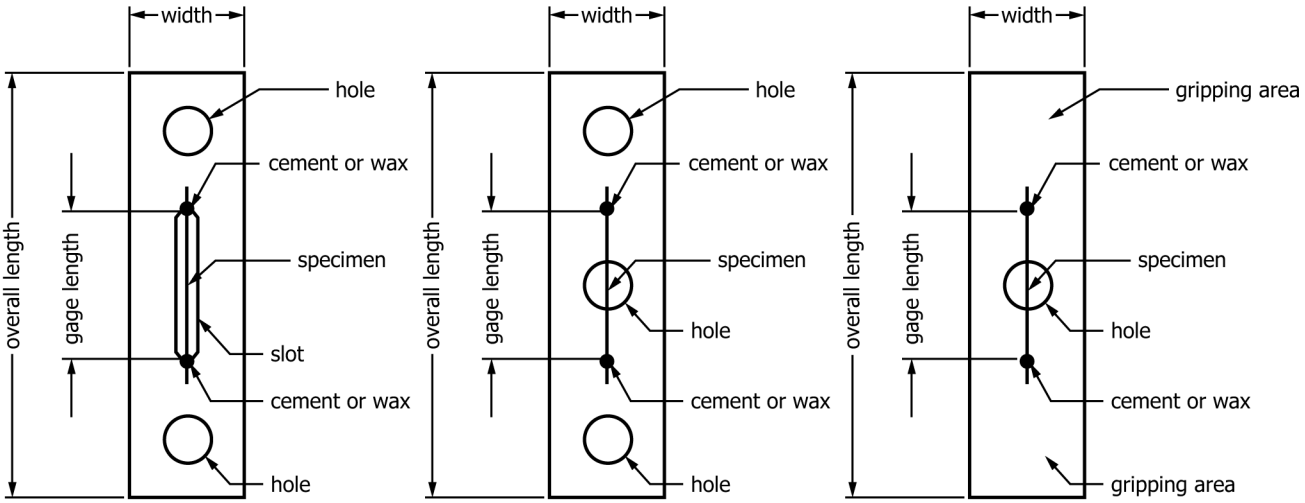

FIG. 3 Examples of Mounting ~~Tab~~Tabs

9.1.2.2 Tape the opposite end of the test specimen to the tab, exercising care to prevent fiber twisting. It has been found that the tensile strength of fibers decreases significantly with increasing torsional strain (**5**).

9.1.2.3 Carefully place a small amount of suitable adhesive (for example, epoxy, red sealing wax) at the marks on the mounting tab that define the gage length, and bond the fiber to the mounting tab.

9.1.2.4 Determine the gage length to the nearest ~~± 5~~ ±5 × 10^{-4} ~~m~~ m or ±1 % of the gage length, whichever is smaller.

9.2 *Optical Strain Flags*—If optical flags are to be used for strain measurement, they may be attached directly to the fibers at this time, using a suitable adhesive or other attachment method. Note that this may not be possible with small-diameter fibers ($d < 5 \times 10^{-6}$ m).

9.3 *Test Modes and Rates*—The test shall be conducted under a constant cross-head displacement rate. Rates of testing must be sufficiently rapid to obtain the maximum possible tensile strength at fracture within 30 s. The user may try as an initial value a test rate of 8×10^{-6} m/s. However, rates other than those recommended here may be used to evaluate rate effects. In all cases, the test mode and rate must be reported.

9.4 Ensure that the machine is calibrated and in equilibrium (no drift).

9.5 Set the cross-head and data recorder speeds to provide a test time to specimen fracture within 30 s.

9.6 Grasp a mounted test specimen in one of the two tab grip areas (or pin load one end of the mounting tab). Zero the load cell.

9.7 Position the cross-head so that the other tab grip area may be grasped as in 9.6. Check the axial specimen alignment using whatever methods have been established, as described in 7.1.2.

9.8 If using tabs, with the mounting tab ~~un-strained,~~unstrained, cut both sides of the tab very carefully at mid-gage as shown in Fig. 4. Alternatively, the sides of the tab can be burned using a soldering iron, for example. If the fiber is damaged, then it must be discarded.

9.9 Initiate the data recording followed by the operation of the test machine until fiber failure. Record both the cross-head displacement and force, and strain if applicable.

9.10 Recover the fracture surfaces and measure the cross-sectional area of a plane normal to the axis of the fiber at the fracture location or in the vicinity of the fracture location. Determine the fiber cross-sectional area with a linear spatial resolution of 1.0 % of the fiber diameter or better, using laser diffraction techniques (**8-11**), or an image analysis system in combination with a reflected light microscope or a scanning electron microscope (**12**) (see Test Methods E1382). Note that in practice, a reflected white light microscope can provide a maximum resolution of 0.5 × 10^{-6} m ~~and therefore~~and, therefore, its use may be impractical when measuring the cross-sectional area of ~~small-diameter~~ small-diameter fibers. Because stiff fibers tend to shatter upon failure, it is recommended to capture the fiber fragments using vacuum grease, because vacuum grease is an effective medium to dampen the energy released by the fiber upon fracture. The user of this standard should be aware that the need to recover the fracture surfaces of the fiber to determine the fiber cross-sectional area is consistent with the need to do fractography to identify the ~~strength-limiting~~tensile-strength-limiting flaws for the proper estimation of the parameters of the distribution of fiber ~~strength-s.~~tensile strengths (see Practice C1322).

NOTE 2—The user of this standard test method must be aware that the diameter of many ceramic fibers varies not only among fibers in a bundle, but also along the length of each fiber (**13-16**). It has been customary to determine individual fiber tensile strength values using the average cross-sectional area of a group of fibers. However, it has been demonstrated that this procedure leads to significant errors both in the determination of the actual fiber

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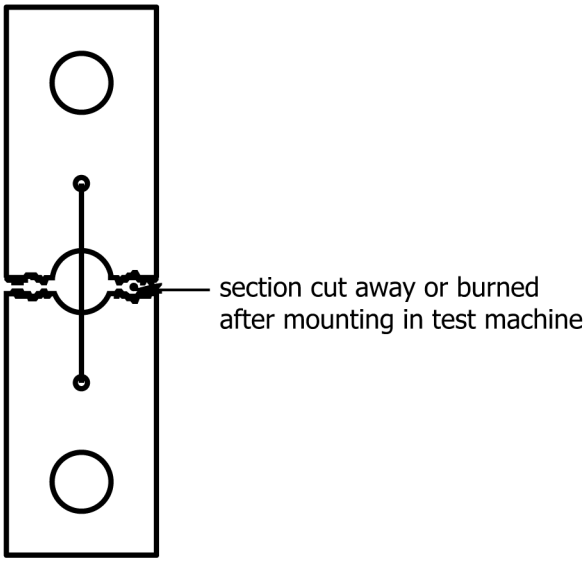

FIG. 4 Cutting Sides of Tab

tensile strength and in the estimates of the parameters of the distribution of fiber tensile strengths (**17-19**).

NOTE 3—When the fiber diameter varies along its length and the diameter of a fiber is measured before the fiber is tested, there is a risk that the measurement will be obtained at a location of the fiber that doesn't coincide with the failure location. Monte Carlo simulations have been carried out to estimate the magnitude of the error in the determination of the tensile strength of a fiber when the value of the cross-sectional area used for the calculation of tensile strength doesn't correspond to that of the fracture plane. The results of these simulations have shown that the magnitude of the error increases with the degree of variability of the fiber diameter along its length (**20**) (see Appendix X1). Therefore, it is necessary to determine the cross-sectional area of the fiber on a plane perpendicular to the axis of the fiber at the location of failure, or in the vicinity of the failure location, after performing the mechanical test, and use that value of the cross-sectional area for the determination of the fiber tensile strength.

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10. Calculations

10.1 *Tensile Strength*—Calculate the tensile strength of the fiber as follows:

$$\sigma_t = \frac{F_f}{A} \tag{2}$$

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where:

σ_t = tensile strength, Pa,
F_f = force to failure, N, and
A = fiber cross-sectional area at fracture plane (normal to fiber axis), m^2.

10.2 *Strain*—Calculate the tensile strain of the fiber as follows:

$$\varepsilon = \frac{\Delta l}{l_o} \tag{3}$$

where:

Δl = the elongation of the gage length, m.

10.2.1 *Direct Measurement of Elongation*—Direct measurement of the specimen elongation (in the gage section) is achieved by monitoring the displacement of the flags attached to the fiber.

10.2.2 *Indirect Measurement of Elongation*—In the absence of a direct measurement of specimen elongation, the actual specimen elongation in the gage length can be determined by subtracting the displacement associated with the system compliance from the total cross-head displacement (**21**).

10.2.2.1 *System Compliance*—The system compliance must be determined experimentally for a given test machine, gripping system, and fiber type. The system compliance is determined as follows:

10.2.2.2 Perform tensile tests according to the procedures given in 9.1 – 9.10 on ~~single fiber~~ single-fiber specimens with various different gage lengths. Test specimens with at least three different gage lengths, and perform at ~~least,~~least three tests for each value of the gage length.

10.2.2.3 For each test, obtain the force versus cross-head displacement curve, and determine the inverse of the slope of the initial linear region of the force versus cross-head displacement curve in m/N. (See Fig. 5.)

(1) Note that the recorded cross-head displacement is:

$$\Delta L = \Delta l + C_S F \tag{4}$$