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Standard Practice for Constant-Amplitude, Axial, Tension-Tension Cyclic Fatigue of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures¹

This standard is issued under the fixed designation C1360; 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 practice covers the determination of constant-amplitude, axial tension-tension cyclic fatigue behavior and performance of continuous fiber-reinforced advanced ceramic composites (CFCCs) at ambient temperatures. This practice builds on experience and existing standards in tensile testing CFCCs at ambient temperatures and addresses various suggested test specimen geometries, specimen fabrication methods, testing modes (force, displacement, or strain control), testing rates and frequencies, allowable bending, and procedures for data collection and reporting. This practice does not apply to axial cyclic fatigue tests of components or parts (that is, machine elements with nonuniform or multiaxial stress states).

1.2 This practice applies primarily to advanced ceramic matrix composites with continuous fiber reinforcement: uni-directional (1-D), bi-directional (2-D), and tri-directional (3-D) or other multi-directional reinforcements. In addition, this practice may also be used with glass (amorphous) matrix composites with 1-D, 2-D, 3-D, and other multi-directional continuous fiber reinforcements. This practice does not directly address discontinuous fiber-reinforced, whisker-reinforced or particulate-reinforced ceramics, although the methods detailed here may be equally applicable to these composites.

1.3 The values stated in SI units are to be regarded as the standard and are in accordance with ~~IEEE/ASTM SI 10~~ Standard: IEEE/ASTM SI 10.

1.4 *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 and health practices and determine the applicability of regulatory limitations prior to use. Refer to Section 7 for specific precautions.*

2. Referenced Documents

2.1 ASTM Standards:²

C1145 Terminology of Advanced Ceramics

C1275 Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperature

D3479/D3479M Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials

D3878 Terminology for Composite Materials

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

E83 Practice for Verification and Classification of Extensometer Systems

E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)

E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System

E468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials

E739 Practice for Statistical Analysis of Linear or Linearized Stress-Life ($S-N$) and Strain-Life ($-N$) Fatigue Data

E1012 Practice for Verification of Test Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application

E1150 Definitions of Terms Relating to Fatigue

E1823 Terminology Relating to Fatigue and Fracture Testing

¹ This practice 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.

*A Summary of Changes section appears at the end of this standard.

3. Terminology Definitions

3.1 Definitions:

3.1.1 Definitions of terms relating to advanced ceramics, fiber-reinforced composites, tensile testing, and cyclic fatigue as they appear in Terminology C1145, Terminology D3878, Terminology E6, and Terminology E1823, respectively, apply to the terms used in this practice. Selected terms with definitions non specific to this practice follow in 3.2 with the appropriate source given in parenthesis. Terms specific to this practice are defined in 3.3.

3.2 Definitions of Terms Non-Specific to This Standard:

3.2.1 *advanced ceramic*, n —A highly engineered, high performance predominately non-metallic, inorganic, ceramic material having specific functional attributes. (See Terminology C1145.)

3.2.2 *axial strain* [LL^{-1}], n —the average longitudinal strains measured at the surface on opposite sides of the longitudinal axis of symmetry of the test specimen by two strain-sensing devices located at the mid length of the reduced section. (See Practice E1012.)

3.2.3 *bending strain* [LL^{-1}], n —the difference between the strain at the surface and the axial strain. In general, the bending strain varies from point to point around and along the reduced section of the test specimen. (See Practice E1012.)

3.2.4 *ceramic matrix composite*, n —a material consisting of two or more materials (insoluble in one another), in which the major, continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, glass, metal or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents. (See Test Method C1275.)

3.2.5 *continuous fiber-reinforced ceramic matrix composite (CFCC)*, n —a ceramic matrix composite in which the reinforcing phase consists of a continuous fiber, continuous yarn, or a woven fabric. (See Terminology C1145.)

3.2.6 *constant amplitude loading*, n —in cyclic fatigue loading, a loading in which all peak loads are equal and all of the valley loads are equal. (See Terminology E1823.)

3.2.7 *cyclic fatigue*, n —the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. (See Terminology E1823.) See Fig. 1 for nomenclature relevant to cyclic fatigue testing.

3.2.7.1 *Discussion*—In glass technology static tests of considerable duration are called “static fatigue” tests, a type of test generally designated as stress-rupture.

3.2.7.2 *Discussion*—Fluctuations may occur both in force and with time (frequency) as in the case of “random vibration.”

3.2.8 *cyclic fatigue life*, N_f —the number of loading cycles of a specified character that a given test specimen sustains before failure of a specified nature occurs. (See Terminology E1823.)

3.2.9 *cyclic fatigue limit*, S_f [FL^{-2}], n —the limiting value of the median cyclic fatigue strength as the cyclic fatigue life, N_f , becomes very large, (for example, $N_f 10^6 - 10^7$). (See Terminology E1823.)

3.2.9.1 *Discussion*—Certain materials and environments preclude the attainment of a cyclic fatigue limit. Values tabulated as “fatigue limits” in the literature are frequently (but not always) values of S_f at 50 % survival at N_f cycles of stress in which the mean stress, S_m , equals zero.

3.2.10 *cyclic fatigue strength* S_N , [FL^2], n —the limiting value of the median cyclic fatigue strength at a particular cyclic fatigue life, N_f (See Terminology E1823.)

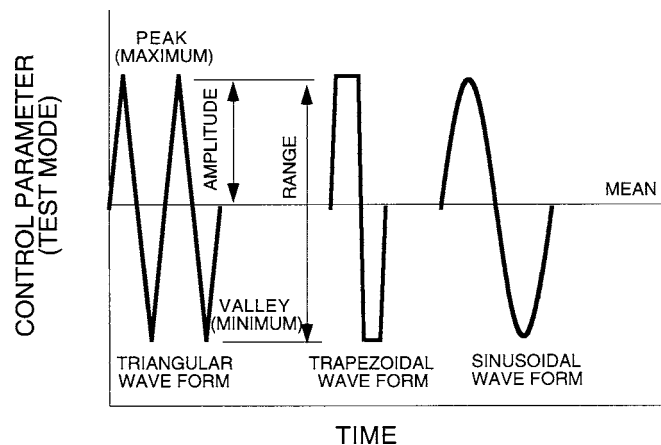


FIG. 1 Cyclic Fatigue Nomenclature and Wave Forms.

3.2.11 *gage length, [L], n*—the original length of that portion of the test specimen over which strain or change of length is determined. (See Terminology E6.)

3.2.12 *force ratio, n*—in cyclic fatigue loading, the algebraic ratio of the two loading parameters of a cycle; the most widely used ratios (See Terminology E1150, E1823):

$$R = \frac{\text{minimum force}}{\text{maximum force}} \text{ or } R = \frac{\text{valley force}}{\text{peak force}}$$

and

$$A = \frac{\text{force amplitude}}{\text{mean force}} \text{ or } A = \frac{(\text{maximum force} - \text{minimum force})}{(\text{maximum force} + \text{minimum force})}$$

3.2.13 *matrix-cracking stress [FL⁻²], n*—The applied tensile stress at which the matrix cracks into a series of roughly parallel blocks normal to the tensile stress. (See Test Method C1275.)

3.2.13.1 *Discussion*—In some cases, the matrix-cracking stress may be indicated on the stress-strain curve by deviation from linearity (proportional limit) or incremental drops in the stress with increasing strain. In other cases, especially with materials that do not possess a linear portion of the stress-strain curve, the matrix cracking stress may be indicated as the first stress at which a permanent offset strain is detected in the unloading stress-strain curve (elastic limit).

3.2.14 *modulus of elasticity [FL⁻²], n*—The ratio of stress to corresponding strain below the proportional limit. (See Terminology E6.)

3.2.15 *proportional limit stress [FL⁻²], n*—the greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law). (See Terminology E6.)

3.2.15.1 *Discussion*—Many experiments have shown that values observed for the proportional limit vary greatly with the sensitivity and accuracy of the testing equipment, eccentricity of loading, the scale to which the stress-strain diagram is plotted, and other factors. When determination of proportional limit is required, specify the procedure and sensitivity of the test equipment.

3.2.16 *percent bending, n*—the bending strain times 100 divided by the axial strain. (See Practice E1012.)

3.2.17 *S-N diagram, n*—a plot of stress versus the number of cycles to failure. The stress can be maximum stress, S_{\max} , minimum stress, S_{\min} , stress range, ΔS or S_r , or stress amplitude, S_a . The diagram indicates the S-N relationship for a specified value of S_m , A , R and a specified probability of survival. For N , a log scale is almost always used, although a linear scale may also be used. For S , a linear scale is usually used, although a log scale may also be used. (See Terminology E1150 and Practice E468.)

3.2.18 *slow crack growth, n*—sub-critical crack growth (extension) that may result from, but is not restricted to, such mechanisms as environmentally-assisted stress corrosion or diffusive crack growth (See Test Method C1275).

3.2.19 *tensile strength [FL⁻²], n*—the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum force during a tension test carried to rupture and the original cross-sectional area of the test specimen. (See Terminology E6.)

3.3 Definitions of Terms Specific to This Standard:

3.3.1 *fracture strength [FL⁻²], n*—the tensile stress that the material sustains at the instant of fracture. Fracture strength is calculated from the force at fracture during a tension test carried to rupture and the original cross-sectional area of the test specimen.

3.3.1.1 *Discussion*—In some cases, the fracture strength may be identical to the tensile strength if the force at fracture is the maximum for the test.

3.3.2 *maximum stress, S_{\max} [FL⁻²], n*—the maximum applied stress during cyclic fatigue.

3.3.3 *mean stress, S_m [FL⁻²], n*—the difference between the mean stress and the maximum or minimum stress such that

$$S_m = \frac{S_{\max} + S_{\min}}{2} \quad (1)$$

3.3.4 *minimum stress, S_{\min} [FL⁻²], n*—the minimum applied stress during cyclic fatigue.

3.3.5 *stress amplitude, S_a [FL⁻²], n*—the difference between the mean stress and the maximum stress such that

$$S_a = \frac{S_{\max} - S_{\min}}{2} = S_{\max} - S_m = S_m - S_{\min} \quad (2)$$

3.3.6 *stress range, ΔS or S_r [FL⁻²], n*—the difference between the maximum stress and the minimum stress such that

$$\Delta S = S_r = S_{\max} - S_{\min} \quad (3)$$

3.3.7 *time to cyclic fatigue failure, t_f [t], n*—total elapsed time from test initiation to test termination required to reach the number of cycles to failure.

4. Significance and Use

4.1 This practice may be used for material development, material comparison, quality assurance, characterization, reliability assessment, and design data generation.

4.2 Continuous fiber-reinforced ceramic matrix composites are generally characterized by crystalline matrices and ceramic fiber

reinforcements. These materials are candidate materials for structural applications requiring high degrees of wear and corrosion resistance, and high-temperature inherent damage tolerance (that is, toughness). In addition, continuous fiber-reinforced glass matrix composites are candidate materials for similar but possibly less-demanding applications. Although flexural test methods are commonly used to evaluate the mechanical behavior of monolithic advanced ceramics, the non-uniform stress distribution in a flexural test specimen in addition to dissimilar mechanical behavior in tension and compression for CFCCs leads to ambiguity of interpretation of test results obtained in flexure for CFCCs. Uniaxially-loaded tensile tests provide information on mechanical behavior for a uniformly stressed material.

4.3 The cyclic fatigue behavior of CFCCs can have appreciable non-linear effects (for example, sliding of fibers within the matrix) which may be related to the heat transfer of the specimen to the surroundings. Changes in test temperature, frequency, and heat removal can affect test results. It may be desirable to measure the effects of these variables to more closely simulate end-use conditions for some specific application.

~~4.4 Cyclic fatigue by its nature is a probabilistic phenomenon as discussed in STP 91A~~

4.4 Cyclic fatigue by its nature is a probabilistic phenomenon as discussed in STP 91A (Ref (1)) and STP 588 (Ref (2)).³ and STP-588. In addition, the strengths of the brittle matrices and fibers of CFCCs are probabilistic in nature. Therefore, a sufficient number of test specimens at each testing condition is required for statistical analysis and design, with guidelines for sufficient numbers provided in STP 91A, (Ref (1)), STP 588, (Ref (2)), and Practice E739. Studies to determine the influence of test specimen volume or surface area on cyclic fatigue strength distributions for CFCCs have not been completed. The many different tensile test specimen geometries available for cyclic fatigue testing may result in variations in the measured cyclic fatigue behavior of a particular material due to differences in the volume of material in the gage section of the test specimens.

4.5 Tensile cyclic fatigue tests provide information on the material response under fluctuating uniaxial tensile stresses. Uniform stress states are required to effectively evaluate any nonlinear stress-strain behavior which may develop as the result of cumulative damage processes (for example, matrix microcracking, fiber/matrix debonding, delamination, cyclic fatigue crack growth, etc.)

4.6 Cumulative damage due to cyclic fatigue may be influenced by testing mode, testing rate (related to frequency), differences between maximum and minimum force (R or A), effects of processing or combinations of constituent materials, and/or environmental influences (including test environment and pre-test conditioning), or both. Some of these effects may be consequences of stress corrosion or sub critical (slow) crack growth which can be difficult to quantify. Other factors which may influence cyclic fatigue behavior are: matrix or fiber material, void or porosity content, methods of test specimen preparation or fabrication, volume percent of the reinforcement, orientation and stacking of the reinforcement, test specimen conditioning, test environment, force or strain limits during cycling, wave shapes (that is, sinusoidal, trapezoidal, etc.), and failure mode of the CFCC.

4.7 The results of cyclic fatigue tests of test specimens fabricated to standardized dimensions from a particular material or selected portions of a part, or both, may not totally represent the cyclic fatigue behavior of the entire, full-size end product or its in-service behavior in different environments.

4.8 However, for quality control purposes, results derived from standardized tensile test specimens may be considered indicative of the response of the material from which they were taken for given primary processing conditions and post-processing heat treatments.

4.9 The cyclic fatigue behavior of a CFCC is dependent on its inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or both. There can be significant damage in the CFCC test specimen without any visual evidence such as the occurrence of a macroscopic crack. This can result in a loss of stiffness and retained strength. Depending on the purpose for which the test is being conducted, rather than final fracture, a specific loss in stiffness or retained strength may constitute failure. In cases where fracture occurs, analysis of fracture surfaces and fractography, though beyond the scope of this practice, is recommended.

5. Interferences

5.1 Test environment (vacuum, inert gas, ambient air, etc.) including moisture content (for example, relative humidity) may have an influence on the measured cyclic fatigue behavior. In particular, the behavior of materials susceptible to slow crack growth fracture will be strongly influenced by test environment and testing rate. Conduct tests to evaluate the maximum strength potential of a material in inert environments or at sufficiently rapid testing rates, or both, to minimize slow crack growth effects. Conversely, conduct tests in environments or at test modes, or both, and rates representative of service conditions to evaluate material performance under use conditions. Regardless of whether testing is conducted in uncontrolled ambient air or controlled environments, monitor and report relative humidity and temperature at a minimum at the beginning and end of each test, and hourly (if possible) if the test duration is greater than 1 h. Testing at humidity levels greater than 65 % relative humidity (RH) is not recommended.

5.2 Rate effects in many CFCCs may play important roles in degrading cyclic fatigue performance. In particular, high testing rates (that is, high frequency) may cause localized heating due to frictional sliding of debonded fibers within the matrix. Such

³ A Guide for Fatigue Testing and The Statistical Analysis of Fatigue Data, ASTM STP 91 A, ASTM, 1963. Alternative reference: *Fatigue Data Analysis*, R.C. Rice, in ASM Handbook, Vol 8, 1985, pp. 695–720.

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

sliding may accelerate mechanical degradation of the composite leading to rapid cyclic fatigue failures. Conversely, low testing rates (that is, low frequency or wave forms with plateaus) may serve to promote environmental degradation as the material is exposed to maximum tensile stresses for longer periods of time.

5.3 In many materials, amplitude of the cyclic wave form is a primary contributor to the cyclic fatigue behavior. Thus, choice of force ratio, R or A , can have a pronounced effect on the cyclic fatigue behavior of the material. A force ratio of $R = 1$ (that is, maximum equal to minimum) constitutes a constant force test with no fluctuation of force over time. A force ratio of $R = 0$ (that is, minimum equal to zero) constitutes the maximum amplitude (that is, amplitude equal to one half the maximum) for tension-tension cyclic fatigue. A force ratio of $R = 0.1$ is often chosen for tension-tension cyclic fatigue so as to impose maximum amplitudes while minimizing the possibility of a “slack” (that is, loose and non-tensioned) force train. The choice of R or A is dictated by the final use of the test result.

5.4 Surface preparation of test specimens, although normally not considered a major concern in CFCCs, can introduce fabrication flaws which may have pronounced effects on cyclic fatigue behavior (for example, shape and level of the resulting stress-strain curves, cyclic fatigue limits, etc.). Machining damage introduced during test specimen preparation can be either a random interfering factor in the determination of cyclic fatigue or ultimate strength of pristine material (that is, more frequent occurrence of surface-initiated fractures compared to volume-initiated fractures), or an inherent part of the strength characteristics to be measured. Surface preparation can also lead to the introduction of residual stresses. Universal or standardized methods for surface preparation do not exist. In addition, the nature of fabrication used for certain composites (for example, chemical vapor infiltration or hot pressing) may require the testing of specimens in the as-processed condition (that is, it may not be possible to machine the test specimen faces without compromising the in-plane fiber architecture). Note that final machining steps may, or may not, negate machining damage introduced during the initial machining. Thus, report test specimen fabrication history since it may play an important role in the cyclic fatigue behavior.

5.5 Bending in uniaxial tensile tests can cause or promote non-uniform stress distributions with maximum stresses occurring at the test specimen surface leading to non-representative fractures originating at surfaces or near geometrical transitions. In addition, if deformations or strains are measured at surfaces where maximum or minimum stresses occur, bending may introduce over or under measurement of strains depending on the location of the strain-measuring device on the test specimen. Similarly, fracture from surface flaws may be accentuated or suppressed by the presence of the non-uniform stresses caused by bending.

5.6 Fractures that initiate outside the uniformly-stressed gage section of a test specimen may be due to factors such as stress concentrations or geometrical transitions, extraneous stresses introduced by gripping, or strength-limiting features in the microstructure of the test specimen. Such non-gage section fractures will normally constitute invalid tests. In addition, for face-forced geometries, gripping pressure is a key variable in the initiation of fracture. Insufficient pressure can shear the outer plies in laminated CFCCs; while too much pressure can cause local crushing of the CFCC and may initiate fracture in the vicinity of the grips.

6. Apparatus

6.1 *Tensile Testing Machines*—Machines used for determining proportional limit stress, ultimate strength or other “static” material properties shall conform to Practices E4. Machines used for cyclic fatigue testing may be either nonresonant mechanical, hydraulic, or magnetic systems or resonant type using forced vibration excited by magnetic or centrifugal force and shall conform to Practice E467.

6.2 *Gripping Devices*—Devices used to grip the test specimens may be of the types discussed in 6.2 of Test Method C1275 as long as they meet the requirements of this practice and Test Method C1275.

6.3 *Load Train Couplers*—Devices used to align the load train and to act as an interface between the gripping devices and the testing machine may be of the types discussed in 6.3 of Test Method C1275 as long as they meet the requirements of this practice and Test Method C1275.

6.4 *Strain Measurement*—Determine strain by means of either a suitable extensometer or strain gages as discussed in Test Method C1275. Extensometers shall satisfy Practice E83, Class B-1 requirements and are recommended instead of strain gages for test specimens with gage lengths of ≥ 25 mm. Calibrate extensometers periodically in accordance with Practice E83.

6.5 *Allowable Bending*—Analytical and empirical studies of the effect of bending on the cyclic fatigue behaviour of CFCCs do not exist. Until such information is forthcoming for CFCCs, this practice adopts the recommendations of Test Method C1275. However, note that unless all test specimens are properly strain gaged and percent bending is monitored during testing, there will be no record of percent bending for each test specimen. Therefore, verify the testing system using the procedures detailed in Practice E1012 and Test Method C1275 such that percent bending does not exceed five at a mean strain equal to either one half of the anticipated strain at the onset of the cumulative fracture process (for example, matrix-cracking stress) or a strain of 0.0005 (that is, 500 micro strain) whichever is greater. Conduct the verification at a minimum at the beginning and end of each test series as recommended in Test Method C1275. An additional verification of alignment is recommended, although not required, at the middle of the test series. In addition, plot a curve of percent bending vs. the test parameter (force, displacement, strain, etc.) to assist in determining the role of bending over the course of the wave form from the minimum to the maximum.

6.6 *Data Acquisition*—If desired, obtain an autographic record of applied force and gage section elongation or strain versus time at discrete periods during cyclic fatigue testing. Either analog chart recorders or digital data acquisition systems can be used for this purpose although a digital record is recommended for ease of later data analysis. Ideally, use an analog chart recorder or plotter

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 shall be accurate to 1.0 % of the recording range and shall have minimum data sampling and acquisition rates sufficient to adequately describe the loading cycle (for example, ~ 100 data points per cycle).

6.7 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured. Measure cross-sectional dimensions to within 0.02 mm using dimension-measuring devices with accuracies of 0.01 mm.

6.8 *Temperature Measurement*—Cyclic fatigue tests may be run at high cyclic frequencies (>50 Hz) that can cause internal heating of the test specimen thereby affecting the cyclic fatigue life especially in the case of debonded and sliding ~~fibers~~ fibers (Ref (3)). If test specimen heating is likely to occur or when there is doubt, monitor the test specimen temperature during the cycling. Possible methods are: the use of radiation thermometer, thermocouples adhered to the specimen, or optical pyrometry.

6.8.1 *Environmental Conditions*—For ambient temperature tests conducted under constant environmental conditions, control temperature and relative humidity to within $\pm 3^{\circ}\text{C}$ and $\pm 10\%$ RH, respectively. Measure and report temperature and relative humidity in accordance with 9.3.5.

7. Precautionary Statement

7.1 During the conducting of this practice, the possibility of flying fragments of broken test material may be high. The brittle nature of advanced ceramics and the release of strain energy contribute to the potential release of uncontrolled fragments upon fracture. Means for containment and retention of these fragments for safety purposes as well as later fractographic reconstruction and analysis are recommended.

7.2 Exposed fibers at the edges of CFCC specimens present a hazard due to the sharpness and brittleness of the ceramic fiber. Inform all persons required to handle these materials of such conditions and the proper handling techniques.

8. Test Specimen

8.1 *Test Specimen Geometry*—Tensile test specimens as discussed in 8.1 of Test Method C1275 may be used for cyclic fatigue testing as long as they meet the requirements of this practice and Test Method C1275.

8.2 *Test Specimen Preparation*—Test specimen fabrication and preparation methods as discussed in 8.2 of Test Method C1275 may be used for cyclic fatigue testing as long as they meet the requirements of this practice and Test Method C1275.

8.3 *Handling Precaution*—Exercise care in storing and handling finished test specimens to avoid the introduction of random and severe flaws. In addition, give attention to pre-test storage of test specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of test specimens prior to testing. If conditioning is required, Test Methods D3479/D3479M recommends conditioning and testing polymeric composite test specimens in a room or enclosed space maintained at a temperature and relative humidity of $23 \pm 3^{\circ}\text{C}$ and $65 \pm 10\%$, respectively. Measure ambient conditions in accordance with Test Method E337.

8.4 *Number of Test Specimens*—The number of test specimens will depend on the purpose of the particular test. Refer to STP 91–A as a guide to determining the number of test specimens and statistical methods.

8.5 *Valid Tests*—A valid individual test is one that meets all the following requirements: all the testing requirements of this Practice and Test Method C1275, and for a test involving a failed test specimen, failure occurs in the uniformly-stressed gage section unless those tests failing outside the gage section are interpreted as interrupted tests for the purpose of censored test analyses.

9. Procedure

9.1 *Test Specimen Dimensions*—Determine the thickness and width of the gage section of each test specimen to within 0.02 mm on at least three different cross-sectional planes in the gage section. To avoid damage in the critical gage section area perform these measurements optically (for example, an optical comparator). Alternatively, mechanical measurements may be made using flat-anvil, ball-tipped, or sharp-anvil micrometers exercising extreme caution to prevent damage to the test specimen gage section. In any case the resolution of the instrument shall be as specified in 6.7. Record and report the measured dimensions and locations of the measurements for use in the calculation of stresses and strains. Use the average of the multiple measurements in the stress calculations.

9.1.1 Conduct periodic, if not 100 %, inspection/measurements of all test specimens and test specimen dimensions to ensure compliance with the drawing specifications. High-resolution optical methods (for example, an optical comparator) or high-resolution digital point contact methods (for example, coordinate measurement machine) are satisfactory as long as the equipment meets the specifications in 6.7.

NOTE 1—The frequency of occurrence of gage section fractures and bending in the gage section are dependent on proper overall test specimen dimensions within the required tolerances.

9.1.2 In some cases, it is desirable, but not required, to measure surface finish to quantify the surface condition. Such methods as contacting profilometry can be used to determine surface roughness perpendicular to the tensile axis. When quantified, report surface roughness as average surface roughness, R_a , or root-mean-square surface roughness, R_q , at a minimum.

9.2 *Test Modes and Rates*: