Standard Practice for Constant-Amplitude, Axial, Tension-Tension Cyclic Fatigue of Advanced Ceramics at Ambient Temperatures[1]

This standard is issued under the fixed designation C 1361; 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 behaviour and performance of advanced ceramics at ambient temperatures to establish "baseline" cyclic fatigue performance. This practice builds on experience and existing standards in tensile testing advanced ceramics at ambient temperatures and addresses various suggested test specimen geometries, test 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 non uniform or multiaxial stress states).

1.2 This practice applies primarily to advanced ceramics that macroscopically exhibit isotropic, homogeneous, continuous behaviour. While this practice applies primarily to monolithic advanced ceramics, certain whisker- or particle-reinforced composite ceramics as well as certain discontinuous fibre-reinforced composite ceramics may also meet these macroscopic behaviour assumptions. Generally, continuous fibre-reinforced ceramic composites (CFCCs) do not macroscopically exhibit isotropic, homogeneous, continuous behaviour and application of this practice to these materials is not recommended.

1.3 The values stated in SI units are to be regarded as the standard and are in accordance with Practice E 380.

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:*

C 1145 Terminology on Advanced Ceramics[2]

C 1273 Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures[2]

C 1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics[2]

E 4 Practices for Force Verification of Testing Machines[3]

E 6 Terminology Relating to Methods of Mechanical Testing[3]

E 83 Practice for Verification and Classification of Extensometers[3]

E 337 Test Method for Measured Humidity with Psychrometer (the Measurement of Wet-and Dry-Bulb Temperatures)[4]

E 467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System[3]

E 468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials[3]

E 739 Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data[3]

E 1012 Practice for Verification of Specimen Alignment Under Tensile Loading[3]

E 1823 Terminology Related to Fatigue and Fracture Testing[3]

IEEE/ASTM SI 10 Standard for Use of the International System of Units (SI) (The Modern Metric System)[5]

2.2 *Military Handbook:*

MIL-HDBK-790 Fractography and Characterization of Fracture Origins in Advanced Structural Ceramics[6]

3. Terminology

3.1 *Definitions*—Definitions of terms relating to advanced ceramics, cyclic fatigue, and tensile testing as they appear in Terminology C 1145, Terminology E 1823, and Terminology E 6, 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.

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[1] This practice is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.01 on Properties and Performance.

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[2] *Annual Book of ASTM Standards*, Vol 15.01

[3] *Annual Book of ASTM Standards*, Vol 3.01.

[4] *Annual Book of ASTM Standards*, Vol 11.03.

[5] *Annual Book of ASTM Standards*, Vol 14.02.

[6] Available from Army Research Laboratory-Materials Directorate, Aberdeen Proving Ground, MD 21005.

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 C 1145.)

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 E 1012.)

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 E 1012.)

3.2.4 *constant amplitude loading, n*—in cyclic fatigue loading, a loading in which all peak loads are equal and all of the valley forces are equal. (See Terminology E 1823.)

3.2.5 *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 E 1823.) See Fig. 1 for nomenclature relevant to cyclic fatigue testing.

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

3.2.5.2 *Discussion*—Fluctuations may occur both in load and with time (frequency) as in the case of random vibration.

3.2.6 *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 E 1823.)

3.2.7 *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, $N>10^6$-10^7). (See Terminology E 1823)

3.2.7.1 *Discussion*—Certain materials and environments preclude the attainment of a cyclic fatigue limit. Values tabulated as cyclic 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.

3.2.8 *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 E 1823.)

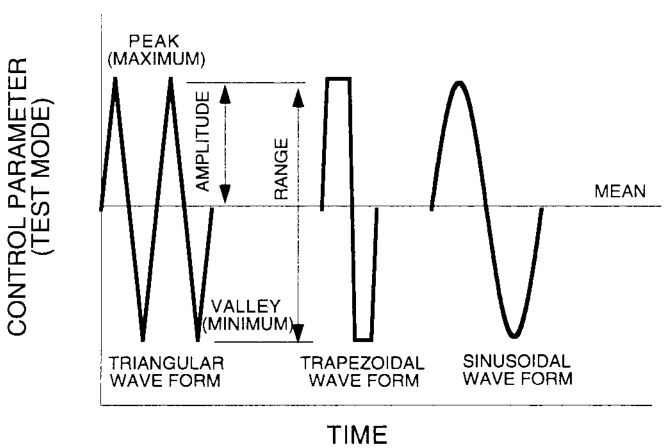

FIG. 1 Cyclic Fatigue Nomenclature and Wave Forms

3.2.9 *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 E 6.)

3.2.10 *load ratio, n*—in cyclic fatigue loading, the algebraic ratio of the two loading parameters of a cycle; the most widely used ratios (see Terminology E 1823):

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

and:

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

3.2.11 *modulus of elasticity* $[FL^{-2}]$, *n*—the ratio of stress to corresponding strain below the proportional limit. (See Terminology E 6.)

3.2.12 *percent bending, n*—the bending strain times 100 divided by the axial strain. (See Practice E 1012.)

3.2.13 *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 E 1823 and Practice E 468.)

3.2.14 *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.

3.2.15 *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 E 6.)

3.3 Definitions of Terms Specific to This Standard:

3.3.1 *maximum stress,* S_{max} $[FL^{-2}]$, *n*—the maximum applied stress during cyclic fatigue.

3.3.2 *mean stress,* S_{max} $[FL^{-2}]$, *n*—the average applied stress during cyclic fatigue such that

$$S_m = \frac{S_{max} + S_{min}}{2} \tag{1}$$

3.3.3 *minimum stress,* $S_{min}[FL^{-2}]$, *n*—the minimum applied stress during cyclic fatigue.

3.3.4 *stress amplitude,* S_a $[FL^{-2}]$, *n*—the difference between the mean stress and the maximum or minimum stress such that

$$S_a = \frac{S_{max} - S_{min}}{2} = S_{max} - S_m = S_m - S_{min} \tag{2}$$

3.3.5 *stress range,* ΔS *or* S_r $[FL^{-2}]$,, *n*—the difference between the maximum stress and the minimum stress such that $\Delta S = S_r = S_{max} - S_{min}$

3.3.6 *time to cyclic fatigue failure, tf [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 High-strength, monolithic advanced ceramic materials are generally characterized by small grain sizes (<50 µm) and bulk densities near the theoretical density. These materials are candidates for load-bearing structural applications requiring high degrees of wear and corrosion resistance, and high-temperature strength. Although flexural test methods are commonly used to evaluate strength of advanced ceramics, the non uniform stress distribution in a flexure specimen limits the volume of material subjected to the maximum applied stress at fracture. Uniaxially-loaded tensile strength tests may provide information on strength-limiting flaws from a greater volume of uniformly stressed material.

4.3 Cyclic fatigue by its nature is a probabilistic phenomenon as discussed in STP 91A and STP 588.**(1,2)**[7] In addition, the strengths of advanced ceramics 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, **(1)** STP 588, **(2)** and Practice E 739. The many different tensile 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 or surface area of material in the gage section of the test specimens.

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

4.5 Cumulative damage processes 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, or environmental influences, or both. Other factors that influence cyclic fatigue behaviour are: void or porosity content, methods of test specimen preparation or fabrication-,test specimen conditioning, test environment, force or strain limits during cycling, wave shapes (that is, sinusoidal, trapezoidal, etc.), and failure mode. Some of these effects may be consequences of stress corrosion or sub critical (slow) crack growth which can be difficult to quantify. In addition, surface or near-surface flaws introduced by the test specimen fabrication process (machining) may or may not be quantifiable by conventional measurements of surface texture. Therefore, surface effects (for example, as reflected in cyclic fatigue reduction factors as classified by Marin **(3)**) must be inferred from the results of numerous cyclic fatigue tests performed with test specimens having identical fabrication histories.

4.6 The results of cyclic fatigue tests of 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.

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

4.7 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.

4.8 The cyclic fatigue behavior of an advanced ceramic 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 test specimen without any visual evidence such as the occurrence of a macroscopic crack. This can result in a specific 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, are 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 mechanical cyclic fatigue behaviour of a material in inert environments to minimize slow crack growth effects. Conversely, conduct tests in environments or at test modes and rates representative of service conditions to evaluate material performance under use conditions, or both. 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 the test duration is greater than 1 h. Testing at humidity levels greater than 65 % relative humidity (RH) is not recommended.

5.2 While cyclic fatigue in ceramics is sensitive to environment at any stress level **(4)** environment has been shown to have a greater influence on cyclic fatigue at higher forces (that is, forces greater than the threshold for static fatigue **(5)**). In this regime, the number of cycles to failure may be influenced by test frequency and wave form. Tests performed at low frequency with wave forms having plateaus may decrease the cycles to failure since the material is subject to maximum tensile stresses (that is, similar to static fatigue) for longer periods of time during each cycle. Conversely, at lower stress levels the cycles to failure are usually not influenced by frequency or wave form, except as noted in 4.3.

5.3 In many materials, amplitude of the cyclic wave form is a primary contributor to the cyclic fatigue behavior. However, in ceramics the maximum stress intensity factor may be the primary contributor of the cyclic fatigue behaviour. Nonetheless, the choice of load ratio, *R* or A, can have a pronounced effect on the cyclic fatigue behavior of the material. A force ratio of R=1 (maximum equal to minimum) constitutes a constant force test with no fluctuation of force over time. A force ratio of R=0 (minimum equal to zero) constitutes the maximum amplitude (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" (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 can introduce fabrication flaws that may have pronounced effects on cyclic fatigue behavior (for example, cyclic fatigue limits, etc.). Machining damage introduced during test specimen preparation can be either a random interfering factor in the determination of 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. Final machining steps may or may not negate machining damage introduced during the initial machining. In addition, the nature of fabrication used for certain advanced ceramics (for example, pressureless sintering or hot pressing) may require the testing of test specimens in the as-processed condition (that is, it may not be allowable to machine the test specimen surfaces within the gage length). Thus, the surface condition produced by processing may dominate cyclic fatigue behaviour. Ideally some quantitative measurement such as surface roughness is recommended as a way of characterizing as-processed surfaces to facilitate interpretation of cyclic fatigue test results. Therefore, report the 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 nonuniform stress distributions with maximum stresses occurring at the test specimen surface leading to possible non-representative fractures originating at surfaces or near geometrical transitions (as opposed to fractures originated from pre-existing or inherent flaws). 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.

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 may constitute invalid tests.

6. Apparatus

6.1 *Tensile Testing Machines*—Machines used for determining ultimate strength or other "static" material properties shall conform to Practices E 4. Machines used for cyclic fatigue testing may be either nonresonant mechanical, hydraulic, or magnetic systems or resonant type using forced vibrations excited by magnetic or centrifugal force and shall conform to Practice E 467.

6.2 *Gripping Devices*—Devices used to grip the tensile specimens may be of the types discussed in 6.2 of Test Method C 1273 as long as they meet the requirements of this practice and Test Method C 1273.

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 C 1273 as long as they meet the requirements of this practice and Test Method C 1273.

6.4 *Strain Measurement*—Determine strain by means of either a suitable extensometer or strain gages as discussed in Test Method C 1273. Extensometers shall satisfy Practice E 83, 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 E 83.

6.5 *Allowable Bending*—Analytical and empirical studies of the effect of bending on the cyclic fatigue behavior of advanced ceramics do not exist. Until such information is forthcoming, this practice adopts the recommendations of Test Method C 1273. However, unless all test specimens are properly strain gaged and percent bending monitored during testing there will be no record of percent bending for each test specimen. Therefore, verify the testing system using the procedure detailed in Practice E 1012 and Test Method C 1273 such that percent bending does not exceed five at a mean strain equal to either one half of the anticipated strain at fracture under monotonic tensile strength testing conditions or a strain of 0.0005 (that is 500 micro strain) whichever is greater. Conduct this verification at a minimum at the beginning and end of each test series as recommended in Test Method C 1273. 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 versus the test parameter (force, displacement, strain, etc.) to assist in understanding or 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 (hysteresis) of the test specimen thereby affecting the cyclic fatigue life. 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 ±3°C and ±10 % RH, respectively. Measure and report temperature and relative humidity in accordance with 9.3.5.

7. Hazards

7.1 During the conducting of this practice, the possibility of flying fragments of broken test material may be great. 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 as well as later fractographic reconstruction and analysis are recommended.

8. Test Specimen

8.1 *Test Specimen Geometry*—Tensile test specimens as discussed in 8.1 of Test Method C 1273 may be used for cyclic fatigue testing as long as they meet the requirements of this practice and Test Method C 1273.

8.2 *Test Specimen Preparation*—Test specimen fabrication and preparation methods as discussed in 8.2 of Test Method C 1273 may be used for cyclic fatigue testing as long as they meet the requirements of this practice and Test Method C 1273.

8.3 *Handling Precaution*—Exercise care in storing and handling finished specimens to avoid the introduction of random and severe flaws. In addition, give attention to pretest storage of test specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of specimens prior to testing. If conditioning is required, condition or test the specimens, or both in a room or enclosed space maintained at ±3°C and ±10 % relative humidity measured in accordance with Test Method E 337.

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 which meets all the following requirements: all the testing requirements of this practice and Test Method C 1273, 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 diameter or the thickness and width of the gage section of each test specimen, or both, 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 make these measurements either optically (for example, using an optical comparator) or mechanically using a flat, anvil-type micrometer. In either case, the resolution of the instrument shall be as specified in 6.7. Exercise extreme caution to prevent damage to the test specimen gage section. Record and report the measured dimensions and locations of the measurements for use in the calculation of the tensile stress at fracture. Use the average of the multiple measurements in the stress calculations.

NOTE 1—Ball-tipped or sharp-anvil micrometers may damage the test specimen surface by inducing localized cracking and, therefore, are not recommended.

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. 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 of the gage section. When quantified, report the direction(s) of the surface roughness measurement and 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:*

9.2.1 *General*—Test modes and rates can have distinct and strong influences on the cyclic fatigue behavior of advanced ceramics even at ambient temperatures depending on test environment or condition of the test specimen. Test modes may involve load, displacement, or strain control. Maximum and minimum test levels as well as frequency and wave form shape will depend on the purpose for which the tests are being conducted. Sine waves provide smooth transitions from maximums to minimums. R ratios of 0.1 are often used for maximum amplitude effect while avoiding slack (that is loose and non-tensioned) force train. Frequencies are chosen to reflect service conditions, generally ranging from 1 to 10 Hz for exploratory tests and may extend to the 1000 Hz range for materials characterization for components. In all cases report the test mode, maximum test level, minimum test level, frequency, wave form, and R or A ratio.

9.2.2 Prior to cyclic fatigue testing, test a sufficient number of control specimens in accordance with Test Method C 1273. STP 588 may provide guidance for the number of control specimens to test. Use the average of the control tests to establish the 100 % level (that is the uniaxial tensile strength of the material) of the cyclic fatigue tests. Cyclic fatigue tests can then be conducted at maximum stresses or strains as percentages of this 100 % level.

9.3 *Conducting the Cyclic Fatigue Test:*

9.3.1 *Mounting the Specimen*—Each grip interface and test specimen geometry discussed in Test Method C 1273 will require a unique procedure for mounting the specimen in the load train. Identify and report any special components which are required for each test. Mark the test specimen with an indelible marker as to top and bottom and front (side facing the operator) in relation to the test machine. In the case of strain-gaged test specimens, orient the test specimen such that the front of the test specimen and a unique strain gage (for example, strain gage 1 designated SG1) coincide.

9.3.2 *Preparations for Testing*—Set the test mode and frequency on the testing machine. Preload the test specimen to remove the slack from the force train. Determine and report the amount of preload for each situation, specific to each material tensile specimen geometry. If strain is being measured, either mount the extensometer on the test specimen gage section and zero the output, or, attach the lead wires of the strain gages to the signal conditioner and zero the outputs. If temperature is being measured, attach the temperature recording equipment. If required, ready the autograph data acquisition systems for periodic data logging.

NOTE 2—If strain gages are used to monitor bending, zero the strain gages with the test specimen attached at only one end of the fixtures, that is, hanging free. This will ensure that bending due to the grip closure is factored into the measured bending. In addition, if test specimen self-heating due to hysteresis is anticipated, strain gages should be temperature compensated following accepted practice.

9.3.3 *Conducting the Test*—Initiate the data acquisition. Initiate the test mode. After testing has begun, check the loading often unless the testing machine is equipped with automatic load maintainers to ensure that loads at peaks and valleys do not vary by greater than 1.0 %. Refer to Practice E 467. Mass inertia effects of the machine fixtures and specimens shall be calibrated by means of strain gages, Wheatstone bridge, and an oscilloscope or oscillograph for the particular load range and machine speed being used. Corrections of loading shall be made to offset these effects and produce the desired loading cycle. Refer to Practice E 467.

9.3.4 Record the number of cycles and corresponding test conditions at the completion of testing. A test may be terminated for one of several conditions: (*1*) test specimen fracture; (*2*) reaching a pre-determined number of run-out cycles; (*3*) reaching a pre-determined test specimen compliance or material elastic modulus, (*4*) reaching a pre-determined phase lag between control mode and response. At test termination, disable the action of the test machine and the data collection of the data acquisition system. Carefully remove the specimen from the grip interfaces. Take care not to damage the fracture surfaces, if they exist, by preventing them from contacting each other or other objects. Place the specimen along with any fragments from the gage section into a suitable, non-metallic container for later analysis.

9.3.5 Determine and report the test temperature and relative humidity in accordance with Test Method E 337 at a minimum at the beginning and end of each test, and hourly if the test duration is greater than one hour.

9.3.6 *Post-Test Fracture Location*—Measure and report the fracture location relative to the midpoint of the gage section. Use the convention that the midpoint of the gage section is 0 mm with positive (+) measurements toward the top of the specimen as tested (and marked) and negative (–) measurements toward the bottom of the specimen as tested (and marked).

NOTE 3—Results from specimens fracturing outside the uniformly stressed gage section may be considered anomalous. These results from test specimens fracturing outside the gage section can still be used as censored tests (that is, tests in which a stress at lest equal to that calculated by Eq 1 was sustained in the uniform gage section before the test was prematurely terminated by a non-gage section fracture). Censored tests are discussed in STP 91A. To complete a required statistical sample for purposes of establishing cyclic fatigue behavior without censoring, test one replacement specimen for each test specimen which fractures outside the gage section.

9.4 *Fractography*—Conduct visual examination and light microscopy to determine the mode and type of fracture. In addition, although quantitatively beyond the scope of this practice, interpretive observations can be made of orientation of fracture plane and other pertinent details of the fracture surface. Fractographic examination of each failed specimen is recommended to characterize the fracture behavior of advanced ceramics. Fractography can be an interpretative analytical method and the guidelines established in Practice C 1322 and MIL-HDBK-790, are recommended to establish objectivity.

9.4.1 If fractography is conducted, it is useful, but not required to note the position of the fracture origin relative to the some position (for example, "front" or "back") around the circumference of the specimen as inserted into the test machine or as tested. This information may be useful in correlating interpreting the effect of specimen misalignment on cyclic fatigue or strength results.

10. Calculation

10.1 *General*—The basic formulae for calculating engineers parameters are given as follows. Additional guidelines for interpretation and reporting cyclic fatigue results are contained in STP 91A **(1)**, STP 588 **(2)** and Practice E 739.

10.2 *Engineering Stress*—Calculate the engineering stress as:

$$\sigma = \frac{P}{A} \tag{3}$$

where:

σ = engineering stress, MPa,
P = applied, uniaxial tensile force, N, and
A = original cross sectional area, mm^2. The cross-sectional area A is calculated as:

$$A = w\,b \text{ for rectangular cross sections} \tag{4}$$

or:

$$A = \frac{\pi d^2}{4} \text{ for circular cross sections} \tag{5}$$

where:

w = average width,
b = average thickness, and
d = average diameter of the gage section, mm, as detailed in 9.1.

10.3 *Engineering Strain*—Calculate the engineering strain as:

$$\epsilon = \frac{(l - l_o)}{l_o} \tag{6}$$

where:

ϵ = engineering strain,
l = gage length (specimen or extensometer gage length) at any time, mm, and
l_o = original gage length, mm. In the case of strain gages, strain is measured directly and Eq 4 is not required.

11. Report

11.1 *Test Set*—Include in the report the following information for the test set. Note any significant deviations from the procedures and requirements of this practice:

11.1.1 Date and location of testing,

11.1.2 Tensile test specimen geometry used (include engineering drawing),

11.1.3 Type and configuration of the test machine (include drawing or sketch if necessary). If a commercial test machine was used, the manufacturer and model number are sufficient for describing the test machine. Good laboratory practice also dictates recording the serial numbers of the test equipment, if available,

11.1.4 Type, configuration, and resolution of strain measurement equipment used (include drawing or sketch if necessary). If a commercial extensometer or strain gages were used, the manufacturer and model number are sufficient for describing the strain measurement equipment. Good laboratory practice also dictates recording the serial numbers of the test equipment, if available,

11.1.5 Type and configuration of grip interface used (include drawing or sketch if necessary). If a commercial grip interface was used, the manufacturer and model number are sufficient for describing the grip interface. Good laboratory practice also dictates recording the serial numbers of the test equipment, if available,

11.1.6 Type and configuration of load train couplers (include drawing or sketch if necessary). If a commercial load train coupler was used, the manufacturer and model number are sufficient for describing the coupler. Good laboratory practice also dictates recording the serial numbers of the test equipment, if available,

11.1.7 Number (n) of specimens tested validly (for example fracture in the gage section). In addition, report the total of number of test specimens tested (n_T) to provide an indication of the expected success rate of the particular test specimen geometry and test apparatus,

11.1.8 Where feasible and possible, all relevant material data including vintage or billet identification. As a minimum, report the approximate date the material was manufactured,

11.1.8.1 For commercial materials, where feasible and possible, report the commercial designation and lot number,

11.1.8.2 For non-commercial materials, where feasible and possible, report the major constituents and proportions as well as the primary processing route including green state and consolidation routes,

11.1.9 Description of the method of specimen preparation including all stages of machining, cleaning, and storage time and method before testing,

11.1.10 Where feasible and possible, heat treatments, coatings, or pre-test exposures, if any were applied either to the as-processed material or to the as-fabricated test specimen,

11.1.11 Test environment and intervals at which measured, including relative humidity (Test Method E 337), ambient temperature, and atmosphere (for example ambient air, dry nitrogen, silicone oil, etc.),

11.1.12 Test mode (force, displacement, or strain control), wave form, actual frequency of testing and R or A ratio,

11.1.13 The stress-life (S-N) or strain-life (ϵ-N) developed for the entire test series in accordance with Practices E 468 and E 739. Alternatively or additionally, stress-time (S-t_f) or strain-time (ϵ-t_f) can be developed for the entire test series.

11.1.14 Percent bending and corresponding average strain in the specimen recorded during the verification as measured at the beginning and end of the test series. In addition, a curve of percent bending versus the test parameter (force, displacement, strain, etc.) is recommended to assist in understanding the role of bending over the course of testing from the minimum to the maximum.

11.1.15 Mean, standard deviation, and coefficient of variation for the following measured properties of the control specimens for each test series as determined using Test Method C 1273:

11.1.15.1 Tensile strength, S_u,

11.1.15.2 Strain at tensile strength, ϵ_u,

11.1.15.3 Fracture strength, S_f,

11.1.15.4 Strain at fracture strength, ϵ_f, and

11.1.15.5 Modulus of elasticity, E, (if applicable).

11.2 *Individual Test Specimens*—Report the following information for each test specimen tested. Note and report any significant deviations from the procedures and requirements of this practice:

11.2.1 Pertinent overall specimen dimensions, if measured, such as total length, length of gage section, gripped section dimensions, etc., mm,

11.2.2 Average surface roughness, µm, if measured, of gage section and the direction of measurement,

11.2.3 Average cross-sectional dimensions, if measured, or cross-sectional dimensions at the plane of fracture in units of mm,

11.2.4 Plots of periodic stress-strain curves, if so recorded, and corresponding cycles,

11.2.5 Maximum cyclic stress, strain, or displacement,

11.2.6 Minimum cyclic stress, strain, or displacement,

11.2.7 Amplitude of cyclic stress, strain, or displacement,

11.2.8 R or A ratio,

11.2.9 Wave form and frequency of testing, including any hold times,

11.2.10 Cycles or time to test termination, or both, and criterion for test termination,

11.2.11 Fracture location relative to the gage section midpoint in units of mm (+ is toward the top of the test specimen as marked and — is toward the bottom of the test specimen as marked with 0 being the gage section midpoint) if relevant, and

11.2.12 Results of fractographic examination as suggested in 9.4.

12. Keywords

12.1 advanced ceramic; S-N curve; tension-tension cyclic fatigue

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(**2**) *Manual on Statistical Planning and Analysis for Fatigue Experiments, ASTM STP 588*, ASTM, 1975.
(**3**) Marin, J, *Mechanical Behaviour of Engineering Materials*, Prentice-Hall, Englewood Cliffs, NJ, 1962, pp. 224.
(**4**) Jacobs, D.S. and Chen, I.W.," Mechanical and Environmental Factors in the Cyclic and Static Fatigue of Silicon Nitride," *Journal of the American Ceramic Society*, Vol 77, No. 5, 1994, pp. 1153-1161.
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