Designation: C1361 − 10 (Reapproved 2019)

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 C1361; 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 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 nonuniform or multiaxial stress states).

1.2 This practice applies primarily to advanced ceramics that macroscopically exhibit isotropic, homogeneous, continuous behavior. 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 behavior assumptions. Generally, continuous fibre-reinforced ceramic composites (CFCCs) do not macroscopically exhibit isotropic, homogeneous, continuous behavior 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 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* Refer to Section 7 for specific precautions.

1.5 *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]

C1145 Terminology of Advanced Ceramics

C1273 Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures

C1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics

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 (ε-***N***) Fatigue Data

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

E1823 Terminology Relating to Fatigue and Fracture Testing

IEEE/ASTM SI 10 American National Standard for Metric Practice

2.2 *Military Handbook:*[3]

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

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

Current edition approved July 1, 2019. Published July 2019. Originally approved in 1996. Last previous edition approved in 2015 as C1361 – 10 (2015). DOI: 10.1520/C1361-10R19.

[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.

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

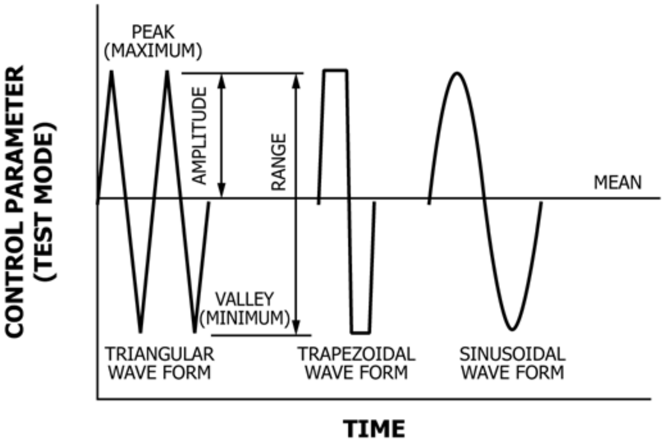

FIG. 1 Cyclic Fatigue Nomenclature and Wave Forms

3. Terminology

3.1 *Definitions*—Definitions of terms relating to advanced ceramics, cyclic fatigue, and tensile testing as they appear in Terminology C1145, Terminology E1823, and Terminology E6, 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 parentheses. 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 *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 E1823.)

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 E1823.) 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 E1823.)

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 E1823.)

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 E1823.)

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 E6.)

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 E1823):

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

and:

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

3.2.11 *modulus of elasticity* $[FL^{-2}]$, *n*—the ratio of stress to corresponding strain below the proportional limit. (See Terminology E6.)

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

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 E1823 and Practice E468.)

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 E6.)

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

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

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 nonuniform 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**).[4] 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 E739. 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 nonlinear 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 behavior 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.

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 behavior 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

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

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 behavior. 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 behavior. 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 nonrepresentative 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 E4. 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 E467.

6.2 *Gripping Devices*—Devices used to grip the tensile specimens may be of the types discussed in 6.2 of Test Method C1273 as long as they meet the requirements of this practice and Test Method C1273.

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 C1273 as long as they meet the requirements of this practice and Test Method C1273.

6.4 *Strain Measurement*—Determine strain by means of either a suitable extensometer or strain gages as discussed in Test Method C1273. 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 behavior of advanced ceramics do not exist. Until such information is forthcoming, this practice adopts the recommendations of Test Method C1273. 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 E1012 and Test Method C1273 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 C1273. 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